

Identification of Geomorphosites and Evaluation of Geoheritage Potential using the M-GAM model in the Purulia District, extended part of Chhotanagpur Plateau, India

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Abstract

The Purulia District an extended part of Chhotanagpur Plateau, India, has great potential for geotourism development because this region experiences a diverse landscape like hills, dams, forests, inselbergs, tors, badlands, springs, waterfalls, and ravines, etc. However, geotourism has not yet fully developed in this region. The main objective of the study is to identify geomorphosites and evaluate the geoheritage potential of the Chhotanagpur Granite Gneissic Complex, particularly in Purulia District. Hence, thirty significant geological or geomorphological sites have been identified for evaluating their geoheritage values and investigating the Geotourism potential. The M-GAM model is adopted for the evaluation of these thirty identified geomorphosites, where the main values and additional values, i.e., scientific/educational values, scenic/aesthetic values, protective values, functional values, and touristic values, are considered. The outcome revealed that a total of eleven geomorphosites come under the Z_{32} field in the M-GAM matrix, representing the highest-ranked category. These include G6-Joychandi Pahar, G7-Chamtaburu Hill, G8-Gorgaburu Hill, G9-Panchakot Pahar, G10-Pakhi Pahar, G11-Mayur Pahar, G12-Gajaburu Hill, G25-Sitakundu Spring, G26-Bamni Falls, G27-Turga Falls, and G30-Khairabera Hill and Forest. These geomorphosites exhibit high main values and high additional values, indicating strong geoheritage importance as well as great geotourism potential. Among all evaluated geomorphosites, G8-Gorgaburu Hill occupies the most valuable geomorphosite, having the highest main values (9.38) and additional value (9.49), whereas nine geomorphosites are categorized within the Z_{22} field, indicating moderate geoheritage and tourism potential. The remaining ten geomorphosites come under the Z_{21} field, characterized by moderate main values but comparatively low additional values. These sites, including G1, G13, G22, G3, G23, G24, G19, G5, G21, and G4 remain low in the context of Geoheritage values. Enhanced accessibility, infrastructure development, and community-based geotourism initiatives could substantially improve their geoheritage utilization.

Keywords: Geosites, Geomorphosites, Geoheritage, Purulia District, M-GAM

1. Introduction

Identification and evaluation of geosites or geomorphosites-related research has emerged in recent decades (Reynard et al. 2016; Reynard and Brilha 2018; Santos et al. 2020; Ghosh et al. 2021; Mahato and Jana 2021; Zorlu et al. 2023; Zorlu and Dede 2023; Quesada-Valverde and Quesada-Roman 2025). In recent years, geomorphosites identification, valuation, geoheritage declaration, and geoconservation-related research still remain pivotal in Geoscience (Quesada-Valverde and Quesada-Roman 2023). Subsequently, geoheritage and geoconservation are interconnected disciplines dedicated to the conservation, sustainable management, and safeguarding of important geomorphological and geological landscapes. This kind of research has advanced considerably in temperate regions, whereas its application in tropical regions remains limited (Quesada-Roman and Perez-Umana 2020). Global assessments of geoconservation and geoheritage-related research were dominated by Italy, Poland, Brazil, Russia, and Egypt, while China contributes the majority of publications. Despite the significant geological and geomorphological diversity in India, there have not been any such scientific articles published from India. So, there is a big methodological, and evidence-based research gap that has been portrayed. It was mentioned by V. S. Kale (2014) that India has rich geological diversity, tectonic history, climatic heterogeneity, and long coastal extent, but due to the lack of a systematic inventory of geosites, geomorphosites, and geoheritage resources for geotourism development, India has failed to stand on the global geosites or geomorphosites map.

According to A. Gary (2004), geodiversity refers to the diversity of geological, geomorphological, and soil features, including their constituent elements, processes, interrelationships, properties, and associated systems, which together represent the abiotic wealth of a region. Geoheritage comprises geodiversity elements that hold notable scientific, cultural, educational, and tourism value. Geosites or geomorphosites, which are the in situ expressions of geodiversity, serve as representative features of a region's geological heritage (Brilha and Reynard 2018; Brilha 2017). They include significant rocks, minerals, fossils, soils, geomorphological features, landscapes and geological or geomorphological processes that together express the abiotic diversity of a region (Brilha 2016; Brilha 2018). Geosites

can be understood through either restrictive or broader approach (Reynard 2009; Brilha 2016). The restrictive approach esteems geosites as geological features of notable paleogeographic significance that warrant conservation (Grandgirard 1999). Conversely, the broader approach includes all geodiversity elements having value from scientific, ecological, economic, cultural, or aesthetic viewpoints. Given its relevance to geotourism development and public engagement, the broader definition is adopted in this study (Panizza 2001; Reynard 2009; Coratza and Hoblea 2018; Santos et al. 2020). The main focus of geotourism is to promote the conservation of natural heritage and related cultural values through educational, interpretive, and recreational activities (Gordon 2018). This focus begins a close connection between geoheritage and geotourism. Hose and Vasiljevic (2012) described geotourism as a context that provides interpretation and visitor services at geoheritage sites and geomorphosites, along with their associated landscapes and features, to enhance public understanding, support research and education, and make stronger conservation outcomes across generations (Hose 2012; Kubalíková 2013; Antic and Tomic 2017).

Identification and conservation of geosites or geomorphosites and geoheritage sites in India have gained momentum in recent decades (Ghosh et al. 2021). The Geological Survey of India first recognized 26 geoheritage sites in 2001 to preserve significant geological features and promote awareness of India's geological history through geotourism. In 2016, the Ministry of Mines, with support from the GSI and state governments, expanded the list by adding six more geoheritage sites. These designated sites are predominantly located in western and southern states, including Rajasthan, Gujarat, Maharashtra, Kerala, Karnataka, Tamil Nadu, and Andhra Pradesh, with comparatively fewer occurrences other part in the country. Although several researchers have identified and assessed potential geoheritage sites across India, studies from eastern India remain comparatively fewer. Thus, our study seeks to fill this knowledge gap by focusing on the objective of identifying of geomorphosites and evaluating of geoheritage potential of the Chhotanagpur Granite Gneissic Complex, particularly in the Purulia District, West Bengal, India. The study documents the geological and geomorphological attributes and evaluates their geoheritage potential to promote the conservation of geoheritage resources in Purulia District.

2. Methods and Materials

2.1. Study area and geological background

In India, there is exceptional geodiversity, encompassing a wide variety of landscapes such as mountain systems, hills, plateaus, plains, lakes, and extensive coastal environments. These diverse topographic features preserve valuable evidence of the country's long and complex geological evolution over billions of years. Among the geologically significant regions of eastern India, the Purulia district of West Bengal presents a distinctive palaeogeographic setting that records some of the earliest stages of crustal development. Purulia District is situated in the western part of the Indian state of West Bengal, bounded by latitudes of 22°42' N to 23°42' N and longitudes of 85°49' E to 86°54' E (Fig. 1). Geological investigations indicate that the basement rocks of the region originated during the Archean Eon, approximately 4 to 5 billion years ago, when life had not yet emerged, and much of present-day Bengal remained submerged beneath ancient seas (Bhattacharya et al. 1985). A major portion of Purulia is part of the Indian Peninsular Shield and displays a complex geological framework. Based on age and origin, the district can broadly be classified into two geomorphic domains: (i) the Archean crystalline shield terrain and (ii) the Gondwana sedimentary basin comprising glacial and fluvial deposits accumulated during the Upper Carboniferous to Triassic periods. The geological architecture of the district has been profoundly influenced by two major tectonic structures, namely the North Purulia Shear Zone (NPSZ) and the South Purulia Shear Zone (SPSZ), which extend along the northern and southern sectors of the district, respectively (Fig. 2). These shear zones have played a crucial role in controlling rock deformation, structural orientation, folding, faulting, and overall landscape evolution. The district is characterized by an undulating terrain dotted with numerous hills and isolated hillocks. Much of the area is covered by red, nutrient-deficient soils that limit agricultural productivity. Coupled with the absence of large-scale industrial development, these environmental and economic constraints have contributed to persistent socioeconomic challenges. Nevertheless, the district possesses an abundance of geological and geomorphological features of scientific, educational, and aesthetic significance. Given this rich geoheritage base, the development of geotourism offers a promising avenue for sustainable regional

110 development, providing opportunities for income generation, heritage conservation, and community

111 participation while enhancing public appreciation of the district's unique geological legacy.

112 **Table 1** Identified geomorphosites in the Purulia District of West Bengal.

Levels of Geomorphosites	Geomorphosites name	Latitude (N)	Longitude (E)
G1	Paharigora Hill	23.552972	86.460552
G2	Pabra Hill	23.600128	86.644066
G3	Bero Hill	23.539482	86.760751
G4	Tilaboni Hill	23.416617	86.551937
G5	Bara Panjania	23.411114	86.518203
G6	Joychandi Pahar	23.522569	86.667339
G7	Chamtaburu	23.276267	85.987801
G8	Gorgaburu	23.144767	86.127224
G9	Panchakot Pahar	23.623628	86.764551
G10	Pakhi Pahar	23.220924	86.123412
G11	Mayur Pahar	23.119435	86.104470
G12	Gajaburu Hill	23.300263	85.997156
G13	Kansra Hill	23.374917	85.956131
G14	Bansa Hill	23.366225	85.926368
G15	Shikra Hill	23.374133	85.959398
G16	Paparu Hill	23.387445	85.928687
G17	Dhalburu Hill	23.382995	85.935536
G18	Belamu Pahar	23.465850	86.052528
G19	Jargobudhi Pahar	23.300491	85.903361
G20	Hathi Pahar	23.290581	86.013054
G21	Kopila Hill	23.385997	85.973396
G22	Tilai Pahar	23.185727	86.231792
G23	Mesya Pahar	23.248299	86.223078
G24	Ushuldunri Pahar	23.204378	86.179481
G25	Sitakundu Spring	23.208197	86.122166
G26	Bamni Falls	23.199627	86.085316
G27	Turga Falls	23.199983	86.075366
G28	Machkanda Falls	23.267378	86.042297
G29	Ghageshwari Falls	23.254738	86.116388
G30	Khairabera Hill and Forest	23.265234	86.007380

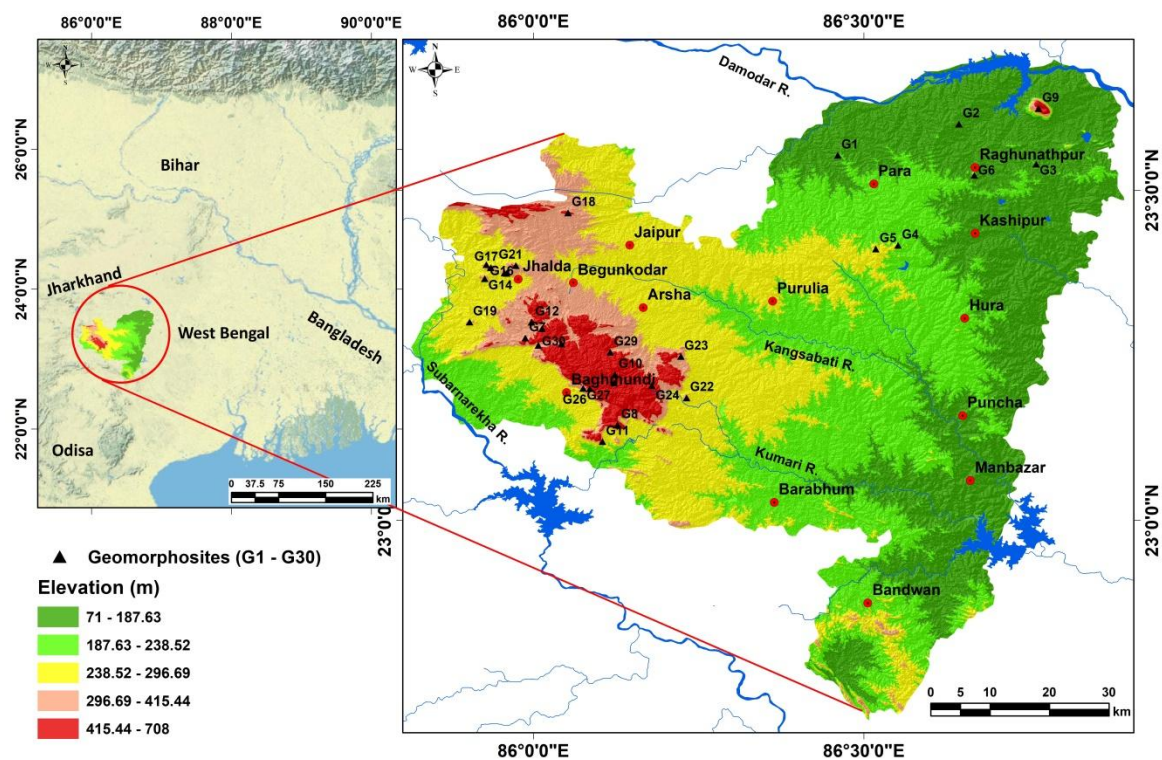


Fig. 1 Location of identified geomorphosites in the Purulia Districts, West Bengal

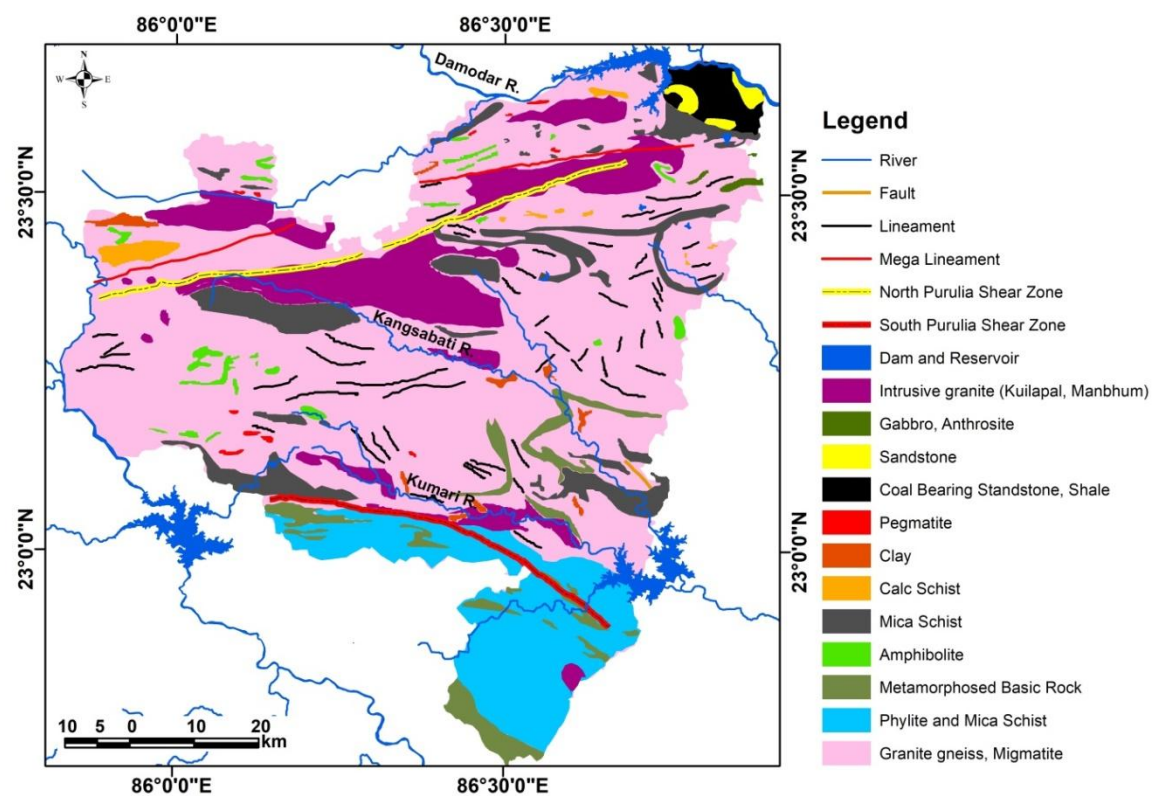


Fig. 2 Geological map of the Purulia District, West Bengal (Geological Survey of India 2022)

2.2. Pre-evaluation stage

The pre-evaluation stage involves an inventory of geomorphosites through extensive fieldwork along with a comprehensive review of existing geological maps, satellite imagery, and prior geomorphological studies to identify potential geomorphosites within the study area. Numerous field trips have been conducted from July 2023 to April 2026 for inventorying the geomorphosites. A multidisciplinary team comprising geomorphologists, geologists, and GIS specialists participated in the field trips, equipped with Garmin handheld GPS devices for aerial exploration. Geomorphosites were inventoried using a standardized protocol adapted from the Inventory of Geosites method proposed by Panizza (2001). Each potential geomorphosite was first located using a high-precision Garmin handheld GPS with sub-meter accuracy, followed by on-site delineation of boundaries via perimeter mapping. Post-field data were digitized using ArcGIS 10.8 software, and M-GAM model were implemented for further analysis. The inventory was validated through cross-checks with peer-reviewed literature and expert consultations to ensure methodological robustness and reproducibility.

2.3. Evaluation stage based on M-GAM model

The Modified Geosite Assessment Model (M-GAM) was proposed by Tomic and Bozic in 2014. The M-GAM has been developed on the foundation of earlier geosite assessment research by various scholars (Hose 1997; Serrano and Gonzalez-Trueba 2005; Bruschi and Cendrero 2005; Pralong 2005; Coratza and Giusti 2005; Pereira and Caetano Alves 2007; Reynard 2008; Erhartic 2010; Tomic 2011; Jonic 2018; Tomic et al. 2020). Opinions of tourists and experts are given equal importance during the evaluation process (Vukovic and Antic 2019; Tomic et al. 2020). The M-GAM contains two main criteria: Main Values (MV) and Additional Values (AV), which are further divided into 12 and 15 sub-criteria, respectively, and each indicator gets weightage within the 0.00 to 1.00. These numerical values are expressed as a five-point Likert scale from low to high importance like 0.00, 0.25, 0.50, 0.75, and 1.00. This classification is based on two broad categories of values: main values, which largely stem from the natural characteristics of the geosites, and additional values, which are predominantly human-induced, and arise from modifications made to facilitate visitors' use. The Main Values (MV) consists of three groups of sub-criteria: VSE, VSA and VPr. On the other hand,

Additional Values (AV) is divided into two groups of sub-criteria: VF_n and VTr. The structure of the main criteria and sub-criteria of the Main Values and Additional Values and their grade values is shown in Table 2.

The total scores, ranging from 0.00 to 1.00, of the 12 sub-criteria under Main Values (MV) and the 15 sub-indicators under Additional Values are determined using the following equation (Equation 1).

$$M - GAM = MV + AV \quad (1)$$

As Main Values and Additional Values consist of 3 and 2 sub-criteria, respectively, and their values are calculated using the following two equations:

$$MV = VSE + VSA + VPr \quad (2)$$

$$AV = VF_n + VTr \quad (3)$$

This procedure is applied to each sub-indicator, after which the values are aggregated according to the M-GAM equation. However, with the inclusion of the importance factor (I_m), the outcomes are more objective and precise. Similar to experts, opinion of visitors is also assigned a numerical value for both Main Values and Additional Values of each sub-criterion. The importance factor (I_m) is then determined as follows equation 4:

$$I_m = \frac{\sum_{k=1}^K Iv_k}{K} \quad (4)$$

Here, Iv_k is the grade for each sub-criterion given by visitors, whereas, K is total number of visitors. Here, the value of I_m can be any value ranging from 0.00 to 1.00. Finally, the M-GAM is expressed by the following equation:

$$M - GAM = MV + AV \quad (5)$$

Where, $MV = \sum_{i=1}^n Im_i \times MV_i$

$AV = \sum_{i=1}^n Im_i \times AV_i$

The M-GAM equation reveals that the I_m values for each sub-criterion, as determined individually by visitors, are multiplied by the corresponding sub-criteria values assigned by experts. Through this procedure, the final value of each sub-criterion within the model is expressed (Table 3 and Table 4).

Criteria/Sub-criteria	0.00	0.25	0.50	0.75	1.00
Main values (MV)					
Scientific/Educational values (VSE)					
C1-Rarity	Common	Regional	National	International	Globally unique
C2-Representativeness	None	Minor	Moderate	Major	Exception
C3-Representation within geoscience	None	Local level	Regional level	National level	International level
C4-Level of interpretation	None	Moderate Complexity; yet challenging to convey to non-experts	Good illustration, but tough to clarify to non- experts	Average complexity; easy to describe to general visitors	Clear illustration; simple to convey to general visitors
Scenic/aesthetic values (VSA)					
C5-Viewing platform	None	1	2-3	4-6	More than 6
C6-Surface	Low	-	Moderate	-	Extensive
C7-Nearby landscape and nature	-	Minor	Moderate	Major	Exception
C8-Environmental fitting of sites	Inappropriate	-	Neutral	-	appropriate
Protection (VPr)					
C9-Present situation	Heavily degraded by human intervention	Severely impacted by natural forces	Moderately degraded (key geomorphic traits intact)	Minimally affected	Undamaged
C10-Conservation level	None	Local level	Regional level	National level	International level
C11-Vulnerability	Irrevocable (possible to complete loss)	High (could be simply damaged)	Medium (could be damaged by natural processes or human activities)	Less (can be damaged due to human activities)	Not any
C12-Number of visitors	0	0-10	10-20	20-50	More than 50
Additional criteria					
Functional values (VFn)					
C13-Accessibility	Unreachable	Low (on foot with special equipment or expert tourist guide)	Medium (by bicycle or other transport that uses muscle power)	High (by car)	Optimal (by bus, train, helicopter,etc.)
C14-Additional natural values	None	1	2- 3	4-6	More than 6
C15-Additional anthropogenic values	None	1	2- 3	4-6	More than 6
C16-Closeness to settlement centers	More than 100 km	100-50 km	50-25 km	25-5 km	Less than 5 km
C17-Adjacency to major roadways	None	Local	Regional	National	International
C18-Additional functional values	None	Low	Medium	High	Unique

Touristic values (VTr)

C19-Promotion	None	Local	Regional	National	International
C20-Annual number of organized visits	None	Less than 12 per year	12-24 per year	24-48 per year	more than 48 per year
C21-Nearness to tourist facilities	More than 50 km	50-20 km	20-5 km	5-1 km	Less than 1 km
C22-Interpretative panels	None	Low quality	Medium quality	High quality	Unique quality
C23-Annual number of visitors	None	Low (less than 5000)	Medium (5001-10000)	High (10001-100000)	Unique (more than 100000)
C24-Tourism infrastructure	None	Low	Medium	High	Unique
C25-Tour guide service	None	Low	Medium	High	Unique
C26-Hotel services	More than 50 km	50-25 km	20-10 km	10-5 km	Less than 5 km
C27-Restaurants	More than 25 km	25-10 km	10-5 km	5-1 km	Less than 1 km

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197 **Table 3** Grade values of sub-indicators given by experts for each geomorphosite
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Criteria/Sub-criteria	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	G14	G15	G16	G17	G18	G19	G20	G21	G22	G23	G24	G25	G26	G27	G28	G29	G30
VSA																														
C1	0.75	0.50	0.50	0.75	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50	0.50	1.00	0.75	0.50	1.00	0.50	0.75	0.50	0.50	0.75	0.50	1.00	1.00	1.00	1.00	1.00	1.00
C2	0.75	0.50	0.75	0.50	0.75	1.00	1.00	1.00	1.00	1.00	0.75	1.00	0.50	0.50	0.75	0.50	0.75	0.75	0.75	0.75	0.50	0.50	0.75	0.75	0.75	1.00	1.00	1.00	1.00	1.00
C3	1.00	1.00	0.75	0.75	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.75	0.75	0.75	0.50	1.00	1.00	0.50	0.75	0.50	0.50	0.75	0.50	1.00	1.00	1.00	0.75	0.75	1.00
C4	0.75	0.75	0.75	0.75	0.75	0.75	1.00	1.00	0.75	0.75	0.75	1.00	0.75	0.75	0.75	0.75	1.00	0.75	0.50	0.75	0.50	0.75	0.50	0.50	0.75	1.00	0.75	0.75	0.75	1.00
VSA																														
C5	0.75	0.50	0.50	0.75	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50	0.75	1.00	0.50	0.75	0.50	0.50	0.50	0.50	0.50	0.75	0.75	1.00	1.00	1.00	1.00	0.75	1.00
C6	0.50	0.75	1.00	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.75	1.00	1.00	1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.50	0.50	1.00	1.00	0.75	0.50	0.50	1.00
C7	0.50	0.75	0.75	0.00	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	1.00	1.00	1.00	1.00	1.00	1.00
C8	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
VP_r																														
C9	0.50	0.50	0.50	0.50	0.50	0.75	1.00	0.75	1.00	1.00	0.75	1.00	0.75	0.25	0.50	0.50	0.75	0.50	0.75	0.50	0.75	0.75	0.75	0.75	1.00	1.00	0.75	1.00	0.75	1.00
C10	0.00	0.00	0.00	0.00	0.00	0.25	0.75	1.00	0.75	0.75	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.75	0.75	1.00	0.00	0.00	1.00
C11	0.50	0.75	0.75	0.50	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.50	0.50	0.50	0.75	0.50	0.75	0.50	0.75	0.75	0.50	0.50	0.75
C12	1.00	1.00	1.00	1.00	0.75	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.75	1.00	0.75	1.00	1.00	0.75	1.00	1.00	1.00	1.00	1.00	1.00
VF_n																														
C13	0.50	0.75	0.75	0.50	0.25	1.00	1.00	1.00	1.00	1.00	0.75	0.75	0.75	0.75	1.00	1.00	1.00	0.75	0.75	0.75	0.50	0.75	0.75	0.75	0.75	1.00	1.00	1.00	1.00	1.00
C14	0.50	0.75	0.75	0.25	0.50	0.75	1.00	1.00	1.00	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	1.00	0.50	0.75	0.50	0.75	0.75	0.50	0.75	1.00	1.00	1.00	1.00	1.00
C15	0.75	1.00	0.50	0.50	0.75	0.75	1.00	1.00	1.00	0.75	0.50	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.50	0.75	0.50	0.75	0.50	0.50	0.75	1.00	1.00	0.75	0.75	1.00
C16	1.00	1.00	1.00	0.75	1.00	1.00	0.50	0.75	0.75	1.00	0.75	0.75	0.50	0.75	0.75	0.50	0.75	0.75	0.50	0.75	0.75	0.50	0.50	0.50	0.75	0.75	0.75	0.50	0.00	0.75
C17	0.50	1.00	0.50	0.25	0.25	1.00	0.75	1.00	0.75	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.75	0.50	0.50	0.50	0.75
C18	0.50	0.25	0.50	0.00	0.00	0.75	0.50	0.75	1.00	0.50	0.75	0.75	0.50	0.50	0.75	0.50	0.75	1.00	0.50	0.50	0.50	0.75	0.50	0.50	0.75	1.00	1.00	1.00	0.75	1.00
VT_r																														
C19	0.25	0.25	0.50	0.25	0.25	0.75	0.75	1.00	0.75	0.75	0.50	0.25	0.25	0.50	0.50	0.75	0.50	0.50	0.25	0.25	0.00	0.25	0.25	0.25	0.50	0.75	0.75	0.25	0.25	0.75
C20	0.50	0.5	0.50	0.25	0.50	1.00	1.00	1.00	1.00	1.00	1.00	0.50	0.50	0.50	0.75	0.50	0.75	0.75	0.25	0.50	0.25	0.50	0.50	0.50	1.00	1.00	1.00	0.75	0.50	1.00
C21	0.50	0.50	0.5	0.50	0.50	1.00	1.00	1.00	0.50	1.00	1.00	0.50	0.25	0.50	0.75	0.75	0.50	0.50	0.50	0.50	0.25	0.50	0.50	0.25	1.00	1.00	1.00	0.50	0.50	1.00
C22	0.00	0.00	0.25	0.00	0.00	0.50	0.50	1.00	0.50	0.25	0.25	0.25	0.25	0.25	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.50
C23	0.25	0.50	0.25	0.25	0.50	0.75	0.75	1.00	1.00	1.00	1.00	0.50	0.50	0.75	1.00	0.75	0.75	0.75	0.50	0.75	0.00	0.50	0.25	0.50	0.75	1.00	1.00	0.75	0.75	0.75
C24	0.25	0.25	0.00	0.00	0.00	0.50	0.50	0.50	0.75	0.50	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.75	0.25	0.00	0.00	0.00	0.25
C25	0.00	0.50	0.00	0.00	0.00	0.25	0.25	0.50	0.00	0.25	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.75	0.00	0.00	0.00	0.00	0.00
C26	0.75	0.50	0.00	0.00	0.00	0.75	0.50	0.75	0.00	0.75	0.25	0.75	0.50	0.75	0.75	0.50	0.50	0.50	0.25	0.50	0.25	0.50	0.50	0.50	0.75	0.75	0.75	0.75	0.75	0.75
C27	0.75	0.75	0.00	0.00	0.00	0.75	0.75	1.00	1.00	0.75	0.50	0.50	0.50	0.50	0.75	0.50	0.50	0.25	0.50	0.50	0.25	0.50	0.50	0.50	0.75	1.00	1.00	0.75	0.75	1.00

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202 **Table 4** Importance factor and total values based M-GAM model
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Criteria/Sub-criteria	<i>I_m</i>	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	G14	G15	G16	G17	G18	G19	G20	G21	G22	G23	G24	G25	G26	G27	G28	G29	G30
VSE																															
C1	0.92	0.69	0.46	0.46	0.69	0.46	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.46	0.46	0.92	0.69	0.46	0.92	0.46	0.69	0.46	0.46	0.69	0.46	0.92	0.92	0.92	0.92	0.92	0.92
C2	0.72	0.54	0.36	0.54	0.36	0.54	0.72	0.72	0.72	0.72	0.72	0.54	0.72	0.36	0.36	0.54	0.36	0.54	0.54	0.54	0.36	0.36	0.54	0.54	0.54	0.72	0.72	0.72	0.72	0.72	0.72
C3	0.68	0.68	0.68	0.51	0.51	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.51	0.51	0.51	0.34	0.68	0.68	0.34	0.51	0.34	0.34	0.51	0.34	0.68	0.68	0.68	0.51	0.51	0.68
C4	0.84	0.63	0.63	0.63	0.63	0.63	0.63	0.84	0.84	0.63	0.63	0.63	0.84	0.63	0.63	0.63	0.63	0.84	0.63	0.42	0.63	0.42	0.63	0.42	0.42	0.63	0.84	0.63	0.63	0.63	0.84
VSA																															
C5	0.82	0.62	0.41	0.41	0.62	0.41	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.41	0.62	0.82	0.41	0.62	0.41	0.41	0.41	0.41	0.41	0.62	0.62	0.82	0.82	0.82	0.82	0.62	0.82
C6	0.81	0.41	0.61	0.81	0.41	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.61	0.81	0.81	0.81	0.81	0.81	0.41	0.41	0.41	0.41	0.41	0.41	0.81	0.81	0.61	0.41	0.41	0.81
C7	0.91	0.46	0.68	0.68	0.00	0.46	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.91	0.91	0.91	0.91	0.91	0.91
C8	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
VPr																															
C9	0.88	0.44	0.44	0.44	0.44	0.44	0.66	0.88	0.66	0.88	0.88	0.66	0.88	0.66	0.22	0.44	0.44	0.66	0.44	0.66	0.44	0.66	0.66	0.66	0.66	0.88	0.88	0.66	0.88	0.66	0.88
C10	0.67	0.00	0.00	0.00	0.00	0.00	0.17	0.50	0.67	0.50	0.50	0.34	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.67	0.00	0.00	0.67
C11	0.53	0.27	0.40	0.40	0.27	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.27	0.27	0.27	0.40	0.27	0.40	0.27	0.40	0.40	0.27	0.27	0.40
C12	0.66	0.66	0.66	0.66	0.66	0.50	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.50	0.66	0.50	0.66	0.66	0.50	0.66	0.66	0.66	0.66	0.66	0.66
Additional values																															
VFn																															
C13	0.82	0.41	0.62	0.62	0.41	0.21	0.82	0.82	0.82	0.82	0.82	0.62	0.62	0.62	0.62	0.82	0.82	0.82	0.62	0.62	0.62	0.41	0.62	0.62	0.62	0.62	0.82	0.82	0.82	0.82	0.82
C14	0.75	0.38	0.56	0.56	0.19	0.38	0.56	0.75	0.75	0.75	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.75	0.38	0.56	0.38	0.56	0.56	0.38	0.56	0.75	0.75	0.75	0.75	0.75
C15	0.71	0.53	0.71	0.36	0.36	0.53	0.53	0.71	0.71	0.71	0.53	0.36	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.36	0.53	0.36	0.53	0.36	0.36	0.53	0.71	0.71	0.53	0.53	0.71
C16	0.68	0.68	0.68	0.68	0.51	0.68	0.68	0.34	0.51	0.51	0.68	0.51	0.51	0.34	0.51	0.51	0.34	0.51	0.51	0.34	0.51	0.51	0.34	0.34	0.34	0.51	0.51	0.51	0.34	0.00	0.51
C17	0.72	0.36	0.72	0.36	0.18	0.18	0.72	0.54	0.72	0.54	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.54	0.36	0.36	0.36	0.54
C18	0.58	0.29	0.15	0.29	0.00	0.00	0.44	0.29	0.44	0.58	0.29	0.44	0.44	0.29	0.29	0.44	0.29	0.44	0.58	0.29	0.29	0.29	0.44	0.29	0.29	0.44	0.58	0.58	0.58	0.44	0.58
VTr																															
C19	0.69	0.17	0.17	0.35	0.17	0.17	0.52	0.52	0.69	0.52	0.52	0.35	0.17	0.17	0.35	0.35	0.52	0.35	0.35	0.17	0.17	0.00	0.17	0.17	0.17	0.35	0.52	0.52	0.17	0.17	0.52
C20	0.62	0.31	0.31	0.31	0.16	0.31	0.62	0.62	0.62	0.62	0.62	0.62	0.31	0.31	0.31	0.47	0.31	0.47	0.47	0.16	0.31	0.16	0.31	0.31	0.31	0.62	0.62	0.62	0.47	0.31	0.62
C21	0.81	0.41	0.41	0.41	0.41	0.41	0.81	0.81	0.81	0.41	0.81	0.81	0.41	0.20	0.41	0.61	0.61	0.41	0.41	0.41	0.41	0.20	0.41	0.41	0.20	0.81	0.81	0.81	0.41	0.41	0.81
C22	0.79	0.00	0.00	0.20	0.00	0.00	0.40	0.40	0.79	0.40	0.20	0.20	0.20	0.20	0.20	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.79	0.79	0.00	0.00	0.40
C23	0.72	0.18	0.36	0.18	0.18	0.36	0.54	0.54	0.72	0.72	0.72	0.72	0.36	0.36	0.54	0.72	0.54	0.54	0.54	0.36	0.54	0.00	0.36	0.18	0.36	0.54	0.72	0.72	0.54	0.54	0.54
C24	0.68	0.17	0.17	0.00	0.00	0.00	0.34	0.34	0.34	0.51	0.34	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.51	0.17	0.00	0.00	0.00	0.17
C25	0.58	0.00	0.29	0.00	0.00	0.00	0.15	0.15	0.29	0.00	0.15	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.44	0.00	0.00	0.00	0.00	0.00
C26	0.78	0.59	0.39	0.00	0.00	0.00	0.59	0.39	0.59	0.00	0.59	0.20	0.59	0.39	0.59	0.59	0.39	0.39	0.39	0.20	0.39	0.20	0.39	0.39	0.39	0.59	0.59	0.59	0.59	0.59	0.59
C27	0.69	0.52	0.52	0.00	0.00	0.00	0.52	0.52	0.69	0.69	0.52	0.35	0.35	0.35	0.35	0.52	0.35	0.35	0.17	0.35	0.35	0.17	0.35	0.35	0.35	0.52	0.69	0.69	0.52	0.52	0.69

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3. Results

3.1. Identification and spatial distribution of geomorphosites in Purulia district

A total of thirty geomorphosites were identified across the Purulia district through extensive field investigations, topographic analysis, and finally the valuation was done by applying the Modified Geosite Assessment Model (M-GAM). The identified geomorphosites comprise hills, escarpments, waterfalls, springs, and micro landforms from the Precambrian landscape (Table 1). The geomorphosites inventory reveals the dominance of residual and structural hills, particularly the Ajodhya Hill region, highlighting the significant influence of Precambrian geological structures on the evolution of the landscape. Among the identified geomorphosites, notable geomorphosites include Joychandi Pahar, Chamtaburu Hill, Gorgaburu Hill, Panchakot Pahar, Pakhi Pahar, Sitakundu Spring, Bamni Falls, Turga Falls, and Khairabera Hill and Forest, etc. (Fig. 4). These sites represent unique geomorphic features that are characterized by exceptional aesthetic/scenic beauty, scientific significance, and geoeducational value. The concentration of geomorphosites in the western and south-western parts of the district is high due to the rugged topography of the Ajodhya Hills, whereas isolated residual hills dominate the northern and eastern parts of the Purulia district (Fig. 1).

3.2. Valuation results of the geomorphosites

A detailed evaluation was carried out through the analysis of both the Main and Additional Values of the geomorphosites. The Main Values encompass 12 sub-criteria under the scientific and educational significance (VSE), scenic and aesthetic quality (VSA), and protection status (VPr) whereas the Additional Values include 15 sub-criteria under the functional (VFn) and tourism-related attributes (VTr) of the geomorphosites. Table 5 shows,

228 G8-Gorgaburu Hill of the Ajodhya range has the highest Main and Additional Values, which
 229 are 9.38 and 9.49, respectively. Similarly, G30-Khairabera Hill and Forest; G26- Bamni
 230 Falls; G7- Chamtaburu Hill; G12- Gajaburu Hill; G9-Panchakot Pahar; G10-Pakhi Pahar;
 231 G27-Turga Falls; G25-Sitakundu Spring; G6-Joychandi Pahar; G11-Mayur Pahar having
 232 their Main Values 9.16, 8.99, 8.99, 8.82, 8.78, 8.78, 8.53, 8.47, 8.23, 8.21 respectively (Table
 233 5). Out of 30 geomorphosites, 11 geomorphosites are very significant in terms of geoheritage
 234 and geotourism development because these geomorphosites have high scientific/educational
 235 values (VSE) and scenic/aesthetic values (VSA), particularly C1-Rarity, C8-Environmental
 236 fitting of sites, C2-Representativeness, C7-Nearby landscape and nature, and C5-Viewing
 237 platform. The VSE score ranges from 1.58 to 3.16. The highest scientific and educational
 238 values (3.16) were calculated for Chamtaburu Hill (G7), Gorgaburu Hill (G8), Gajaburu Hill
 239 (G12), Bamni Falls (G26), and Khairabera Dam Hill and Forest (G30). These sites reveal
 240 remarkable rarity, representativeness, interpretative potential, and geoscientific significance.
 241 Their geomorphic characteristics clearly demonstrate the geological evolution of the
 242 Chotanagpur Plateau and provide excellent opportunities for scientific research and
 243 educational activities. On the other hand, Kopila Hill (G21), Jargobudhi Pahar (G19),
 244 Ushuldunri Pahar (G24), and Tilai Pahar (G22) obtained comparatively lower VSE scores.
 245 These sites possess lower representativeness and limited scientific visibility despite their
 246 local geomorphological significance. The scenic and aesthetic values (VSA) generally
 247 represent high values across most of the geomorphosites, with scores ranging between 1.87
 248 and 3.39. The maximum VSA score (3.39) was attained by Joychandi Pahar (G6),
 249 Chamtaburu Hill (G7), Gorgaburu Hill (G8), Panchakot Pahar (G9), Pakhi Pahar (G10),
 250 Mayur Pahar (G11), Sitakundu Spring (G25), Bamni Falls (G26), and Khairabera Hill and
 251 Forest (G30) (Table 5). These high scores reflect the presence of extensive geomorphic
 252 exposures, panoramic viewpoints, surrounding natural landscapes, and strong environmental

integration. Particularly, the waterfall geomorphosites and the Ajodhya Hill landscape provide visually striking terrain forms that significantly enhance their geoheritage appeal. Tilaboni Hill (G4) recorded the lowest VSA value (1.87), primarily due to limited landscape diversity and fewer observation points. Protection values ranged from 1.28 to 2.61. Khairabera Dam–Hill–Forest (G30) achieved the highest protection value (2.61), followed by Chamtaburu Hill (G7), Panchakot Pahar (G9), Pakhi Pahar (G10), and Bamni Falls (G26) with scores of 2.44 (Table 5). Higher protection values are associated with relatively undisturbed geomorphic conditions, lower vulnerability, and existing conservation measures. In contrast, Bansa Hill (G14) exhibited the lowest protection value (1.28), indicating greater susceptibility to anthropogenic disturbances and limited conservation initiatives.

Additional Values (AV) encompass Functional Values (VF_n) and Touristic Values (VTr), which collectively determine the practical utilization and tourism potential of the geomorphosites. Functional values varied from 1.64 to 3.95 (Table 5). Gorgaburu Hill (G8) attained the highest VF_n score (3.95), followed closely by Panchakot Pahar (G9), Bamni Falls (G26), and Khairabera Hill and Forest (G30) (3.91). These geomorphosites benefit from favourable accessibility, connectivity, proximity to settlements, additional natural attractions, and infrastructure. The location of the geomorphosites within Purulia District has a greater possibility of establishing a tourism corridor, which further enhances their functional significance. Tilaboni Hill (G4) registered the lowest functional value (1.64), indicating inadequate accessibility and limited facilities. Touristic value indicates considerable variation among the sites, ranging from 0.73 to 5.54. Gorgaburu Hill (G8) achieved the highest touristic value (5.54), followed by Bamni Falls (G26) (4.90), Turga Falls (G27) (4.73), Joychandi Pahar (G6) (4.47), Pakhi Pahar (G10) (4.45), Sitakundu Spring (G25) (4.36), and Khairabera Hill and Forest (G30) (4.33). The elevated tourism values of these sites are attributed to higher visitor numbers, tourism infrastructure, and the availability of hotels,

restaurants, and other facilities. Furthermore, the integration of these geomorphosites within the Ajodhya Hills and its surroundings contributes significantly to their popularity. In contrast, Kopila Hill (G21) recorded the lowest touristic value (0.73), reflecting limited tourism infrastructure, poor promotion, and less number of visitors.

Table 5 Position of the geomorphosites by applying M-GAM model

Levels of Geomorphosites	Geomorphosites name	Main Values VSE + VSA + VPr	Σ	Additional Values VF _n + VTr	Σ	Field
G1	Paharigora Hill	2.54 + 2.33 + 1.37	6.24	2.65 + 2.34	4.99	Z ₂₁
G2	Pabra Hill	2.13 + 2.55 + 1.50	6.18	3.43 + 2.62	6.05	Z ₂₂
G3	Bero Hill	2.14 + 2.75 + 1.50	6.39	2.86 + 1.44	4.30	Z ₂₁
G4	Tilaboni Hill	2.19 + 1.87 + 1.37	5.43	1.64 + 0.91	2.55	Z ₂₁
G5	Bara Panjania	2.31 + 2.53 + 1.33	6.17	1.97 + 1.25	3.22	Z ₂₁
G6	Joychandi Pahar	2.95 + 3.39 + 1.89	8.23	3.75 + 4.47	8.22	Z ₃₂
G7	Chamtaburu Hill	3.16 + 3.39 + 2.44	8.99	3.45 + 4.28	7.73	Z ₃₂
G8	Gorgaburu Hill	3.16 + 3.39 + 2.39	9.38	3.95 + 5.54	9.49	Z ₃₂
G9	Panchakot Pahar	2.95 + 3.39 + 2.44	8.78	3.91 + 3.86	7.79	Z ₃₂
G10	Pakhi Pahar	2.95 + 3.39 + 2.44	8.78	3.25 + 4.45	7.70	Z ₃₂
G11	Mayur Pahar	2.77 + 3.39 + 2.05	8.21	2.84 + 3.55	6.39	Z ₃₂
G12	Gajaburu Hill	3.16 + 3.39 + 2.27	8.82	3.02 + 2.38	5.40	Z ₃₂
G13	Kansra Hill	1.96 + 2.55 + 1.72	6.23	2.70 + 1.98	4.68	Z ₂₁
G14	Bansa Hill	1.96 + 2.96 + 1.28	6.20	2.87 + 2.73	5.60	Z ₂₂
G15	Shikra Hill	2.60 + 3.16 + 1.50	7.26	3.22 + 3.54	6.66	Z ₂₂
G16	Paparu Hill	2.02 + 2.75 + 1.50	6.27	2.91 + 2.71	5.62	Z ₂₂
G17	Dhalburu Hill	2.52 + 2.96 + 1.72	7.20	3.22 + 2.49	5.71	Z ₂₂
G18	Belamu Pahar	2.77 + 2.75 + 1.50	7.02	3.35 + 2.32	5.67	Z ₂₂
G19	Jargobudhi Pahar	1.76 + 2.35 + 1.42	5.53	2.34 + 1.63	3.97	Z ₂₁
G20	Hathi Pahar	2.37 + 2.35 + 1.37	6.09	2.87 + 2.16	5.03	Z ₂₁
G21	Kopila Hill	1.58 + 2.35 + 1.42	5.35	2.30 + 0.73	3.03	Z ₂₁
G22	Tilai Pahar	1.79 + 2.35 + 1.72	5.86	2.85 + 1.98	4.83	Z ₂₁
G23	Mesya Pahar	2.16 + 2.55 + 1.59	6.30	2.52 + 1.80	4.32	Z ₂₁
G24	Ushuldunri Pahar	1.76 + 2.55 + 1.55	5.86	2.34 + 1.78	4.12	Z ₂₁
G25	Sitakundu Spring	2.77 + 3.39 + 2.31	8.47	3.02 + 4.36	7.38	Z ₃₂
G26	Bamni Falls	3.16 + 3.39 + 2.44	8.99	3.91 + 4.90	8.81	Z ₃₂
G27	Turga Falls	2.95 + 3.19 + 2.39	8.53	3.73 + 4.73	8.46	Z ₃₂
G28	Machkanda Falls	2.78 + 2.99 + 1.81	7.58	3.38 + 2.69	6.07	Z ₂₂
G29	Ghageshwari Falls	2.78 + 2.78 + 1.59	7.15	2.90 + 2.53	5.43	Z ₂₂
G30	Khairabera Hill and Forest	3.16 + 3.39 + 2.61	9.16	3.91 + 4.33	8.24	Z ₃₂

4. Discussions

4.1. Diverse geological or geomorphological contexts in the geomorphosites of the Purulia district

This research finding exposes a diverse range of active or dynamic and inherited geological or geomorphological sites within the studied region, reflecting the concepts that were earlier defined by

Reynard (2004). According to him, active or dynamic geomorphosites are characterised by ongoing geological and geomorphological processes and their associated landforms, whereas inherited geomorphosites preserve the evidence of processes that occurred in the past. In our study area, active or dynamic geomorphosites includes fluvial landforms and semi-arid landforms whereas inherited geomorphosites includes tectonic origins. The identified a total of 30 geomorphosites for this research, highlighting a diverse range of landforms throughout the district. Especially, the waterfalls and springs like G-26 Bamni Falls, G-27 Turga Falls, G-28 Machkanda Falls, G-29 Ghageshwari Falls, and G-25 Sitakundu Spring highlight not only the region's geodiversity but also offer visitors an immersive experience in the purely natural environments. On the other hand, the hills and 'tilas' (mounds) of Purulia district are ancient geological formations, primarily representing the easternmost extension of the Chhotanagpur Plateau. Geologically, they are made of Precambrian metamorphic and igneous rocks, such as granite and gneiss, belonging to the Chhotanagpur Granite Gneissic Complex (Fig. 2). These bedrock foundations originated from intense tectonic activity, magmatic intrusions, and metamorphism that occurred more than 1.6 billion years ago (Singh 1969). These remarkable landforms of Purulia district strengthen the district's potential as a destination for nature-oriented recreation and sustainable tourism.

4.2. Geoheritage potentiality of the geomorphosites in Purulia district

The evaluated outcomes are shown in Table 3, Table 4, Table 5, and Fig. 4. The M-GAM assessment classified the 30 geomorphosites into three evaluation fields: Z_{21} , Z_{22} , and Z_{32} (Table 5). No sites were placed within the highest category (Z_{33}), suggesting that although several geomorphosites possess substantial geoheritage value, further improvements in tourism management and conservation are required to attain the highest geoheritage status. A total of twelve geomorphosites were classified within the Z_{32} field, representing the highest-ranked category identified in the study area (Fig. 3). These include Joychandi Pahar (G6), Chamtaburu Hill (G7), Gorgaburu Hill (G8), Panchakot Pahar (G9), Pakhi Pahar (G10), Mayur Pahar (G11), Gajaburu Hill (G12), Sitakundu Spring (G25), Bamni Falls (G26), Turga Falls (G27), and Khairabera Hill and Forest (G30). These geomorphosites exhibit

high values of each sub-criterion under main values and additional values, indicating strong geoheritage significance as well as considerable geotourism potential. Among all evaluated sites, Gorgaburu Hill (G8) emerged as the most valuable geomorphosite, recording the highest total additional value (9.49) and one of the highest main values (9.38) (Table 5). As the highest peak in West Bengal, Gorgaburu Hill combines exceptional scientific importance, scenic quality, accessibility, and tourism attractiveness, making it a flagship geoheritage resource of the district. Similarly, Khairabera Hill and Forest (G30), Bamni Falls (G26), and Turga Falls (G27) achieved remarkably high scores owing to their integrated natural landscapes, recreational opportunities, and established tourism infrastructure. Eight geomorphosites were categorized within the Z_{22} field, indicating moderate geoheritage and tourism potential (Fig. 3). These sites possess relatively high scientific and scenic values but require improvements in visitor facilities, interpretation systems, and promotional strategies. The remaining ten geomorphosites were placed in the Z_{21} field, characterized by moderate main values but comparatively low additional values (Fig. 3). These sites, including Paharigora Hill, Bero Hill, Tilaboni Hill, Bara Panjania, Jargobudhi Pahar, and Kopila Hill, remain underutilized despite their geomorphological significance. Enhanced accessibility, infrastructure development, and community-based geotourism initiatives could substantially improve their geoheritage utilization. Moreover, all the identified geomorphosites in Purulia district are crucial to visitors for observing aesthetic beauty along with flora and fauna in this region. In the cultural context, Ajodhya and surroundings sites have a close relationship with society and their culture, economic activity, and recreational utilities, and the Ajodhya hill region is the home of many tribal indigenous people. Aesthetic or scenic values, most of the geomorphosites associated with hills and waterfalls have high scores because the Purulia district is an extended part of the Chhotanagpur Plateau, which is known for its unique geological and geomorphological features and formations. In terms of promotion, all identified geomorphosites in the Purulia district have had a reasonable investment in infrastructure, connectivity and other facilities for the use of visitors. In the case of the risk of assessment, most of the sites are vulnerable due to rock dwellers, and mining activities, witnessed in G-1 Paharigora Hill, G-4 Tilaboni Hill, G-5 Bara Panjania, and some pockets of the Ajodhya hill region.

344 In recent decades, the large-scale demolition of billion-year-old Precambrian geosites and
345 geomorphosites in Purulia, West Bengal, has been operated by industrial projects, uncontrolled
346 resource abstraction, and rapid landuse modification. These unique Archean residual hillocks,
347 inselbergs, bornhardts, tors, mushroom rocks, geothermal springs, and hills of the Chhotanagpur
348 Plateau face severe environmental degradation. The Geological Survey of India (GSI) and the Atomic
349 Minerals Directorate (AMD) have identified significant deposits of rare earth elements and related
350 critical minerals across the North Purulia Shear Zone (NPSZ) and the South Purulia Shear Zone
351 (SPSZ). Ultimately, Purulia is known to host around 14 and 17 rare earth-bearing minerals, primarily
352 occurring in monazite, allanite, and the euxenite-aeschynite groups. The district also contains allied
353 deposits of columbite-tantalite, lithium, beryllium, and apatite-magnetite. Now, India aims to reduce
354 dependence on imported critical minerals, and Purulia is being considered as a strategic mining
355 destination. The extended part of the Chhotanagpur Plateau, particularly Purulia's Precambrian
356 geosites and geomorphosites are of enormous scientific prominence. These billion-year-old landforms
357 are the natural deed of the Precambrian landforms evolution of eastern India, and they should be
358 preserved. If govt. should make proper policy and plan for geoheritage declaration and geotourism
359 development, they can earn huge revenue and maintain the tribal and non-tribal livelihood through
360 conservation strategies.

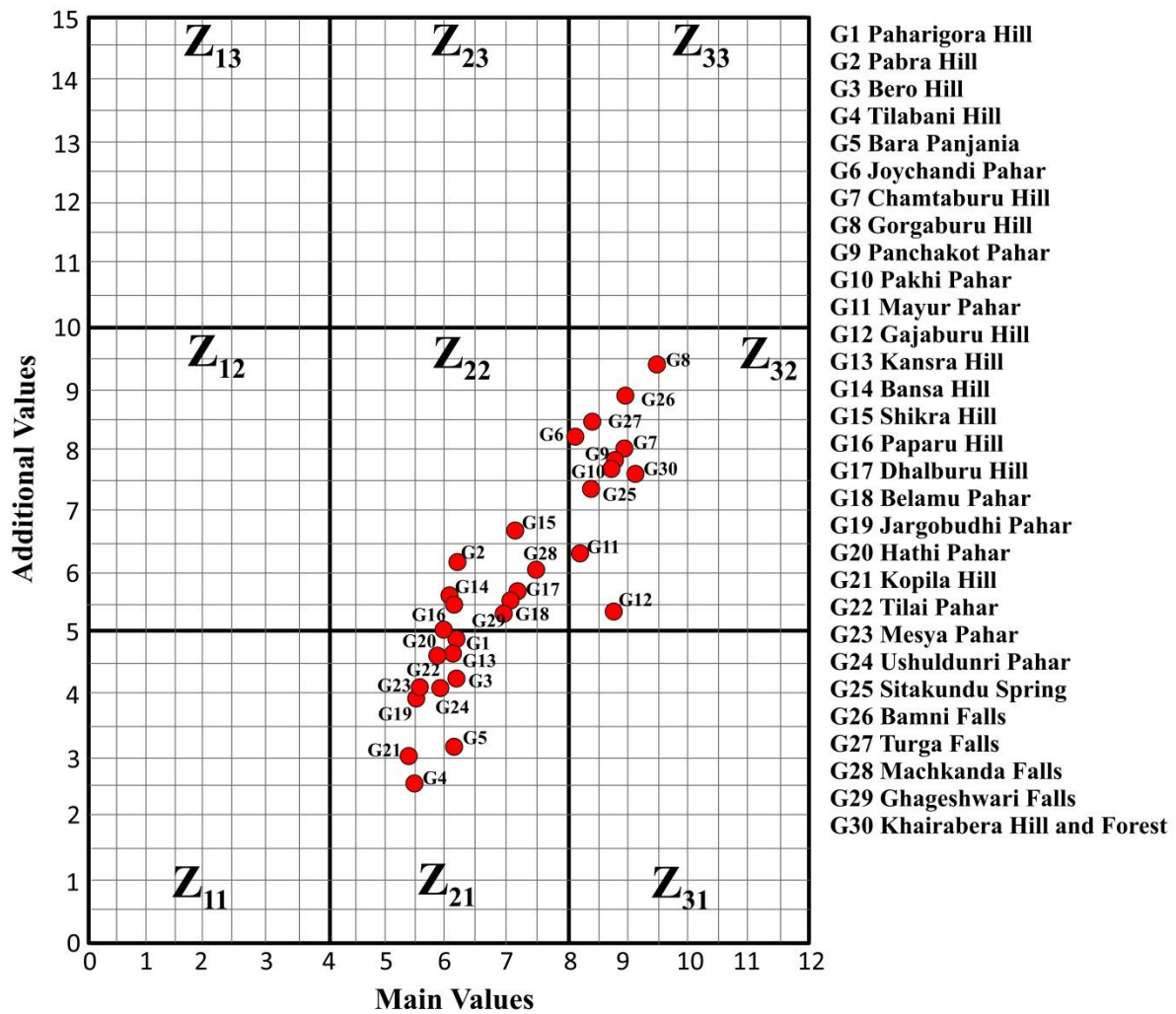


Fig. 3 Position of the identified geomorphosites of Purulia District in the M-GAM matrix

4.3. Geoheritage Conservation and Geotourism Development

The results demonstrate that Purulia District has experienced a diverse and valuable assemblage of geomorphosites with considerable geoheritage and geotourism potential. The predominance of Z_{32} classified sites within the Ajodhya hill region highlights its role as the principal geoheritage hotspot region of the district. The study further reveals that scenic and scientific values are generally high across most geomorphosites, whereas deficiencies primarily exist in tourism infrastructure, interpretative facilities, and conservation management. Consequently, future geoheritage planning should prioritize the development of interpretative centres, geotrails, information panels, visitor management systems, and community participation programmes. The integration of these

geomorphosites into a district-level geotourism framework could significantly contribute to sustainable tourism development, local livelihood generation, and long-term conservation of the unique geoheritage resources of the Purulia District.



Fig. 4 Field photographs of the identified geomorphosites in the Purulia District, extended part of Chhotanagpur Plateau: **a.** and **h.** Mushroom structured rocks in Pabra Hill; **b.** Granitoid batholith Joychandi Pahar; **c.** Bero Hill; **d.** Belamu Pahar; **e.** Pakhi Pahar (known for giant rock carvings of birds); **f.** Pabra Hill; **g.** Machkanda Falls; **i.** Turga Falls; **j.** Bamni Falls; **k.** Shikra Hill; **l.** Gajaburu Hill; **m.** Kansra Hill.

5. Conclusion

This study of geomorphosites in Purulia District, West Bengal, reveals a crucial geomorphological or geological diversity, with thirty identified geomorphosites that provide a foundation for the

development of geoheritage resources. In this study, we have found that Purulia District has many distinguished geosites or geomorphosites with significant potential for the development of geotourism, and it has also been observed that some of the evaluated geomorphosites are still facing access difficulties but have great geotouristic potential. The selected geomorphosites in this region have all the natural properties for geotourism or geoheritage development, but most of the sites are lacking in tourist facilities. All the identified thirty geomorphosites have been evaluated by applying the M-GAM model, and the results have revealed that G8, G26, G27, G6, G7, G9, G10, G30 and G25 stand out with great significance in terms of educational, scientific, and touristic potential. The rest of the geomorphosites require further investigation for the improvement of touristic values as well as the enhancement of protection, management, and planning. Furthermore, parallels the enhancement of these sites as well as highlights the promotional activities, effective awareness, and marketing initiatives that may attract more tourists every year, which can benefit the local community by creating new job opportunities and income for the local economy. However, any geotourism-related studies, particularly in locations such as those situated within ecologically sensitive mountainous, hilly and forested landscapes where environmental protection must remain a priority, should be carefully planned and managed in accordance with sustainable development principles.

CRedit authorship contribution statement

Prasanta Mandal.: conceptualization, methodology, formal analysis, writing - original draft, writing - review & editing, visualization; **Biswajit Bera.:** supervision, conceptualization, formal analysis, writing - original draft, writing - review & editing

Declaration of conflict interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Ethical statement

Not applicable, because this article does not contain any studies with human or animal subjects.

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