

RESEARCH ARTICLE

River Health Assessment of the Ganga River via
Geomorphic Metrics: The Anthropocene ContextRajiv Sinha¹  | Haridas Mohanta^{1,2} | Kanchan Mishra³ ¹Department of Earth Sciences, Indian Institute of Technology Kanpur, Kanpur, India | ²Department of Earth Sciences, Sambalpur University, Sambalpur, Odisha, India | ³Department of Geosciences, Faculty of Mathematics and Natural Sciences, University of Tübingen, Tübingen, GermanyCorrespondence: Rajiv Sinha (rsinha@iitk.ac.in)

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ABSTRACT

Rivers, particularly large river systems, constitute one of the most fundamental life-support systems that have sustained civilisations and are projected to be a critical determinant for the future sustenance of human civilisations. A river can be termed a healthy ecosystem only when all the flora and fauna are in and along the river, the cultivation in floodplains is healthy, and the river's form is in equilibrium. The Ganga River system in India is a large river system with high geodiversity and biodiversity, where about one-third of India's population depends on the river directly or indirectly. This study focuses on the development of a Geomorphic River Health Index (gRHI) based on eight geomorphic attributes derived from geospatial data, including sinuosity, braid-channel ratio, width/depth ratio, occupancy, floodplain development, bar density, bar complexity and stream power. The selected river health parameters were analysed using a multi-criteria decision-making technique, the Analytic Hierarchy Process (AHP), in a GIS framework. We adopted a five-fold river health classification framework (i.e., near-pristine, good, fair, poor and degraded) for the entire Ganga River system from Gomukh to Farakka. Our results, based on geospatial data and supported by field observations, indicate that most reaches of the Ganga River in the higher mountainous stretch are in 'near pristine' condition, while some in the lower reaches fall into the 'good' and 'fair' classes. In contrast, several reaches in the alluvial part show 'poor' river health, primarily associated with flow reduction and sediment accumulation leading to morphological degradation, which is well manifested in geomorphic indicators used for river health assessment in this study. The geomorphic framework presented in this study can serve as a good template to evaluate river health and link this to scenarios of habitat suitability, environmental flows and flood risk associated with large river systems.

1 | Introduction

A river can be considered a healthy ecosystem only when all flora and fauna are in and along the river, the cultivation in the floodplains is healthy, and the river's form is in equilibrium. Traditionally, river health assessment (RHA) has focused on water quality indices (Ott 1978) and/or biological status (Wright 1995; Meyer 1997; Boulton 1999; Kleynhans 1999) of the river and has often been limited by spatial scale and data availability. Such assessments rarely integrate geomorphic and

ecological data to evaluate whether river structure is appropriate for its environmental/landscape setting for performing various functions such as sediment transport, nutrient cycling, energy exchange, support for riparian vegetation and ecosystem (in-channel and floodplain), maintenance of longitudinal and lateral connectivity, geodiversity and biodiversity.

In a geomorphic context, the analysis of river character and behaviour through identification of geomorphic units provides a useful platform for RHA (Fryirs and Brierley 2022). In large

rivers exhibiting significant geomorphic diversity, it is important to design criteria for River Health Assessment (RHA) separately for different geomorphic settings. For example, Rosgen (1994) classified homogeneous stream types based on a few geomorphic parameters such as sinuosity, width/depth ratio and gradient. Brierley and Fryirs et al. (2008) defined River Health based on the River Styles Framework using morphological attributes. Further research emphasised that the geomorphic attributes help to quantify catchment characteristics and river channel modification through erosional and depositional processes (Khan et al. 2021; Fryirs and Brierley 2022), in addition to floodplain degradation through encroachment or bank erosion. The catchment-scale flow modifications result in stream power that is often manifested in sediment transport characteristics (Downs and Piegay 2019) via morphological changes. Therefore, the geomorphic attributes can serve as important 'geoindicators' for the status of rivers and the degradation (if any) in terms of river health.

Numerous factors can be attributed to the degradation of river health, including riverbed sedimentation, sand mining and discharge of untreated sewage into the river. Many large rivers across the world such as the Mississippi, Rio Grande, Hailu, Nile and Yellow River have undergone significant changes in form and processes due to human interventions in the last couple of decades (Mack and Leeder 1998; Richard and Julien 2003; Moussa et al. 2001; Ma et al. 2012; Sadek 2013; Yang et al. 2012; Bentley et al. 2016; El Bastawesy et al. 2015). Human interventions such as dams and barrages enhance the morphological alteration through channel shifting, narrowing and increased hydrological changes downstream of the dam. The construction of dams and barrages also influences the habitat of the aquatic species. For example, the dam construction across the Rio Grande River led to the alteration of the river form from braided to a straight and narrow channel that resulted in a reduction in the rate of migration of meandering stretches (Friedman et al. 1998; Richard and Julien 2003). Conspicuous morphological changes were reported in the Nile River after the Aswan Dam construction in Egypt (Saad 2002; Moussa et al. 2001; Sadek 2013). Alteration in the riparian vegetation is also reported to have negative impacts because of the construction of dams around the world (Friedman et al. 1998; New and Xie 2008; Sun et al. 2014; Uddin et al. 2014; Kellogg and Zhou 2014).

In India, RHA protocols have generally included water quality parameters and biological indicators such as fish and insects (Singh and Saxena 2018), and holistic frameworks including catchment, floodplain, river channel and flow health are lacking (Nandi et al. 2016). Several studies on RHA, mostly at the local scale, focused on water quality indices, for example, Yamuna River at Allahabad (Sharma, Singal, and Patra 2008), Swan River in Himachal Pradesh (Sharda and Sharma 2013), Godavari River in peninsular India (Chavan et al. 2009), whereas some of these included ecological parameters and biological indicators, for example, Chambal (Yadav et al. 2014), Niglad (Sharma, Sharma, et al. 2008) and Kosi River (Kumar et al. 2024). In addition, a couple of studies have focused on the eco-geomorphic assessment of the Ganga River in selected reaches. For example, Sonkar et al. (2019) assessed planform and hydraulic geometry in relation to the Varanasi Turtle Sanctuary. Sonkar and Gaurav (2020) assessed the impact of large barrages on the

habitat of the Ganga River dolphin. In the reach between the Narora and Farakka barrages, the authors used time-series remote sensing and discharge data to constrain the impacts on morphology and ecology in the vicinity of the barrages. A major conclusion from this study was that the decline of dolphin population was associated with changes in hydraulic geometry, and the loss of connectivity emphasises the need for incorporating geomorphological attributes in RHA. Given the geomorphic diversity of Himalayan river systems (Sinha et al. 2005, 2017), it is imperative to develop region-specific protocols for RHA, taking into consideration river channel and floodplain attributes.

The Ganga River in the Himalayan foreland flows through diverse climatic and geomorphic settings. The Ganga River supports a very rich biodiversity, including the endangered river dolphin and several other aquatic mammals (Smith et al. 1994; Sonkar and Gaurav 2020; Sonkar et al. 2024). Despite several national programmes such as the Ganga Action Plan (GAP I and II) and Ganga River Basin Management Plan (GRBMP), a comprehensive RHA of the Ganga is still lacking. Our earlier work highlighted the geomorphic diversity of the Ganga River (Sinha et al. 2005, 2017), which has significant implications for river management. The present study takes this work forward and uses a set of geomorphic indices, derived from remote sensing datasets and integrated into a GIS framework, to develop a Geomorphic River Health Index (gRHI) that is (a) process-based, (b) accounts for regional geomorphic diversity and (c) framed in terms of channel morphometry. We then integrate the gRHI scores to propose river health classes (RHC) and investigate the drivers.

The main purpose of this paper is to design a simple approach for a quick river health assessment based on geomorphic criteria. While it is well-established that rivers adjust over time across different river types, our approach is currently based on one-time measurements of geomorphic attributes rather than a temporal assessment. So, the issues of river adjustments over time are not being addressed here. Also, the geoindicators have been chosen to reflect the river typology and the diversity of forms based on Sinha et al. (2017). It is important to note that there is still no geomorphology-based approach for river health assessment for a river as diverse as the Ganga. This work has considered two broad categories, mountainous and alluvial, where the river process-form relationship is likely to be very different, rather than designing different criteria for each class, which would become too cumbersome to implement. However, the spatial variability in geomorphic parameters captures the morphological diversity in the mountainous and alluvial reaches and hence gets manifested in the RHA. Our intention is not to develop a prescriptive approach; instead, we attempt to develop a protocol that is implementable in the field by river managers for a quick assessment using a minimal dataset.

2 | The Ganga River: Flow Characteristics and Morphological Diversity

The Ganga River rises in the Gangotri glacier in the Himalayas at an altitude of 7010 m above mean sea level (Figure 1). The Ganga and its tributaries are fed by melting snow and ice from glaciers in the Himalaya. The river then flows through

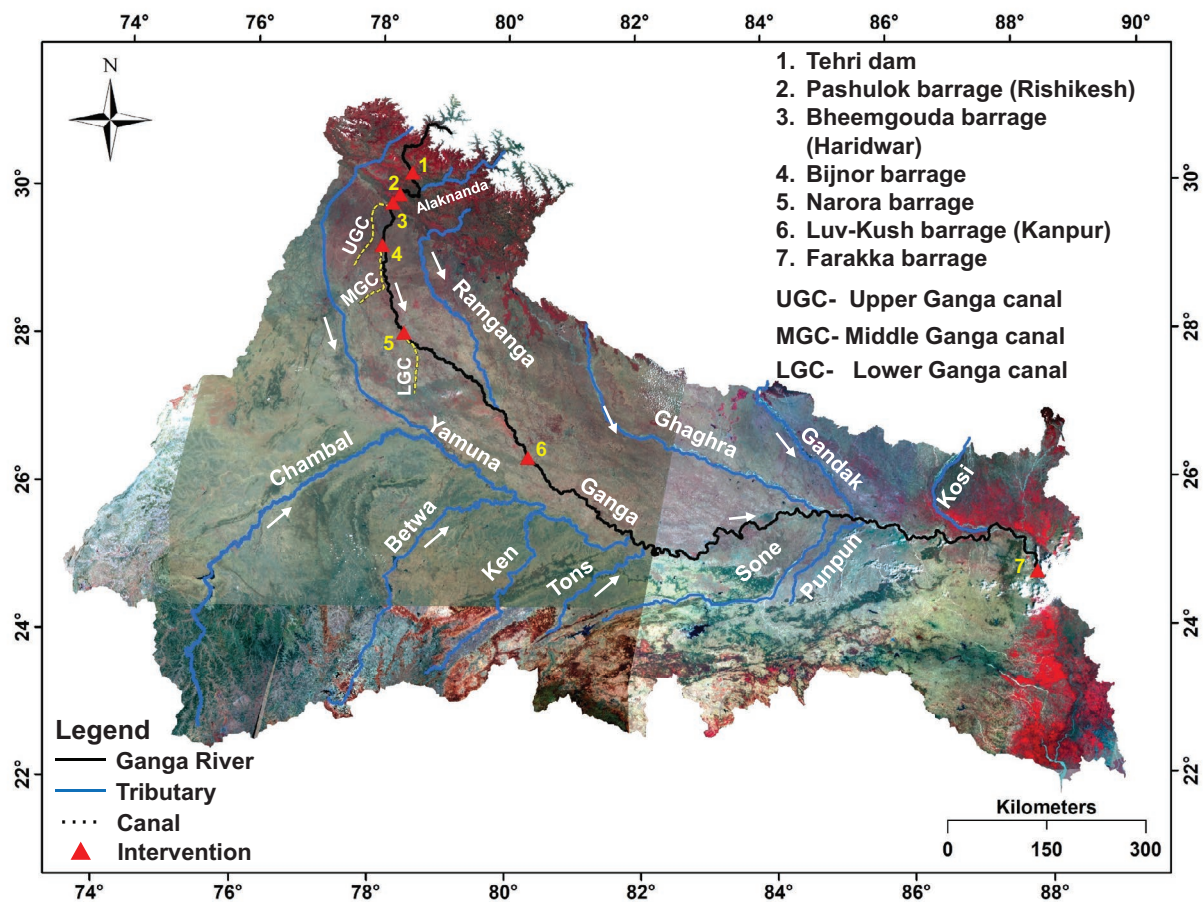


FIGURE 1 | The Ganga River basin showing the major tributaries and major interventions along the river. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/ra.70195)]

the plains and finally drains into the Sundarbans delta in the Bay of Bengal. The average annual rainfall in the Ganga basin varies from 600 mm in the western part to 1200 mm in the central part and 1400 mm in the eastern part. This rainfall variability, as well as tributary influences at several points, is manifested in a general downstream increase in discharge as shown by the hydrographs at different hydrological stations (Roy and Sinha 2017; Khan et al. 2018). These hydrographs characteristically begin to rise in June, peak in August and then start to decline, typical of a monsoonal climatic system. Discharge variability along the Ganga, coupled with changes in channel slope, are reflected in significant variations in stream power from upstream to downstream (Sinha et al. 2005, 2017). Furthermore, the Ganga is one of the highest sediment load-carrying rivers in the world, as most of its tributaries drain through the tectonically active Himalayan hinterland and add to the sediment budget of the Ganga system. At Farakka, the total annual suspended sediment load of the Ganga is ~200 million tonnes based on historical measurements (Sinha et al. 2023), whereas the estimate of unregulated sediment flux from the INCA model is approximately 356 Mtyr^{-1} (Khan et al. 2018). This difference may indicate the impact of the Farakka barrage on the sediment regime of the Lower Ganga River.

The Ganga River system has three distinct segments in terms of geomorphology—the upper mountainous segment

(Gomukh to Haridwar), the middle alluvial and interfluvial segment (Haridwar to Varanasi) and the lower alluvial and deltaic plains (Varanasi to Farakka). In the upper mountainous segment, the Ganga River system is made up of several tributaries such as the Alaknanda, Mandakini, Pindar, Nandakini and Bhilangana. The Ganga River enters the alluvial plains near Haridwar with a large channel belt, and some major tributaries that join in the middle stretch include the Ramganga, Rapti, Sarda and Kali. Several regulatory structures, such as the Bheemgouda Barrage, Bijnor Barrage and Kanpur Barrage, and abstraction through the upper Ganga canal, middle Ganga canal and lower Ganga canal, influence the river flow significantly in this segment (Figure 1). The Yamuna River joins the Ganga River near Allahabad, and in turn, receives significant contributions from several cratonic rivers such as the Chambal, Betwa, Ken and Tons. The lower segment is characterised by both alluvial and cratonic reaches. The Gandak, Ghaghra and Kosi from the north and the Sone and Punpun from the south join the Ganga River in this segment. The Ganga finally feeds into the Ganga-Brahmaputra-Meghna (GBM) delta, which includes the Sundarbans, the largest mangrove forest in the world (Wahid et al. 2007), most of which lies in Bangladesh.

The Ganga River system is characterised by significant morphological diversity from upstream to downstream that has been attributed to its varied hydrological characteristics (Sinha

et al. 2005). For example, the rivers of the Eastern Gangetic Plains (EGP) are dominantly aggradational, attributed to low stream power and high sediment flux, whereas rivers draining the Western Gangetic Plains (WGP), with high stream power and low sediment load, are dominantly degradational. Irrespective of their size, the WGP rivers are incised, while the EGP rivers exhibit wide and shallow channels. Further work also highlighted this contrast in morphologic diversity and characterised the WGP and EGP rivers as supply-limited and transport-limited systems, respectively (Roy and Sinha 2017; Swarnkar et al. 2020). The Lower Ganga River is characterised by a highly aggradational regime because of low slope, confluence of several highly sediment-charged rivers and reduction of non-monsoonal flows resulting from upstream abstraction (Sinha et al. 2023). Such morphological diversity, driven by varied hydrological characteristics, poses a significant challenge in the assessment of river health, as multiple factors play differential roles in different reaches along the river.

Our previous work (Sinha et al. 2017) proposed a formal classification of the Ganga River following a hierarchical scheme and recognised 10 different classes of the Ganga River based on (a) landscape setting, (b) channel and active floodplain properties and (c) channel planform parameters. It was suggested that the remarkable reach-scale variability of the Ganga River, as well as alterations in river form because of human interventions, warrant careful consideration of river morphology in designing sustainable management strategies. The present work takes this idea further and attempts to design specific geomorphic criteria to assess river health at the reach scale, integrating geomorphic diversity.

3 | Concept, Data and Methodology

3.1 | River Health Assessment: Conceptual Development and Multidimensional Perspectives

The concept of River Health Assessment (RHA) has acquired multiple perspectives because rivers are complex socio-ecological systems in which hydrological, geomorphological, ecological, biogeochemical and human processes interact across spatial and temporal scales. Consequently, scientists from different disciplines—including geomorphologists, ecologists, hydrologists, water-quality specialists and environmental managers—have approached river health from different perspectives and have designed different sets of indicators. While some approaches primarily evaluate the physicochemical quality of river water, others focus on biological integrity, habitat condition, flow regime, geomorphic stability, ecosystem functioning or the capacity of rivers to provide ecosystem services. It is important to note that river health is much broader than water quality alone and is increasingly viewed as an integrated measure of the condition, functioning, resilience and sustainability of a river system.

Early conceptualisations of river health emphasised the ecological condition of rivers and their capacity to sustain biological communities and ecosystem functions. Meyer (1997), Boulton (1999), and Karr (1999) contributed to the development of ecological approaches wherein river health was associated with the maintenance of ecosystem integrity, biological

diversity, ecological processes and the capacity of rivers to support human uses. These approaches represented an important transition from conventional pollution assessment towards a more holistic understanding of river condition. In this context, a healthy river was not necessarily defined as one with pristine water chemistry, but rather as a system capable of maintaining its characteristic ecological structure and functioning under natural or acceptable levels of human disturbance.

An important feature of the early development of RHA was the recognition that river condition should be evaluated using multiple indicators rather than a single environmental variable. Fairweather (1999), for example, proposed a hierarchical approach to environmental assessment that incorporated indicators derived from technical expertise as well as public and community-based observations. This perspective highlighted the importance of combining scientific measurements with societal perceptions of environmental condition. Such approaches are particularly relevant because rivers are simultaneously ecological systems and resources that support agriculture, domestic water supply, fisheries, transportation, recreation, cultural activities and other ecosystem services.

Norris and Thoms (1999) further broadened the concept by considering river health in relation to the physical and biological characteristics of river ecosystems. Their framework recognised that river condition can vary along gradients from relatively 'pristine' to 'highly degraded' states and from 'excellent' to 'poor' ecological condition. Importantly, biological communities cannot be considered independently of the physical environment in which they occur. Habitat structure, energy sources, flow characteristics and other physical attributes provide the environmental template within which biological processes operate. This perspective established an important basis for subsequently integrating hydrological and geomorphological characteristics into river-health assessments.

A major component of RHA has subsequently been the assessment of water quality. Conventional water-quality-based approaches evaluate parameters such as temperature, dissolved oxygen, pH, turbidity, electrical conductivity, transparency, nutrients, biochemical oxygen demand (BOD), chemical oxygen demand (COD) and various pollutants. These variables provide important information about the chemical and physicochemical condition of rivers and have therefore formed the basis of several river-health and pollution indices. Commonly applied approaches include the Water Quality Index or Ecological Quality Index, River Pollution Index and Overall Pollution Index (Singh and Saxena 2018). Such indices provide a means of reducing complex water-quality datasets to interpretable measures of river condition and are particularly useful for identifying pollution gradients and comparing river reaches. However, water-quality indicators alone cannot fully characterise river health. A river may exhibit relatively good chemical water quality while experiencing substantial hydrological alteration, sediment imbalance, channel modification, habitat degradation or loss of longitudinal and lateral connectivity. Conversely, naturally high turbidity or sediment concentrations in some river systems may not necessarily indicate ecological degradation because they can represent inherent characteristics of the natural flow and sediment regime. Therefore, water-quality measurements need to be

interpreted within the broader physical and ecological context of the river.

Hydrological condition represents another fundamental component of river health. Richter et al. (1996, 1997) emphasised the importance of maintaining appropriate streamflow regimes for sustaining river ecosystems and proposed approaches for linking flow requirements with river ecosystem management. The ecological significance of a river is not determined simply by the quantity of water present but also by the magnitude, frequency, duration, timing and rate of change of flows. High flows may be essential for sediment redistribution, channel maintenance, floodplain inundation, nutrient exchange and habitat renewal, whereas low-flow conditions may control habitat availability, water temperature, dissolved oxygen and aquatic organism survival. Consequently, alteration of the natural flow regime by dams, abstraction, regulation, inter-basin transfers and other interventions can substantially modify river health even where conventional water-quality indicators remain within acceptable limits.

The importance of integrating physical and biological dimensions was demonstrated by subsequent multidisciplinary assessments. For example, Aazami, Esmaili-Sari, et al. (2015) assessed river health in the Tajan River, Iran, using physicochemical parameters such as water temperature, dissolved oxygen, pH, turbidity and transparency. Further work on the same river used a multi-metric macroinvertebrate index and species traits (Aazami, Esmaili Sari, et al. 2015). Similarly, Yadav et al. (2014) evaluated the condition of the Chambal River using water-quality-related indicators. These studies demonstrate the usefulness of physicochemical measurements for identifying spatial variations in river condition and pollution status. Nevertheless, such approaches primarily describe the chemical environment and provide limited information about the physical processes responsible for maintaining channel and habitat dynamics.

More integrated approaches have attempted to overcome this limitation by combining multiple dimensions of river condition. Kim and An (2015), for example, developed an integrated assessment for the Nakdong River, South Korea, incorporating habitat, water-quality and biological health indicators. Their assessment included parameters such as pool substrate characteristics, channel-flow condition, biochemical oxygen demand, chemical oxygen demand and the abundance of native and sensitive species. Such approaches recognise that river health emerges from the interaction between the physical environment, water chemistry and biological communities rather than from any single environmental attribute.

The development of RHA can therefore be viewed as a progression from single-parameter pollution assessment towards multidimensional assessment of river-system condition. The first generation of approaches was largely concerned with identifying contamination and evaluating water quality. Subsequent approaches incorporated biological integrity and habitat condition, while later frameworks increasingly recognised the importance of hydrological alteration, geomorphic processes, ecosystem functioning and human pressures. This evolution reflects a broader shift in river science from

viewing rivers primarily as channels conveying water towards understanding them as dynamic, interconnected socio-ecological systems.

The inclusion of human dimensions further expands the concept of river health. Rivers provide a wide range of ecosystem services, including water supply, irrigation, fisheries, nutrient cycling, flood regulation, sediment transport, recreation and cultural values. At the same time, human activities can modify the physical and ecological processes that sustain these services. An RHA framework that incorporates ecosystem services can therefore provide a stronger basis for river management by connecting ecological condition with societal dependence on river systems. Participatory monitoring and local knowledge, as highlighted by Fairweather (1999), can further complement technical measurements by identifying changes in river condition that may not be readily captured by conventional monitoring programmes.

Despite these advances, several existing RHA approaches remain dominated by biological and physicochemical indicators, with comparatively limited integration of geomorphic processes, sediment dynamics, hydrological variability and river connectivity. This is a significant limitation because the long-term health of a river depends not only on the quality of its water or the status of its biological communities, but also on the continued functioning of the physical processes that generate and maintain habitats. A more process-based RHA should therefore move beyond simply measuring environmental attributes and should assess whether the fundamental hydrological and geomorphological processes required to sustain ecological functions remain intact.

Accordingly, River Health Assessment can be conceptualised as an integrated evaluation of the structure, processes, functions and resilience of a river system, together with the pressures acting upon it and the services it provides to society. Such a framework provides a basis for linking river hydrology, geomorphology, ecology, water quality and human use within a common assessment system. It also shifts the emphasis from measuring isolated indicators of degradation towards understanding the underlying processes that control river condition and its capacity to recover from disturbance. Over time, several country-specific RHA protocols have been developed, depending upon the priorities in each country. A few notable examples are from Australia (AusRivAS 2001), the US Wadeable Streams Assessment (USEPA 2006), the European STAR project (Hering et al. 2006) and South Africa's River Health Programme (Dallas et al. 2010), which focused on the identification of potential risks to aquatic systems and the promotion of biodiversity. The fundamental premise in most of these protocols is to design a score to assess the deviation of the river condition compared to a 'reference' condition, that is, the least modified river corridor in a region (Wohl et al. 2024).

3.2 | Geomorphic Context in River Health Assessment

Geomorphology plays a very important role in river health assessment because channel form and sediment dynamics provide

the physical foundation of river ecosystems. Channel width, depth, planform, bed material, bank condition, bedforms, sediment transport, erosion and deposition, floodplain connectivity and channel migration influence habitat diversity and the capacity of rivers to adjust to changing water and sediment inputs. River channels are dynamic systems rather than static conduits, and their health depends partly on whether geomorphic processes remain within a range that allows the system to maintain or reorganise its characteristic structure and functions. Excessive sediment supply, sediment starvation, channel incision, bed aggradation, bank erosion, artificial channelisation and disruption of sediment connectivity can therefore produce substantial changes in river condition that may not be captured by conventional water-quality or biological indices.

River health assessments are often aimed at identifying sustainable solutions for 'river restoration', that is, returning rivers to pre-disturbance conditions. However, given the extent of anthropogenic disturbance on rivers, it is often impractical to achieve restoration as (a) several anthropogenic disturbances are irreversible, (b) need to reconcile human needs with river protection and (c) difficulties in defining pre-disturbance or reference condition (Jungwirth et al. 2002; Dufour and Piegay 2009; Piegay et al. 2023). Therefore, a more practical approach is that of 'river rehabilitation' or 'river repair', which aims to restore the damaged ecosystem functions and improve river status (River Futures) to achieve an alternative steady state (Aronson et al. 1993; Brierley and Fryirs 2008; Fryirs et al. 2008; Morandi and Piegay 2017).

One of the major emphases of this paper is to highlight how geomorphic attributes and process understanding of rivers can improve RHA and river rehabilitation by rebuilding river forms and improving physical processes (Brierley and Fryirs 2022; Piegay et al. 2023; Wohl et al. 2024). In most cases, the expectation is that morphological measures will improve the channel and riparian habitats, and consequently, the river ecology. Morphological measures impact river energy, resistance and responsiveness, which in turn drive river adjustments and future channel states; therefore, they are critical for sustainable rehabilitation of rivers. An important consideration in such measures is the availability of historical (pre-disturbance) geomorphic datasets on river morphodynamics, which can inform the selection of appropriate rehabilitation measures (Wohl et al. 2024). Historical geomorphic analysis may not provide an ideal 'reference' condition but certainly helps in understanding the temporal evolution and impacts of episodic extreme events such as large avulsions or floods and the potential future trajectory of rivers (Brierley and Fryirs 2016). Wohl et al. (2024) have highlighted several scenarios where non-consideration of geomorphic context in river rehabilitation work can fail or will only produce short-term benefits.

The morphological measures can be designed at multiple scales, ranging from reconstructing/protecting in-stream morphology at the local scale (e.g., riffle, pool and bar) or regional scale (e.g., modification of channel meanders or substrate) to restoring channel-floodplain connectivity (e.g., repositioning of levees, reconnecting paleochannels). A 'river corridor', including the active channels, floodplain and the underlying hyporheic zone (Baptist et al. 2004; Harvey and Gooseff 2015; Wohl 2021), is often considered an optimum scale that reflects channel-floodplain

interactions and fluxes (Wohl et al. 2024) necessary to maintain river health. It is a widely accepted view to allow rivers to have space to perform their basic functions, including water and sediment transport, and other processes such as migration and avulsion. Several terms have been used to describe this concept, such as 'room for the river' (Baptist et al. 2004), 'freedom space' (Biron et al. 2014), 'fluvial territory' (Ollero et al. 2010) and 'erodible corridor' (Kondolf 2011; Piegay et al. 2005). More recent work by Glassic et al. (2025) has emphasised that all healthy rivers should maintain (a) adequate river space, (b) natural flow, sediment and vegetation regime appropriate for their geomorphic setting and river type and (c) structural forcing to support geomorphic diversity.

In the Anthropocene context, a large-scale assessment of human-induced drivers may also be required, for example, increased sediment flux due to catchment erosion, or land-cover changes and sediment trapping in dams or barrages (Downs and Piegay 2019; Ma et al. 2012; Sinha et al. 2023). It is important, however, to understand that such assessments and solutions must take into consideration the geomorphic diversity of the rivers—a 'one-size-fits-all' approach often does not work because rivers have variable sensitivity and therefore differential responses to the same measure. It is therefore important to understand that the rivers are likely to respond to the imposed conditions and follow different trajectories of river adjustment, depending upon geomorphic attributes such as resilience, sensitivity and vulnerability (Fryirs 2017). This realisation forms the basis of geomorphic process-based RHA and rehabilitation, promoting nature-based solutions. Such approaches for river repair have led to the foundation of the interdisciplinary 'river science' (Pickett et al. 1994; NAS 2007; Sinha et al. 2012; Thoms et al. 2016; Garcia et al. 2021).

3.3 | Datasets and Approach Developed for This Study

There has been a strong line of research on morphological diversity, hydrology, sediment transport and ecosystem assessment in the Ganga River (Sinha et al. 2005, 2023; Roy and Sinha 2017, 2018; Mathur and Kapoor 2019a, 2019b; Swarnkar et al. 2020). However, a systematic RHA using a physical template has not yet been undertaken. Globally, the focus has shifted to maintaining a broad range of physical habitats in a river system (Blue and Brierley 2016) to keep the rivers healthy. Therefore, this study develops a physical template based on selected geomorphic attributes for assessing river health in a diverse river system such as Ganga. Our primary consideration was to select simple morphological parameters to reflect the diversity as well as to be easy to measure from publicly available datasets so that the resultant river health index is implementable by river managers.

The present study builds upon our previous work on the morphological classes for the Ganga River (Sinha et al. 2017), wherein two broad landscape settings of the river, namely, mountainous and alluvial, were identified, and 10 river classes were mapped. We have used the morphometric data presented in our previous work (Sinha et al. 2017). In addition, hydrological characteristics were represented by stream power computed from discharge

and the longitudinal profile derived from the SRTM DEM (90 m resolution).

Data were integrated to compute reach-scale gRHI using the Analytic Hierarchy Process (AHP) (Saaty 1980; Siddiqui et al. 1996) within a GIS framework. This method uses pairwise comparisons among the selected parameters to calculate their Relative Importance Weightage (RIW) values. These RIWs are multiplied by the original morphometric data at different levels to compute gRHI. Specific details of the AHP and steps followed to generate the gRHI values are discussed later. In the final synthesis, the gRHI scores for each of the morphological parameters were integrated to categorise the final river health classes (RHC) of individual reaches and their causal factors.

4 | River Health Parameters and Design of Geomorphic River Health Index

4.1 | Rationale for Selection of Geomorphic Attributes for River Health Assessment

Our study builds on the geomorphic diversity and process understanding of the Ganga River over the last few decades. Geomorphic diversity along the Ganga is driven by strong contrasts in hinterland and precipitation characteristics (Sinha et al. 2005), which set regional-scale controls on hydrology and sediment transport and drive morphological characteristics. Detailed hydrological analysis further supported this, characterising different parts of the Ganga system as supply-limited and transport-limited (Roy and Sinha 2017, 2018). A formal classification of the Ganga River typologies based on morphometric parameters (Sinha et al. 2017) was based on the previous process understanding, and this also allowed us to design a set of river health parameters for this study, as listed in Table 1, along with their definitions and expressions.

We have selected a total of eight parameters, namely, channel sinuosity (CS), braid-channel ratio (BCR), bar density (BD), bar complexity (BC), floodplain development (FD), occupancy (OP), width/depth ratio (W/D) and stream power (SP). The selection of these parameters is driven by our intention to keep the scheme simple and usable for rapid assessment of river health by practitioners using geomorphic attributes. Our previous work (Sinha et al. 2017) presented a detailed dataset on fourteen morphological attributes of the Ganga River, which identified the ten process-based river types of the Ganga. We have selected two parameters (CS and BCR) directly from this dataset and designed six additional parameters to reflect the morphological diversity of the river in the mountainous and alluvial reaches. For example, CS, BCR, BD and BC are important channel belt parameters focused on the morphometric attributes of bars and channels. OP and FD indicate the lateral connectivity component, where active floodplain width and valley width are considered. In addition, the W/D ratio, representing cross-sectional form and SP, integrating hydrology and longitudinal slope, were also used for gRHI calculation. The following sections present a quick summary of the geomorphic attributes, focusing on the significance of each of these parameters from a river health perspective for the Ganga River.

4.1.1 | Channel Sinuosity (CS)

CS is the ratio of channel length to the valley length, which is the measure of the meandering of a river (Friend and Sinha 1993; Figure 2a and Table 1), and a sinuosity index of 1.3 or 1.5 is commonly used to distinguish mildly sinuous and typical meandering rivers (Schumm 1977; Thorne 1997). Curves, or meanders, provide a platform to absorb and dissipate river energy. It leads to the formation of point bars and other planform features which provide suitable habitats. The low velocity of a sinuous river creates a medium for the stream biota to move for nutrients and breeding. Bends of the sinuous river have a balanced tendency to absorb the increased river energy to protect the channel from excessive erosion during flooding (Knighton and Nanson 1993) and provide refuge for fish and aquatic invertebrates. Hence, the degree of sinuosity is important for the river health Index.

Figure 3 plots the CS variation of the entire Ganga River along with other morphometric datasets, namely valley width, channel belt width and floodplain width. In upper mountainous reaches (1–34) with narrow valleys and thin channels (Figure 3a,b), the average CS was measured as 1.39 with a maximum of 2.43 and a minimum of 1.03 (Figure 3c). Around Rishikesh and Haridwar (reaches 28–30), where the river enters the alluvial plains and the valley broadens, CS was observed to be very low (average sinuosity 1.15). In the middle alluvial reaches (31–64) with exceptionally wide valleys, significant variation in CS is observed in all geomorphic classes, varying from 1.22 to 2.45. In the lower alluvial and deltaic stretch, the maximum CS of 2.6 was recorded near Suapur (reach 68), whereas the minimum value of 1.1 was recorded near Chausa (reach 70).

4.1.2 | Braid Channel Ratio (BCR)

The BCR directly reflects the multiplicity of channels. It was measured as the ratio between the sum of the mid-channel lengths of all the secondary channels in a reach and the length of the midline of the primary channel (Friend and Sinha 1993) (Figure 2b, Table 1). In multi-channel rivers, the widest channel was interpreted as the primary channel. Higher values of BCR are manifested as a larger number of bars in the channel belt. Typically, moderate BCR values are suitable for stream biota as they use the bars for their resting place. In the present gRHI framework, the reaches with very high BCR values are considered poor indicators of river health, as they tend to lower the longitudinal connectivity and therefore restrict the hydrological and nutrient fluxes.

In the mountainous reaches of the Ganga River, the BCR is very low (as the channels tend to be steep, narrow and incised with very few bars; Figure 3b,c). Between Rishikesh and Haridwar (reaches 28–30), the average BCR was computed as 1.98 with a maximum value of 2.78 near Rishikesh and a minimum value of 1.21 near Haridwar. At Haridwar_DS (reach 31), BCR increases sharply to approximately 3.5, marking the transition from the mountainous to the piedmont setting. The alluvial reaches, on the other hand, are characterised by higher BCR values (Figure 3c) as lower slopes and wider channels (Figure 3a,b) promote the formation of bars. We recorded BCR values of 1.65–2.7 in the alluvial reaches, and they typically increase around the

TABLE 1 | Parameters for computing the Geomorphic River Health Index (gRHI).

Term	Expression	Process interpretation and implication for river health
Sinuosity (CS)	$CS = \frac{L_{cmax}}{L_r}$	A high value would indicate better support for biological activity. A very high value in multi-channel reach might reflect imbalance in sediment-water ratio.
Braid channel ratio (BCR)	$BCR = \frac{L_{dot}}{L_{cmax}}$	Moderate values are good for biota; higher values tend to lower the hydrological connectivity.
Bar density (BD)	$BD = \frac{\sum BA}{\sum CA}$ Where BA is Bar area and CA is Channel area	High values indicate high sediment-water discharge ratio. Very high values will indicate degeneration of river. Moderate values are good for biota as it would indicate the presence of ample substrate for biological activities.
Bar complexity (BC)	$BC = \left[\frac{\text{Bar Perimeter}}{\text{Bar Area}} \right]$	Measures complexity of the bar margins. High to moderate values indicate presence of bars of varied sizes. Good for biota.
Occupancy (OP)	$OP = \frac{AFLw + AFRw}{Vw}$ Where AFLw is width of left active floodplain and AFRw is the width of right one. Vw is the width of the valley.	Measures landscape scale equilibrium of the river system. A value close to 1 would indicate that the channel belt and its floodplains fully occupying the lateral accommodation space. A small value (say, <0.5) would indicate an under-fit system. Moderate to high values are considered good for river health.
Floodplain development (FD)	$FD = \frac{Cbw}{Sw}$ Where Cbw is channel belt width and Sw is the width of entire floodplain from left floodplain margin to right including the channel belt.	Low values might indicate flood prone/ avulsive system. Moderate values (say, around 0.5) should indicate a stable system with good lateral connectivity. High values should indicate incised/embanked or partly abandoned system.
Width/Depth ratio (W/D)	$W/D = \frac{W}{D_{max}}$ Where W is bankfull width and D_{max} is maximum depth	Low to moderate w/d ratios favour turbulence and oxygenation; increased W/D ratio results in less canopy cover.
Stream power (SP)	Energy dissipation rate per unit downstream length of a stream. $SP = \gamma QS$ Where γ is the specific weight of water, approximately 9800 N m^{-3} Q is discharge in $\text{m}^3 \text{ s}^{-1}$ S is the dimensionless energy slope.	Low to moderate stream power just enough to maintain the present morphology should favour good river health.

confluence points (Figure 3c). Typically, moderate BCR values are suitable for stream biota as they use the bars for their resting place. In the present gRHI framework, the reaches with very high BCR values are considered poor indicators of river health, as they tend to lower the longitudinal connectivity and therefore restrict the hydrological and nutrient fluxes.

4.1.3 | Bar Density (BD)

BD comprises almost all channel belt attributes, which include side bar, point bar, alluvial island and mid-channel bar along with the channel area. These bars contribute significantly to the ecosystem in terms of habitat. They define the sediment

regimes in each reach of the river depending on their typology and geomorphic setting (Wohl et al. 2015; Glassic et al. 2025). In geomorphic terms, they define the aggradational or degradation zone in a river, including anthropogenic disturbances (Wohl et al. 2015; Poepl et al. 2020; Sinha et al. 2023). In general, bars increase the morphological and habitat diversity, but research has shown that both very low and very high bar density can indicate altered river functioning (Crosato and Mosselman 2009). Therefore, low to moderate bar density can indicate active sediment-water interactions and morphological complexity and hence good river health, whereas very high BD indicates sediment imbalance and very low BD indicates river degradation. It has been suggested that both aquatic and riparian organisms are influenced by and often adapt to different sediment regimes

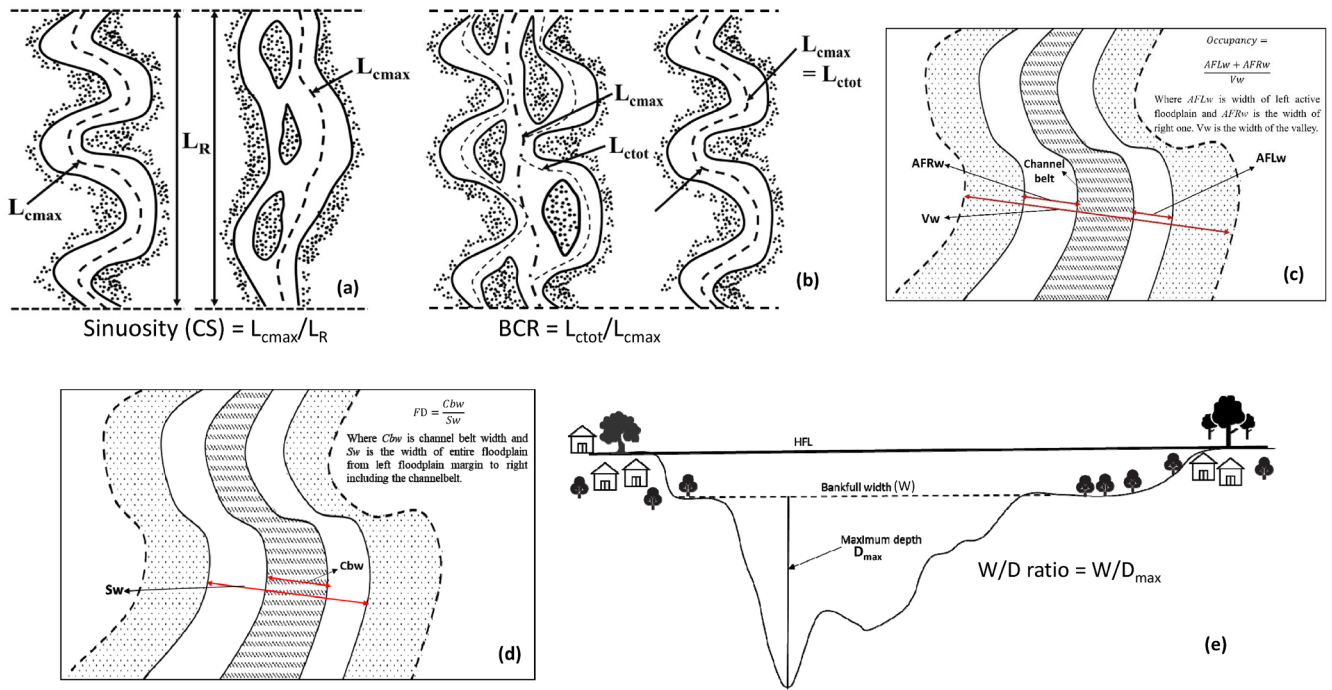


FIGURE 2 | Geomorphic parameters used for river-health assessment: (a) sinuosity, (b) braid-channel ratio, (c) occupancy, (d) floodplain development and (e) cross-sectional parameters (bankfull width, maximum depth). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

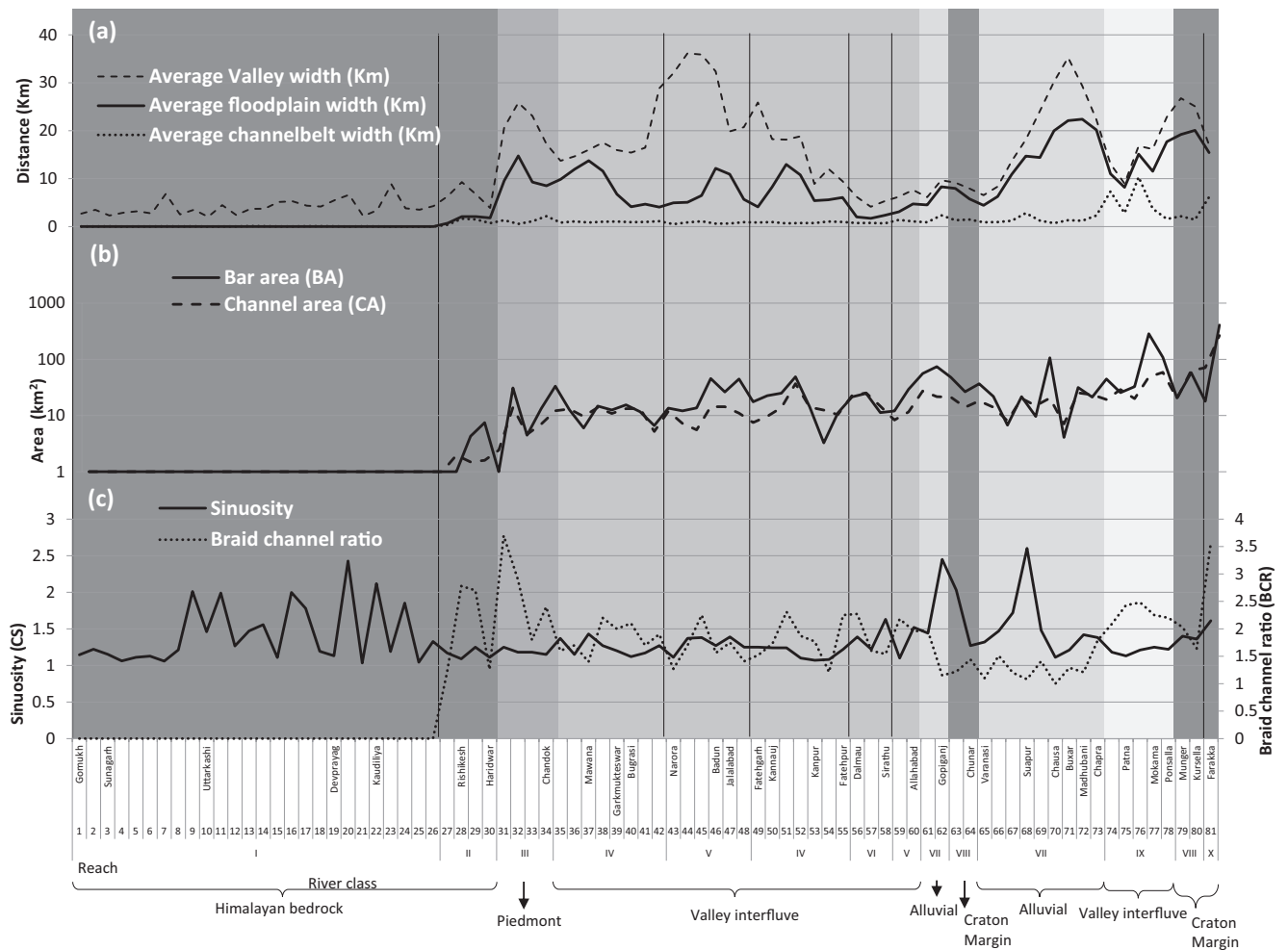


FIGURE 3 | Plot showing the reach scale variability of (a) average valley width, floodplain width and channel belt width (b) bar area and channel area and (c) sinuosity and braid-channel ratio (modified after Sinha et al. 2017).

(Wood and Armitage 1997; Newcombe and Macdonald 1991), and therefore, the quantification of BD along a large river reflects distinct sediment regimes and therefore habitat suitability.

In this work, we first measured the total area of in-channel features (i.e., mid-channel bar, side bar, point bar and alluvial island) in each reach. BD was subsequently computed by taking the ratio of bar area to channel area for each reach (Table 1). Since the mountainous reaches have very narrow valleys and both channel and bar areas are very low (Figure 3a,b), BD was measured for the middle and lower alluvial reaches only, and it varied from values close to 1 to as high as 5–6 in certain reaches (Figure 4a). Relatively high BD values were recorded near Jalalabad (reach 47), downstream of Allahabad (reach 61), upstream of Chausa (reach 69) and downstream of Patna (reach 76). The highest value of nearly 6 was recorded downstream of Patna at reach 76 (Figure 4a). In contrast, relatively low BD values occur near Kanpur (reach 53), Suapur (reach 68) and Bhagalpur (reach 80). This variability reflects local differences in sediment deposition and bar abundance rather than a consistent downstream trend.

4.1.4 | Bar Complexity (BC)

Bars provide an essential platform for living, spawning and hatching for aquatic biota. BC refers to the shape of the bars and represents the diversity of bar types and hence the habitat present in each reach. Therefore, it is conceptually different from bar density and should be assessed separately, although they are often interpreted together. A large number of bars with different

shapes and sizes would constitute a complex river ecosystem and a physically diverse habitat in terms of flow patterns, residence times for water, sediment and vegetation at spatial and temporal scales (Glassic et al. 2025). Bar complexity can reveal whether sediment supply and transport capacity are relatively well matched. Balanced sediment supply and variable flows may result in deposition and reworking and complex bar morphology. Where sediment supply is excessive, bars may become large and rapidly aggrading. Conversely, sediment starvation can produce relatively simple, incised or armoured channels. BC can therefore be considered as a measure of structural diversity required for a healthy river (Glassic et al. 2025), which creates a suitable habitat for various aquatic biota. However, not all healthy rivers necessarily have high structural diversity (Zhang and Fryirs 2024), and therefore, this needs careful consideration for river restoration efforts. In general, high to moderate values of BC are considered good for river health as it indicates greater habitat heterogeneity and active sediment dynamics.

In this work, BC was calculated by taking the ratio of the average bar perimeter to the bar area, and like bar density, it was also measured for the middle and lower reaches only (Table 1). In a river system, the degree of heterogeneity is controlled by the values of bar complexity; typically, reaches with moderate BC values make good habitat. We have noted several reaches in the Ganga River with very high bar complexity of 10–18, while moderate values of 4–6 are common in others (Figure 4b). High BC values were recorded near Garmukteshwar (reach 39), Kanpur (reach 53) and Bhagalpur (reach 80), where values reached approximately 15, 18 and 11, respectively. In comparison, moderate

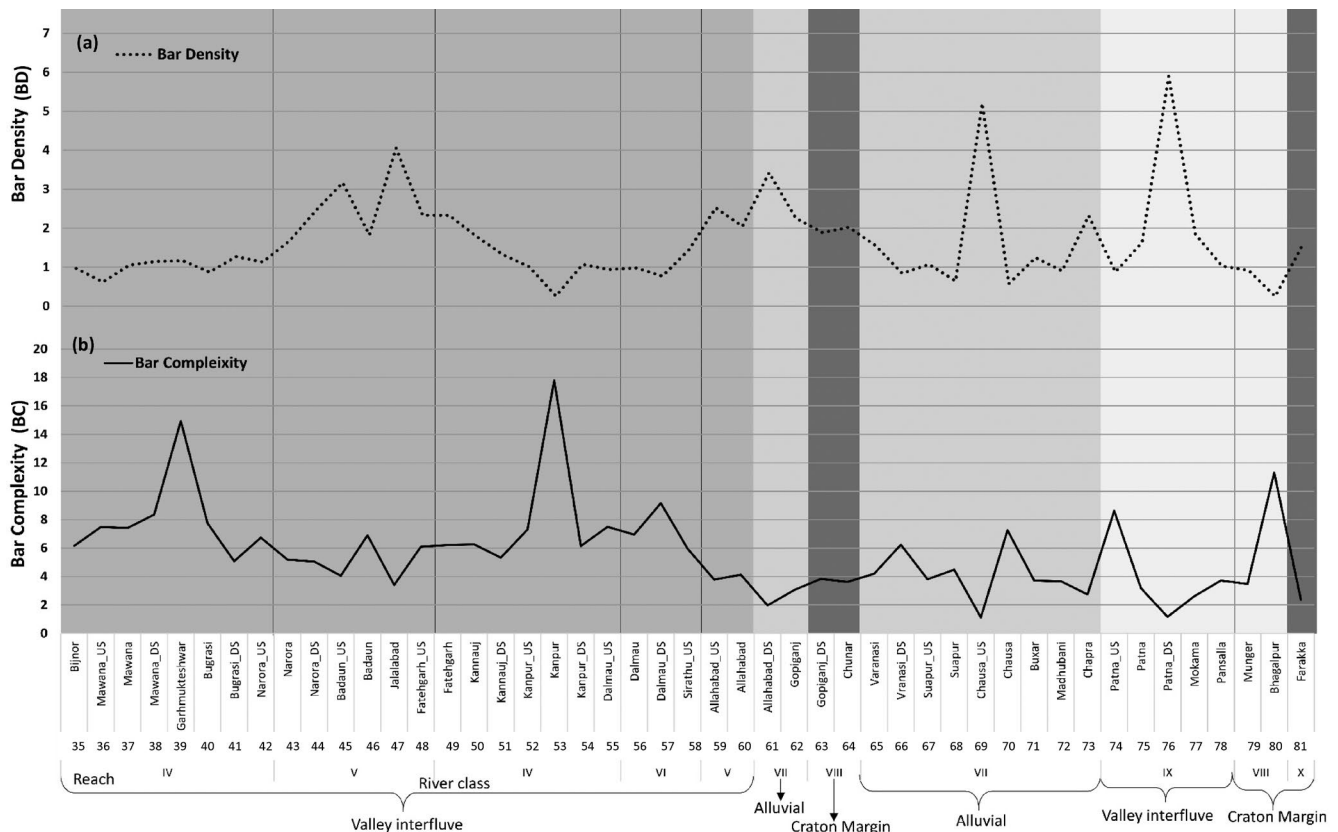


FIGURE 4 | Plot showing the reach scale variability of (a) bar density (BD), and (b) bar complexity (BC).

BC values of approximately 4–6 were common across several other reaches.

4.1.5 | Occupancy (OP)

OP defines the lateral accommodation within the valley margin. It also represents the relationship between the valley width and the floodplain width on both sides and therefore provides a quantitative measure of 'river space'. In river ecosystems, several geomorphic and ecological functions, such as lateral channel adjustments, bank erosion, terrace development (Brierley and Fryirs 2005; Sholtes et al. 2018; Glassic et al. 2025), maintenance of riparian vegetation (Florsheim and Mount 2002) and the exchange of sediment and nutrients (Wood and Armitage 1997), are facilitated through these floodplains. Hence, moderate to high values of occupancy are good for river health. A very high value of OP disturbs the balance of channel-floodplain interaction, and a very low value is insufficient for adequate nutrient transfer and may therefore reduce habitat suitability.

For the computation of OP, the width of the left and right active floodplains was measured. The ratio between the sum of floodplain widths (i.e., $AFL_w + AFR_w$) and the valley width (V_w) provides the occupancy value (Figure 2c, Table 1). In mountainous reaches of the Ganga River, active floodplains on either side of the river occur in patches (Figure 3a), thereby resulting in low values of occupancy. OP remains close to 0 across most Himalayan bedrock reaches (reaches 1–26) and begins to increase in the piedmont reaches (reaches 27–30). In contrast, the alluvial reaches are characterised by wide active floodplains (Figure 3a) that provide the necessary lateral connectivity

between the channel belt and floodplain. We have documented the OP values of more than 0.5 in several downstream alluvial reaches of the Ganga River, particularly around reaches 35–38, 50–52, 61–73 and 77–81 (Figure 5a).

4.1.6 | Floodplain Development (FD)

Floodplain development (FD) also represents the lateral connectivity between the channel and floodplain in a given reach. A river with a well-developed floodplain can support geomorphic equilibrium and good river health. In addition to providing adequate 'river space', floodplain development determines the suitability of the habitat in the sense that lower FD values suggest better lateral connectivity, enhancing the exchange of carbon and nutrients (Wood and Armitage 1997; Glassic et al. 2025) and therefore creates a functional riverscape and 'shifting habitat mosaics' (Stanford et al. 2005; Ward et al. 1999). FD has been related to two main drivers, stream power and sediment supply and therefore, it is strongly controlled by catchment characteristics such as geology and drainage network density (Jain et al. 2008). Importantly, a river running through a naturally developed floodplain can have good health, while a heavily urbanised but hydraulically connected floodplain may retain some functions. What matters most is the degree of alteration relative to the river's natural/reference condition.

In this work, FD has been defined as the ratio between channel belt width (Cbw) and the entire floodplain width (i.e., $Sw = AFL_w + AFR_w + Cbw$), and therefore, represents floodplain development with respect to the entire channel belt in a

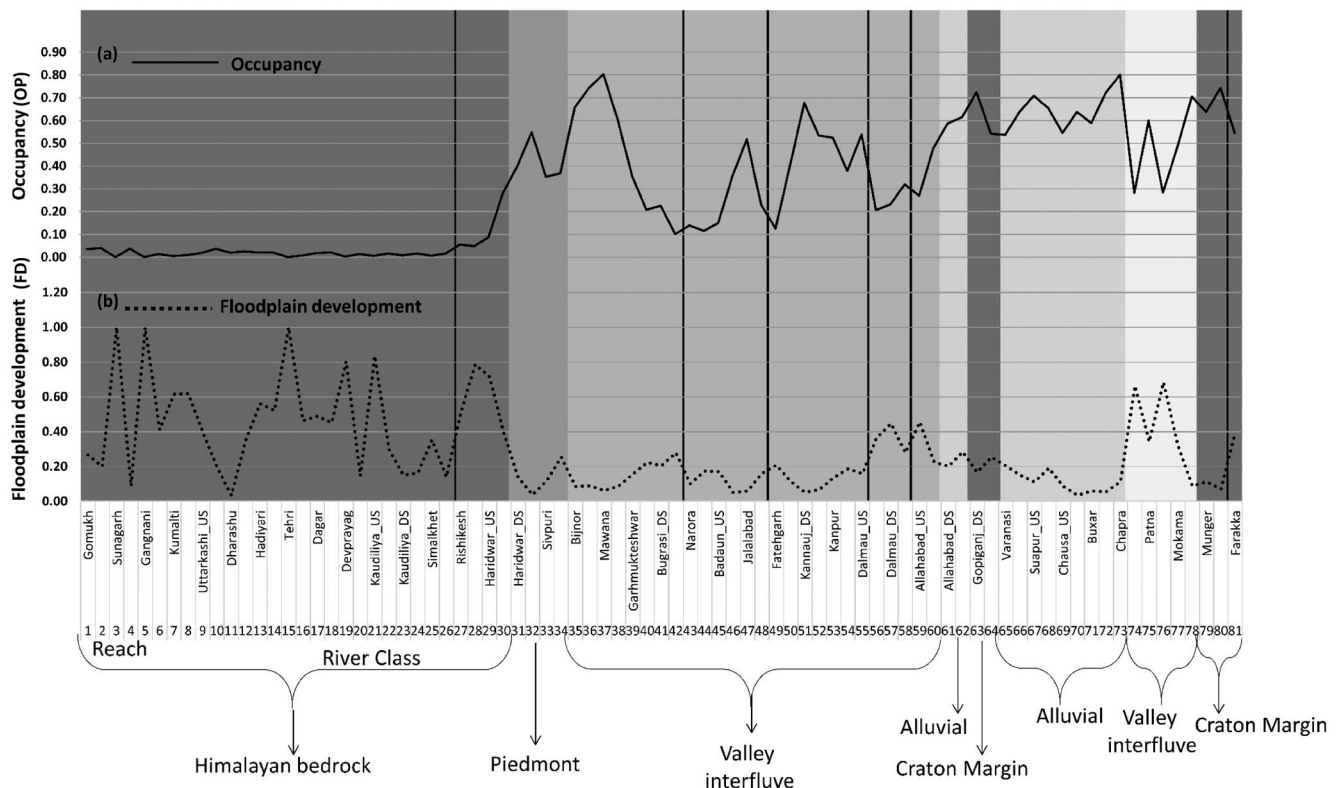


FIGURE 5 | Plot showing the reach scale variability of (a) occupancy (OP) and (b) floodplain development (FD).

given reach (Figure 2d, Table 1). As mentioned earlier, patchy development of the floodplain in the mountainous reaches with narrow channels (Figure 3a) gives rise to FD values close to 1. It includes reaches such as Sunagarh (reach 3), Gangnani (reach 5), Tehri (reach 15), Devprayag (reach 19) and Kaudiliya_US (reach 21) (Figure 5b). Whereas most alluvial reaches are characterised by values of FD < 1 across most valley-interfluvial, alluvial and craton-margin reaches, as the channel belts are also very wide. Local increases occur near Dalmau_DS (reach 57), Allahabad_US (reach 59) and around Patna (reaches 74–76), where values reach approximately 0.4–0.7 (Figure 5b).

4.1.7 | Width/Depth Ratio (W/D)

The W/D ratio (Figure 2e, Table 1) has long been used as an indicator of channel shape, stability and the percentage of muddy sediments along the channel perimeter and banks and is positively related to discharge and sediment load. High values of the width/depth ratio indicate less vegetation cover, which is helpful for the growth of invertebrates suitable for fish. Moderate values are considered suitable for aquatic biota and preferred as good habitat. Varying depth zones in a river are essential for stream organisms of all age groups. We measured cross-sections at several points and computed W/D ratios at these locations. Channel depths are generally < 5 m in the mountainous reaches but often exceed 10 m

in the alluvial reaches, sometimes reaching > 20 m (Figure 6a). The W/D ratios are highly variable in the mountainous reaches (< 10), including Gomukh (reach 1) to Simakhet (reach 25), indicating narrow and incised channels, except at a few locations where wider valleys occur. In the alluvial reaches, including the piedmont region, W/D ratios generally exceed 100, indicating wide and shallow channels, barring a few confined reaches (Figure 6a). Particularly high W/D ratios were recorded near Garmukteshwar (reach 39), Kannauj (reach 50), Kanpur_US (reach 52), Allahabad (reach 60), Chunar (reach 64), Madhubani (reach 72), Pansalia (reach 78), Munger (reach 79) and Farakka (reach 81).

4.1.8 | Stream Power (SP)

A river is not just a conduit of water but also transports sediments and nutrients from upstream to downstream. SP was calculated by taking the ratio of energy expenditure to unit channel width for each reach using the expression provided in Table 1. A continuous profile of stream power distribution was generated using the discharge-area relationship following Jain et al. (2006). Stream power reflects the energy available to the system and the power to transport sediments, and floodplain development (Jain et al. 2008). In the present gRHI framework, moderate to high SP values are accepted as good for habitat suitability, as this maintains the balance between erosion and deposition and therefore creates a stable

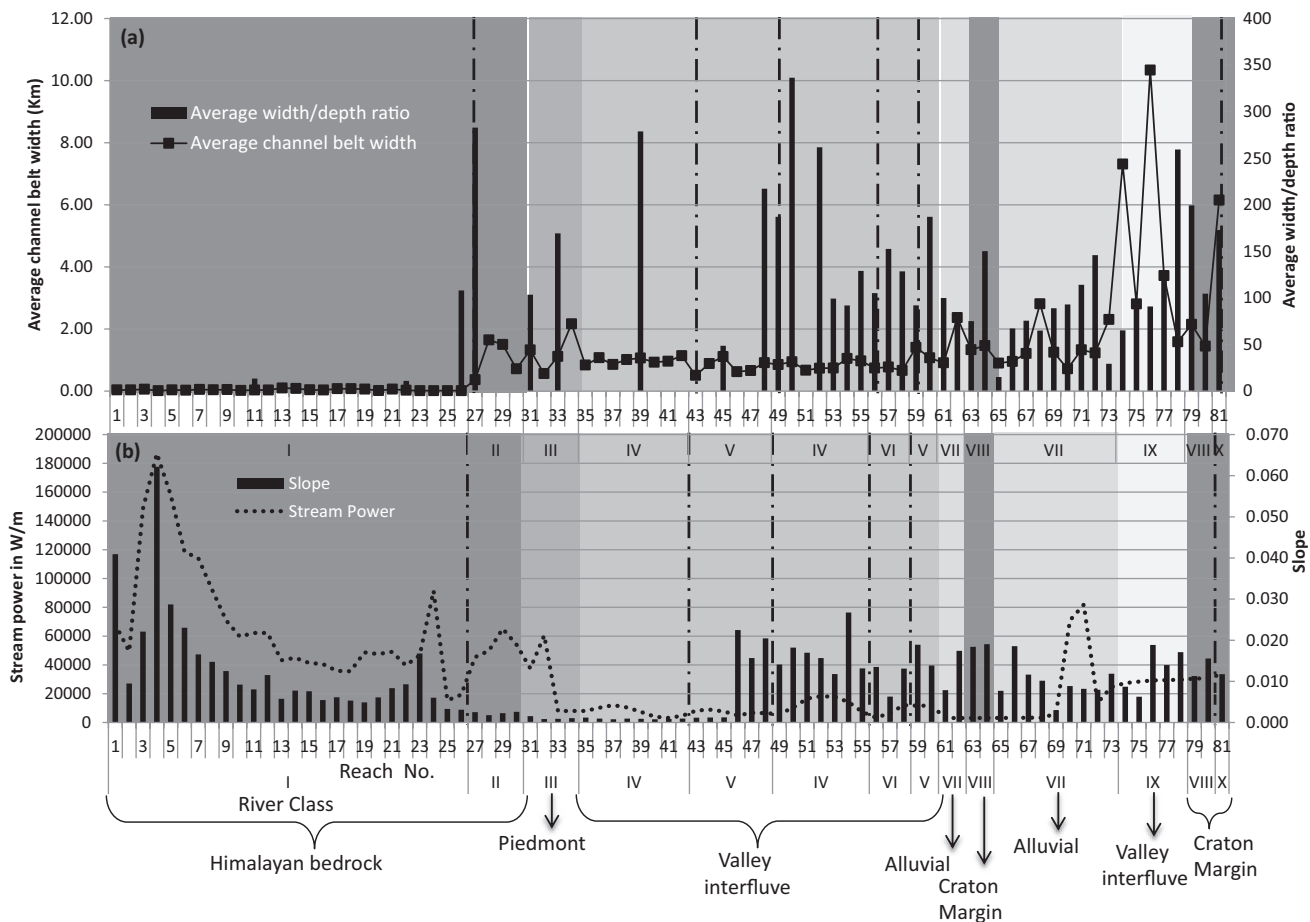


FIGURE 6 | Plot showing the reach scale variability of (a) average W/D ratio and average channel belt width, and (b) slope and unit stream power (SP) (based on data from Sinha et al. 2017).

channel form. High SP values correspond to steep, straight reaches and bedrock gorges, whereas low values occur in wide alluvial reaches where aggradation is dominant. Changes in channel slope or discharge alter SP and may disturb the river equilibrium.

Sinha et al. (2017) demonstrated that stream power variability drives the morphological diversity along the Ganga River in a major way. For example, high SP values in the mountainous reaches between Gomukh (reach 1) and Simakhet (reach 25) result in very few channel bars and hence low BCR and bar density, except for a few wider reaches. The highest SP values occur in the upper Himalayan reaches, particularly between Sunagarh (reach 3) and Gangnani (reach 5), with another local increase near Simakhet (reach 25) (Figure 6b). The sinuosity of the river in the mountainous stretch is governed by bedrock properties.

In the piedmont region between Rishikesh (reach 27) and Haridwar_DS (reach 31) and further downstream in the alluvial reaches, a drop in the slope and stream power because of an increase in valley width results in dissipation of energy along the cross section, leading to extensive bar deposition and an increase in BCR (Figure 6b), forming highly braided channels and alluvial islands. In the alluvial reaches downstream of Allahabad (reach 60), the stream power decreases further (Figure 6b), which results in channel transformation from high-energy braided to low-energy meandering systems as reflected in higher CS in several reaches (Figure 3c). Downstream of Chapra (reach 73), several sediment-charged tributaries such as the Ghaghra, Gandak and Kosi rivers join the Ganga from the north, and the river regains its braided morphology (Figure 3c). Large alluvial islands and anabranching patterns in several reaches in this stretch reflect the dominance of the depositional regime, owing to a decrease in SP (Sinha et al. 2017).

4.2 | Design of the Geomorphic River Health Index (gRHI)

We have integrated several geomorphic parameters for RHA using the AHP within a GIS framework. AHP is a multicriteria decision-making method based on pairwise comparisons using Saaty's nine-point scale (Table A1 in the supplementary) (Saaty 1980; Siddiqui et al. 1996). It has been widely applied to various applications such as flood risk analysis (Sinha et al. 2008; Stefanidis and Stathis 2013; Kazakis et al. 2015; Mayaja et al. 2016; Mishra and Sinha 2020), water quality assessment (Do et al. 2013; Bhutiani et al. 2016) and watershed management (Young et al. 2010; Yavuz and Baycan 2013; Rahmati et al. 2016) and RHA (Xia et al. 2014; Zhang et al. 2015; Song et al. 2015). The procedure involved six steps, shown schematically in Figure 7 and described below.

- I. Defining the objective or goal: The objective of this study is the RHA of the Ganga River.
- II. Selection of the decision factors: Geomorphic parameters influencing river health were identified based on the process understanding described in Section 4.1.
- III. Constructing the decision hierarchy: The key geomorphic parameters were arranged at Level 2, while their

value classes were arranged at Level 3. Separate decision hierarchies were developed for the mountainous and alluvial reaches (Tables 2 and 3).

- IV. Calculating the relative Importance Weightage (RIW): Pairwise-comparison matrices were constructed, and the RIW of each hierarchical parameter was calculated. This step involves the computation of eigen vectors and the computation of RIWs as follows:

$$\text{Eigen vector, } E_i = \sqrt[n]{a_1 \cdot a_2 \cdot a_3 \dots a_n}$$

where $a_1, a_2, \dots, a_n$ are values of the row elements.

$$\text{RIW}_{ij} = \frac{E_i}{E_i^n}$$

This was followed by the estimation of the eigen vectors by multiplying all the elements in a row and taking the n th root of the product, where n is the number of row elements. Finally, RIW assigned to each hierarchy element was determined by normalising the eigenvector of the decision matrix. Normalisation of the eigen vectors was accomplished by dividing each eigen vector element by the sum of all eigen vector elements in a particular row.

- V. Computing the gRHI index: For each reach, the observed value of each parameter was assigned to the corresponding Level 3 value class. The reach-scale gRHI was then calculated by integrating the Level 2 and Level 3 RIWs:

Finally, the reach-scale gRHI was computed as follows:

$$\text{gRHI} = \sum_{i=1}^{N_2} [(RIW_i^2) * (RIW_{ij}^3)]$$

where gRHI = Geomorphic River Health Index, N_2 = the number of Level 2 decision factors, RIW_i^2 = relative importance weight of Level 2 decision factor i , RIW_{ij}^3 = relative importance weight of Level 3 sub-factor j of Level 2 decision factor i .

- VI. Ranking the gRHI values into various RHC: The reach-scale gRHI values were grouped into setting-specific river-health classes. The pairwise-comparison scores were assigned based on previous process-based studies of the Ganga River, field observations and the geomorphic interpretations presented in Section 4.1. In practice, the expression of the decision-makers involves some subjectivity that may lead to some inconsistency in the matrix. So, we also performed the consistency test by computing the consistency ratio (CR), defined as,

$$\text{CR} = \frac{\text{CI}}{\text{RI}}$$

where RI is the random inconsistency index as defined by Saaty (1980) that depends on the sample size. CI is the Consistency Index defined as:

$$\text{CI} = \frac{\lambda_{\max} - n}{n - 1}$$

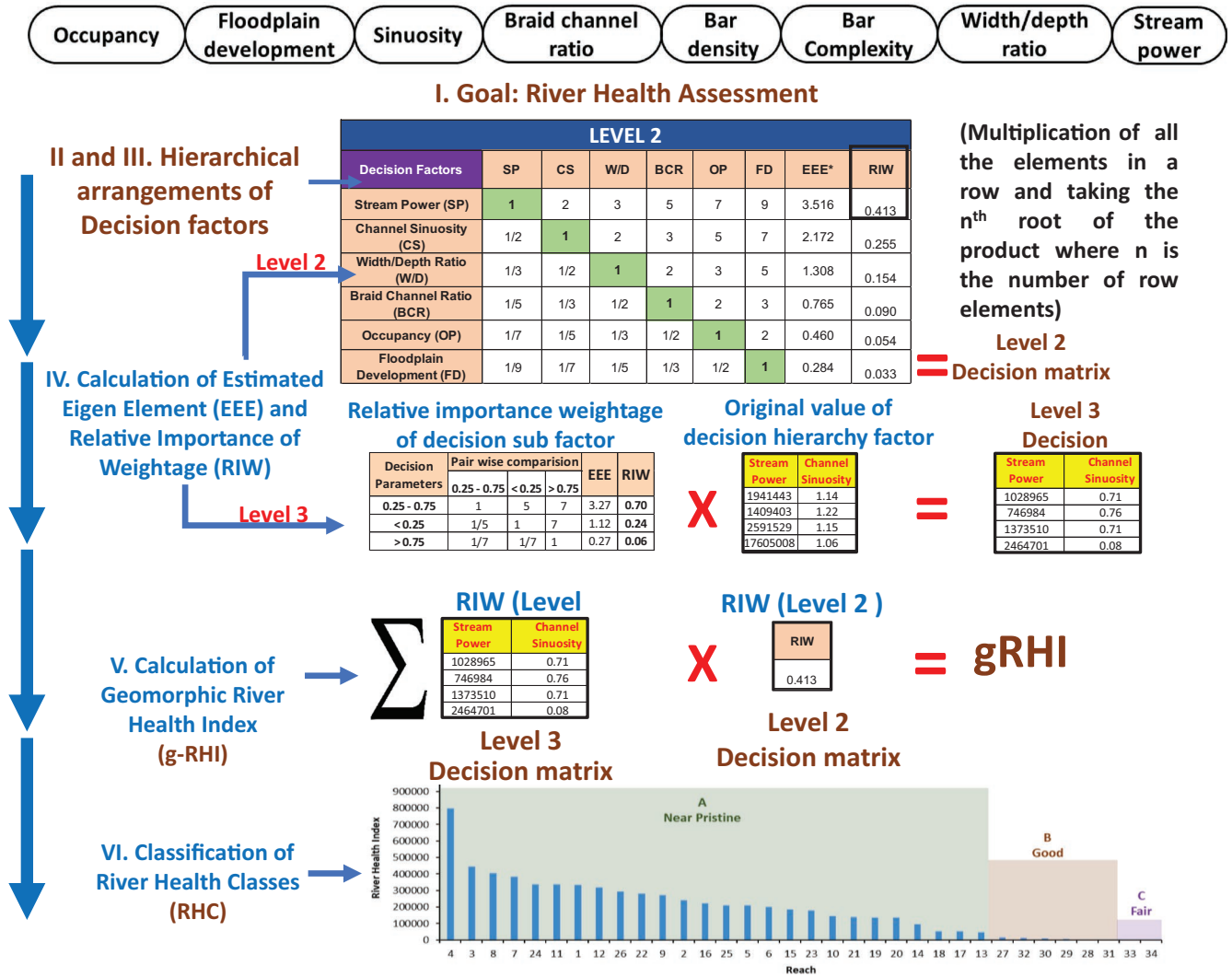


FIGURE 7 | Steps used to calculate the Geomorphic River Health Index (gRHI). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/ra.70195)]

where n is the number of criteria and $\lambda_{\max}$ (largest eigenvalue) is the sum of the products between each element of the RIW and the column totals of the matrix of decision factors.

$$\lambda_{\max} = \frac{[E]}{n}$$

where $[E]$ is the consistency vector, defined as:

$$[E] = \frac{\sum \text{of row of normalisation matrix}}{\text{RIW}}$$

If CR is < 0.10 , the pairwise comparisons are reliable, while $CR \geq 0.10$ indicates inconsistent judgements (Siddayao et al. 2015). We have calculated the consistency ratio for the gRHI parameters (Level 2) as well as the sub-factors (Level 3).

It is important to note that geomorphic setting and river types influence the RHA in a major way, as different types of rivers require different river space, flow and sediment regimes and structures to maintain their health (Glassic et al. 2025). For this work, we have considered two broad categories of geomorphic settings, mountainous and alluvial. We have divided the entire Ganga River into a total of 81 reaches, out of

which the upper 34 reaches were classified as mountainous and the remaining 47 as alluvial reaches. The mountainous reaches (1–30) are characterised by steep bedrock valleys, deep gorges and sinuous channels in the upper part, while the lower reaches (31–34) represent the transition from bedrock channels to alluvial reaches, marked by a piedmont setting and braided channels (Sinha et al. 2017). The alluvial reaches (35–81) are characterised by contrasting landscape settings and channel morphologies that are reflected in their geomorphic attributes. Such a significant difference in the river regime necessitated designing different weightage schemes (decision matrix) of the gRHI parameters for the mountainous and alluvial reaches (discussed next).

4.3 | Decision Matrix for Mountainous Reaches

Table 2 shows the decision matrix of Level 2 parameters created for the mountainous reaches of the Ganga River. The paucity of bars and active floodplains was observed in most reaches due to high stream power and narrow cross sections, except for a few reaches close to the mountain front, where floodplain pockets were reported on both sides of the river.

TABLE 2 | Decision matrix for Levels 2 and 3 parameters and computation of Relative Importance Weightage (RIW) for mountainous reaches.

Mountainous reaches (Level 2)								
Decision factors	SP	CS	W/D	BCR	OP	FD	E _i	RIW
Stream power (SP)	1	2	3	5	7	9	3.516	0.413
Channel sinuosity (CS)	1/2	1	2	5	7	9	2.172	0.255
Width/depth ratio (W/D)	1/3	1/2	1	6	7	9	1.308	0.154
Braid channel ratio (BCR)	1/5	1/5	1/6	1	7	9	0.765	0.090
Occupancy (OP)	1/7	1/7	1/7	1/7	1	9	0.460	0.054
Floodplain development (FD)	1/9	1/9	1/9	1/9	1/9	1	0.284	0.033
λ_{max} = 6.058; CI = 0.012; RI = 1.24; CR = 0.009								
Mountainous reaches (Level 3)								
Decision factors	Cell attribute value			E _i	RIW	Level	Remark	
Stream power (SP)	2,000,000–4,000,000			1.817	0.528	Moderate	Good	
	< 2,000,000			1.145	0.333	Low	Fair	
	> 4,000,000			0.481	0.140	High	Poor	
λ_{max} = 3.054; CI = 0.026; RI = 0.58; CR = 0.046								
Channel sinuosity (CS)	1.1–2			2.759	0.641	Moderate	Good	
	> 2			1.260	0.293	High	Fair	
	1–1.1			0.288	0.067	Low	Poor	
λ_{max} = 3.100; CI = 0.050; RI = 0.58; CR = 0.086								
Width/depth (W/D) ratio	10–100			2.759	0.641	Moderate	Good	
	< 10			1.260	0.293	Low	Fair	
	> 100			0.288	0.067	High	Poor	
λ_{max} = 3.100; CI = 0.050; RI = 0.58; CR = 0.086								
Braid channel ratio (BCR)	> 2			2.621	0.635	High	Good	
	1.1–2			1.186	0.287	Moderate	Fair	
	< 1.1			0.322	0.078	Low	Poor	
λ_{max} = 3.094; CI = 0.047; RI = 0.58; CR = 0.081								
Occupancy (OP)	0.010–0.025			3.302	0.701	Moderate	Good	
	< 0.010			1.145	0.243	Low	Fair	
	> 0.025			0.265	0.056	High	Poor	
λ_{max} = 3.108; CI = 0.054; RI = 0.58; CR = 0.093								
Floodplain development (FD)	0.25–0.75			3.175	0.699	Moderate	Good	
	< 0.25			1.077	0.237	Low	Fair	
	> 0.75			0.292	0.064	High	Poor	
λ_{max} = 3.094; CI = 0.047; RI = 0.58; CR = 0.081								

Therefore, based on our process understanding, SP was assigned the highest weightage amongst all Level 2 parameters (Table 2). The Ganga River in these reaches exhibits a narrow and sinuous morphology, and a few reaches exhibit the development of point bars and channel multiplicity. Accordingly, CS, W/D ratio and BCR were considered as parameters of

higher significance. The remaining parameters, including OP and FD, were given lower importance for RHA in these reaches. The parameters, such as BD and BC, were not considered for health assessment in these reaches, as most of the reaches do not show any significant bars. For each of the Level 2 parameters, a Level 3 decision matrix was constructed using

TABLE 3 | Decision matrix for Levels 2 and 3 parameters and computation of Relative Importance Weightage (RIW) for alluvial reaches.

Alluvial reaches (Level 2)										
Decision factors	OP	FD	BCR	BD	BC	CS	W/D	SP	E _i	RIW
Occupancy (OP)	1	2	3	4	5	6	7	8	3.764	0.328
Floodplain development (FD)	1/2	1	2	3	4	5	6	7	2.662	0.232
Braid channel ratio (BCR)	1/3	1/2	1	2	3	4	5	6	1.819	0.159
Bar density (BD)	1/4	1/3	1/2	1	2	3	4	5	1.223	0.107
Bar complexity (BC)	1/5	1/4	1/3	1/2	1	2	3	4	0.818	0.071
Channel sinuosity (CS)	1/6	1/5	1/4	1/3	1/2	1	2	3	0.550	0.048
Width/depth ratio (W/D)	1/7	1/6	1/5	1/4	1/3	1/2	1	2	0.376	0.033
Stream power (SP)	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	0.266	0.023
λ_{max} = 8.288; CI = 0.041; RI = 1.41; CR = 0.029										
Alluvial reaches (Level 3)										
Decision factors	Cell attribute value			E _i	RIW	Level		Remark		
Occupancy (OP)	0.25–0.75			3.302	0.701	Moderate		Good		
	< 0.25			1.145	0.243	Low		Fair		
	> 0.75			0.265	0.056	High		Poor		
λ_{max} = 3.108; CI = 0.054; RI = 0.58; CR = 0.093										
Floodplain development (FD)	0.075–0.50			3.175	0.699	Moderate		Good		
	< 0.075			1.077	0.237	Low		Fair		
	> 0.50			0.292	0.064	High		Poor		
λ_{max} = 3.094; CI = 0.047; RI = 0.58; CR = 0.081										
Braid channel ratio (BCR)	> 2			2.466	0.627	High		Good		
	1.5–2			1.101	0.280	Moderate		Fair		
	1–1.5			0.368	0.094	Low		Poor		
λ_{max} = 3.086; CI = 0.043; RI = 0.58; CR = 0.074										
Bar density (BD)	1.0–4.0			2.759	0.641	Moderate		Good		
	< 1			1.260	0.293	Low		Fair		
	> 4			0.288	0.067	High		Poor		
λ_{max} = 3.1; CI = 0.050; RI = 0.58; CR = 0.086										
Bar complexity (BC)	4.0–10.0			2.29	0.60	Moderate		Good		
	< 4.0			1.10	0.29	Low		Fair		
	> 10			0.40	0.10	High		Poor		
λ_{max} = 3.086; CI = 0.043; RI = 0.58; CR = 0.074										
Channel sinuosity (CS)	1.25–2			2.466	0.627	Moderate		Good		
	> 2			1.101	0.280	High		Fair		
	1–1.25			0.368	0.094	Low		Poor		
λ_{max} = 3.100; CI = 0.050; RI = 0.58; CR = 0.086										
Width/depth ratio (W/D)	100–250			2.466	0.627	Moderate		Good		
	< 100			1.101	0.280	Low		Fair		
	> 250			0.368	0.094	High		Poor		

(Continues)

TABLE 3 | (Continued)

Alluvial reaches (Level 3)					
Decision factors	Cell attribute value	E_i	RIW	Level	Remark
$\lambda_{max} = 3.086$; CI = 0.043; RI = 0.58; CR = 0.074					
Stream power (SP)	5000–10,000	1.817	0.528	Moderate	Good
	< 5000	1.145	0.333	Low	Fair
	> 10,000	0.481	0.140	High	Poor
$\lambda_{max} = 3.054$; CI = 0.027; RI = 0.58; CR = 0.046					

the class intervals of the values (Table 2). The consistency ratio (CR) was found to be satisfactory (i.e., $CR \leq 0.10$ or $\leq 10\%$) for both Levels 2 and 3 decision factors.

4.4 | Decision Matrix for Alluvial Reaches

In the alluvial reaches, the stream power of the river is low, and lateral erosion dominates over vertical cutting. Therefore, the parameters such as OP and FD influence the RHA in a major way. Most of the alluvial reaches show significant channel multiplicity, and a variety of bars characterise their morphology. The only exceptions are the reaches between Allahabad and Varanasi, where some meandering was documented due to a shallow basement in the zone of the southern cratonic margin. Further downstream, a drastic change in morphology is documented in terms of the development of alluvial islands and anabranching channels. Therefore, parameters such as BCR, BD and BC were taken as the next highest Level 2 weights, followed by CS, W/D and SP. Analogous to the mountainous reaches, moderate values were evaluated in the good class for every parameter. Table 3 shows the Level 2 and Level 3 decision matrix developed for the alluvial reaches. The CR values were below 0.10 for both Levels 2 and 3 decision factors, indicating acceptable consistency.

4.5 | River Health Classes (RHC)

Based on the approach and parameters outlined above, the RHA of the Ganga River for the mountainous and alluvial reaches was carried out separately. We have attempted here to develop a platform for RHA based on a physical template using geomorphological parameters. Based on the AHP-GIS-based integration of 8 geomorphic attributes, a gRHI score was obtained for each reach, which was then categorised in terms of river health class (RHC) based on major breaks in the distribution and field observations (Tables A2 and A3 in supplementary). Figure 8 shows the conceptualisation of RHC based on the integrated geomorphic parameters for the mountainous and alluvial reaches. In the mountainous reaches, we have classified these reaches into three RHCs in terms of river health, namely near pristine, good and fair. In contrast, the alluvial reaches were classified into 4 categories, namely good, fair, poor and degraded. The RIW of each parameter is based on the decision matrix discussed above, and the desired values (high, moderate, low) are also shown in different colours. It is important to note, however, that the final

RHC is not dependent on high or low values of any single parameter but is decided by a combination of optimal values of several parameters.

5 | River Health Assessment of the Ganga River

5.1 | Mountainous Reaches

In the mountainous reaches, a total of thirty-four reaches between Gomukh (reach 1) and Chandok (reach 34) along the Bhagirathi River were included. Reaches 1–26 fall in the Himalayan bedrock region and reaches 27–34 fall in the piedmont zone. Based on the gRHI score and field observations, we have identified three classes, namely near pristine, good and fair (Figure 9). We note a systematic pattern in RHC along the river in the mountainous reaches. Reaches 1–26 fall in the near pristine class, 27–32 fall in the good class and 33–34 fall in the fair class. We describe the geomorphic attributes of each class next.

- Near Pristine:** Reaches having gRHI values greater than 18,000 were classified as near pristine RHC. In the Himalayan bedrock region, all the reaches from Gomukh (Reach 1) to Rishikesh (U/s) (Reach 26) show distinct gRHI values. All these reaches show high stream power and balanced natural sinuosity. In narrow valleys, no active floodplain is present, and hence occupancy is low, but the channel touches the hill slopes, resulting in good lateral connectivity. In several reaches, patchy floodplains are present (e.g., reaches 19 and 21 at Devprayag and Kaudiala, respectively); FD values are high, which improves the lateral connectivity as well as gRHI scores (Figure 9a). A snapshot of a satellite image and a field photograph at Devprayag (Figure 9b,c), which falls in the Near pristine class, clearly shows that the river has good longitudinal connectivity and the reach is well organised in terms of riffles and pools. Both left and right banks have alternate bars, and riparian vegetation is well within the annual flood level, thereby providing good lateral connectivity.
- Good:** Reaches having gRHI values between 18,000 and 1000 were classified as 'Good' RHC. A total of 6 reaches between Rishikesh (Reach 27) and Balawali (Reach 32) fall in this class (Figure 9a). This stretch is the transition zone between hill and plain where the Ganga River enters the plains, and the landscape setting is piedmont. Despite

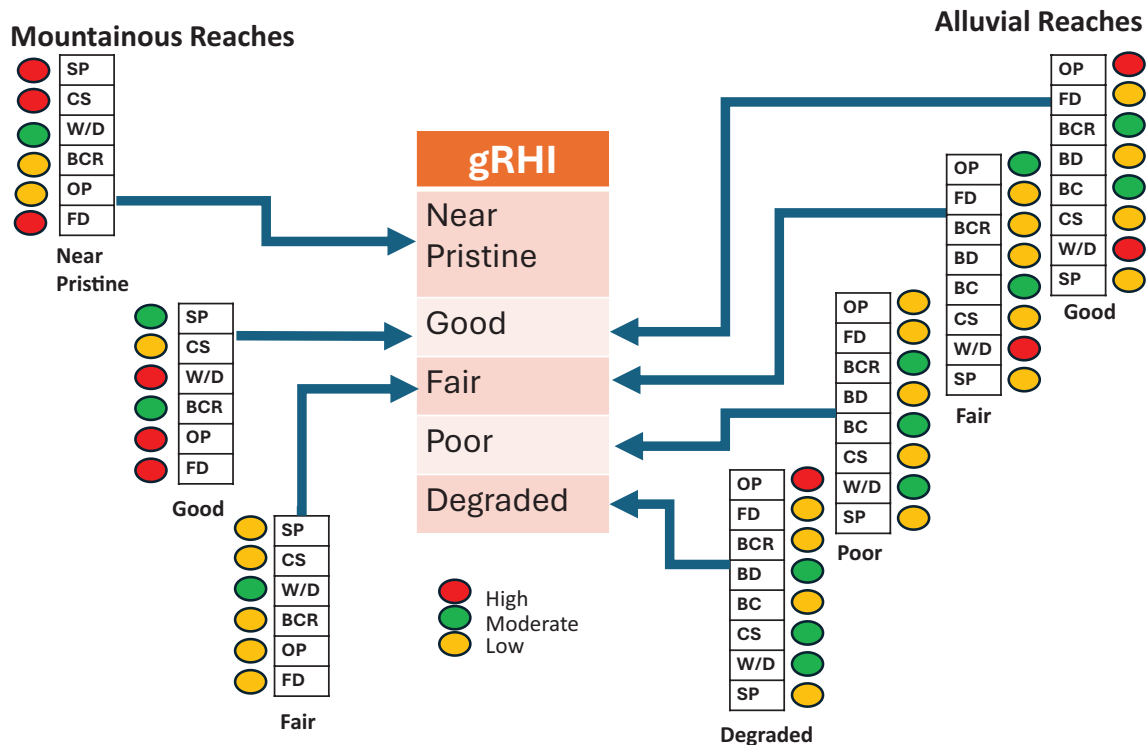


FIGURE 8 | Conceptualisation of River Health Classes (RHC) based on 8 different geomorphic parameters (OP—occupancy, FD—floodplain development, BCR—braid-channel ratio, BD—bar density; BC—bar complexity, CS—channel sinuosity; W/D—width to depth ratio, SP—stream power) arranged as per their relative importance for mountainous and alluvial reaches. The desired values for each parameter have been shown as high (red), moderate (green) and low (yellow). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rra.20195)]

a significant channel widening, moderate values of stream power are maintained in these reaches (Figure 6b). In all these 6 reaches, we document high occupancy and floodplain development (Figure 9d,e), suggesting good lateral connectivity between the channel belt and active floodplain. Field observations show wide and shallow channels, but with good longitudinal connectivity in such reaches (Figure 9e). Heterogeneity is maintained here with a moderate braid channel ratio, while sinuosity is low (Figure 3c). A moderate stream power (Figure 6) is also reflected in gravel-sized channel sediments scattered on both banks (Figure 9e).

- c. **Fair:** Reaches having gRHI values less than 1000 were categorised as ‘Fair’. Shivpuri (Reach 33) and Chandok (Reach 34) fall in this class. These two reaches show wide and shallow channels (moderate W/D ratio), low occupancy and floodplain development, poor lateral connectivity and low braid channel ratio (Figure 8). Good to moderate sinuosity was documented in this stretch, and low stream power was computed. Figure 9f shows a snapshot of a satellite image around Chandok (reach 34), which falls in fair RHC. A wide and shallow channel with a stabilised sand bar within the channel belt is also seen in the field photograph (Figure 9g), which partially confines the channel as it is beyond the annual flooding level. Floodplain development is poor and mostly occupied by agricultural land, which sometimes extends into the active channel belt. Natural riparian vegetation is absent on either side of the channel.

5.2 | Alluvial Reaches

A total of 47 alluvial reaches, starting from Bijnor (reach 35) to Farakka (reach 81), were classified into 4 classes based on the gRHI scores. Unlike the mountainous reaches, these classes are randomly distributed along the river and do not show any systematic downstream pattern.

- a. **Good:** Reaches with gRHI values greater than 80 were categorised in the ‘Good’ RHC (Figure 10a). Of the 15 reaches in this class, 12 are located upstream of the Ganga-Yamuna confluence. The other three reaches are Chausa (reach 70), Buxar (reach 71) and Mokama (reach 77). Most of these reaches exhibit high values of OP and W/D ratios, suggesting wide valleys with large accommodation space. The multi-channel systems have moderate bar complexity, but BD is low (Figure 8). SP is generally low in most of these reaches, except for a jump in two reaches near Chausa (reach 70) and Buxar (reach 71) due to high discharge values (Figure 6b); this led to relatively higher gRHI scores for these two reaches compared to others. Figure 10b shows a snapshot of a satellite image of reach 57 at Dalmau, which has been classified as ‘good’ RHC. This reach shows shallow and wide channels, as also verified in the field (Figure 10c), but with a good braid channel ratio and complex bars in an unconfined valley setting. Active floodplain on either side of the channel provides good lateral connectivity as well as good floodplain occupancy (Figure 10c).

b. **Fair:** Reaches with gRHI scores of between 40 and 80 were categorised in Fair class (Figure 10a). Out of a total of 10 reaches classified as 'Fair' RHC, 5 reaches are upstream of the Ganga-Yamuna confluence, 1 reach is downstream of this confluence and 4 reaches are in the Munger-Farakka stretch (Craton margin) (Figure 10a). In these reaches, moderate occupancy values due to partial confinement are documented, which also restrict floodplain development, although W/D ratios are high. These characteristics suggest good lateral connectivity in these reaches. Low BCR, low sinuosity, low BD and moderate BC were documented for the reaches in this class (Figure 10c). SP is generally low except for a few reaches upstream of Farakka (reaches 79–81, Figure 6b). Reach 54 at Jajmou (close to Kanpur) has been classified in 'fair' RHC, where the river is partially confined by 10–15 high cliffs (Figure 10d,e), restricting the lateral connectivity along the right bank. Along the left bank, the channel is unconfined with moderate floodplain occupancy.

c. **Poor:** Reaches with gRHI scores between 20 and 40 were classified as 'poor'. The highest number of 17 reaches are classified as poor, which are distributed in the entire alluvial stretch starting from Mawana (reach 38) to downstream of Patna (reach 76) (Figure 10a). The transition from Fair to Poor class is caused by a reduction in OP and W/D ratio, accompanied by an increase in BCR. FD and CS remain low, suggesting a decrease in lateral connectivity in these reaches (Figure 8). BD is low, but bar complexity is moderate (Figure 4), suggesting a lack of ample substrate for habitats. Low SP in most of these reaches also suggests a lack of active sediment transport except in a few reaches downstream of Buxar (reaches 72–76) where moderate SP and good FD (Figures 5b and 6b) are recorded because of a sudden increase in valley width as well as average channel belt width (Figures 3a, 5b, and 6b). Figure 10f shows an example of a poor RHC from reach 63 at Debeypur where the shallow and wide channel is characterised by low bar density and a very narrow

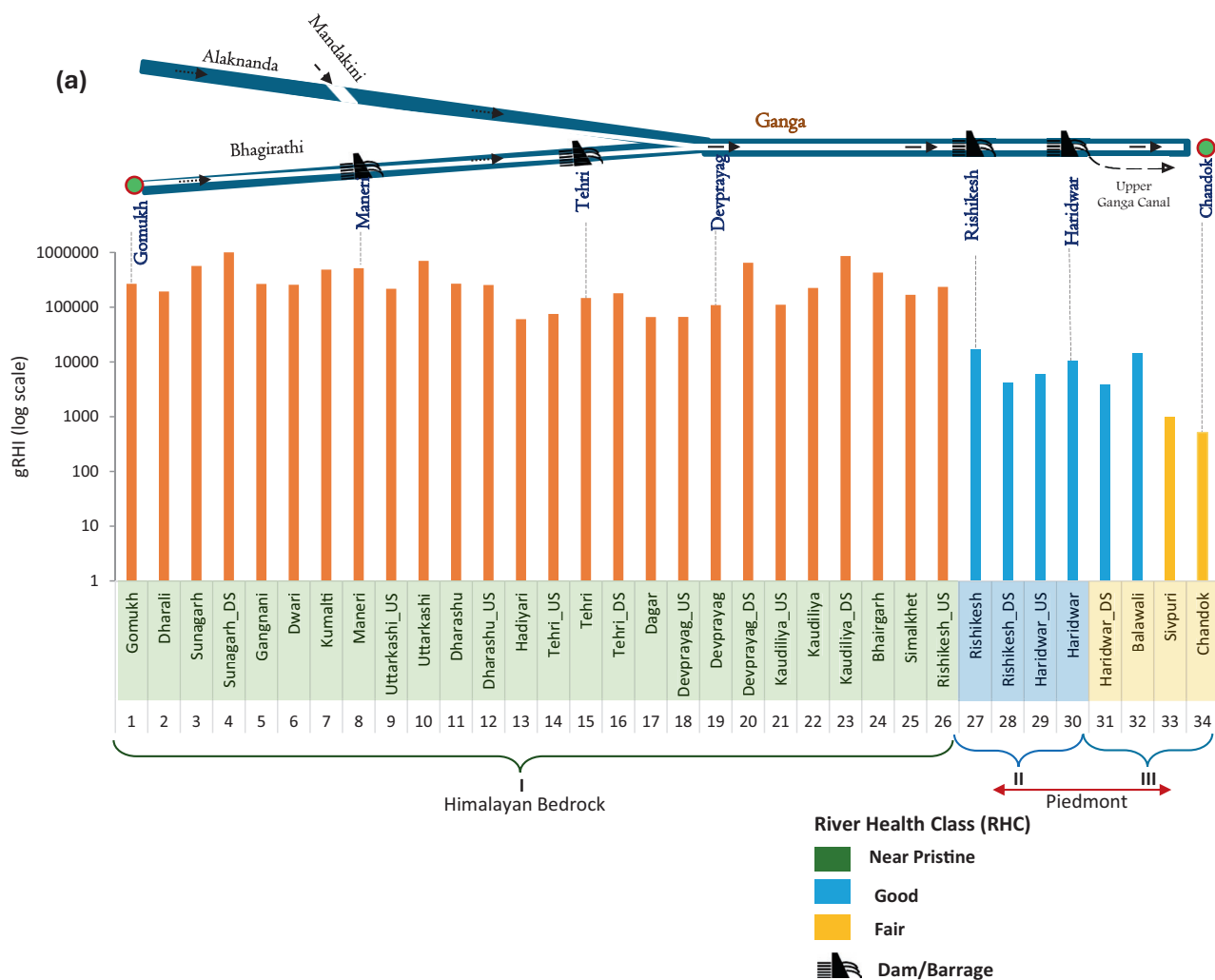


FIGURE 9 | (a) Distribution of river health classes (RHC) in the mountainous reaches; (b) a snapshot of satellite image and (c) field photo showing the reach at Devprayag (reach 19) classified as 'near pristine' with good longitudinal and lateral connectivity, natural channel belt and riverbed, high stream power; (d) satellite image and (e) field photograph of a 'good' RHC at Rishikesh (reach 27) with good longitudinal and lateral connectivity, natural channel belt and riverbed and moderate stream power; (f) satellite image and (g) field photograph of a 'fair' RHC at Chandok (reach 34) showing a wide, shallow channel with low occupancy and floodplain development. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

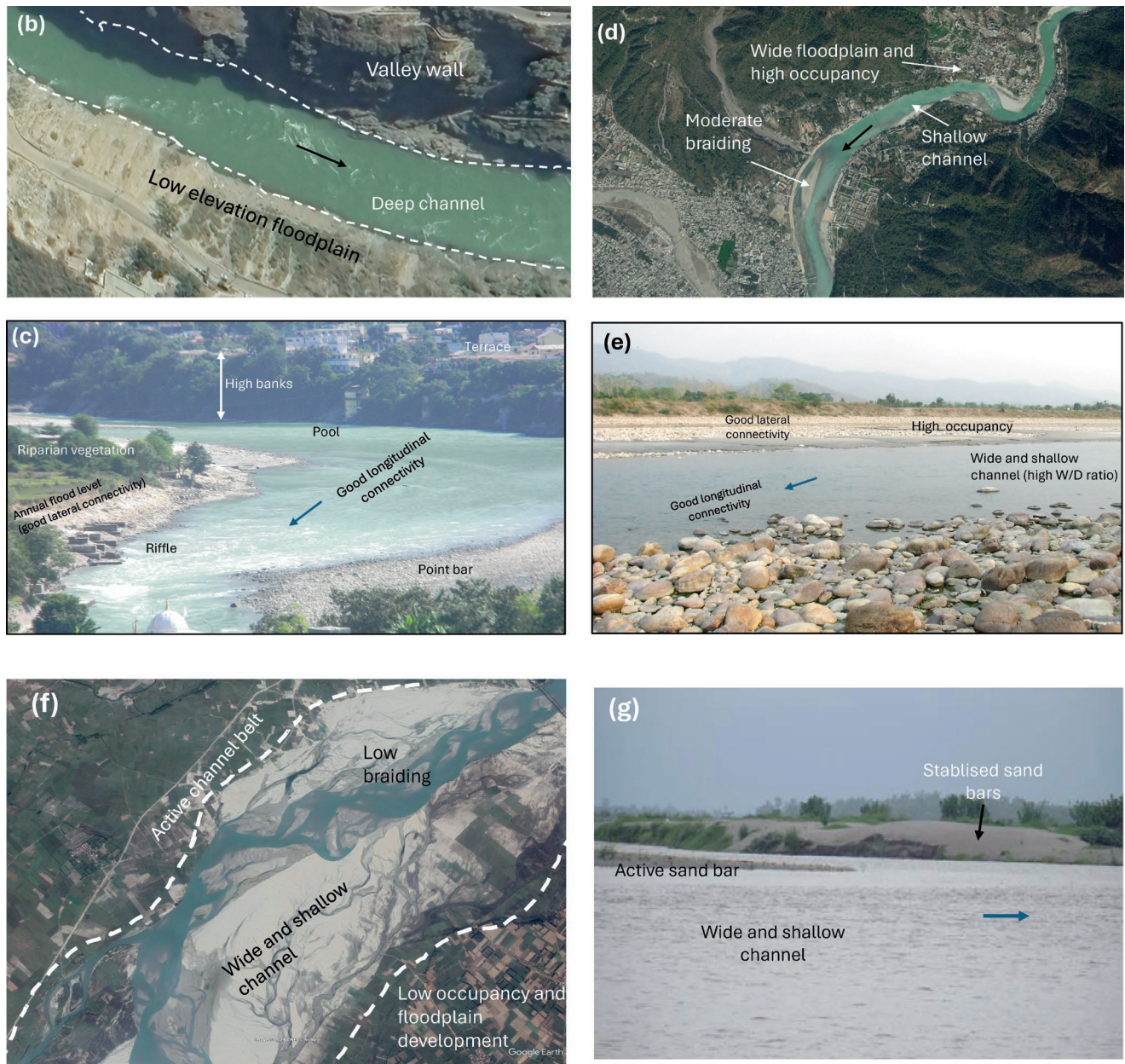


FIGURE 9 | (Continued)

floodplain with poor lateral connectivity. Discontinuous cliffs along the right bank result in low occupancy as well (Figure 10g).

- d. **Degraded:** A total of four reaches (62, 63, 64 and 68) were classified as 'degraded' with gRHI scores of less than 20 (Figure 10a). All these four reaches are located downstream of Allahabad. Most of these reaches are characterised by moderate values of BD, CS and W/D ratio, but bar complexity is low (Figure 8). OP is high (Figure 5a), but valley width is low, FD is poor and channels are confined (Figure 3a). SP is very low in all these reaches (Figure 6b). An example of a degraded reach (63) shows partial confinement and low floodplain development on the satellite image (Figure 10h) and highly degraded slopes and poor lateral connectivity in the field

(Figure 10i). Bar density and BCR values are high, but bar complexity is low.

6 | Discussion

6.1 | Do Landscape Settings and River Typology Influence RHC?

A significant diversity in the landscape setting and hydromorphological attributes of the Ganga River has previously been recognised (Sinha et al. 2005; Roy and Sinha 2017). Based on these characteristics, Sinha et al. (2017) identified ten river classes across 81 reaches extending from Gomukh to Farakka. This work has advanced these ideas to formulate geomorphic indices for

the assessment of river health in terms of RHCs along the Ganga River. Here, we attempt to understand the relationship between geomorphic and river health classes and examine if the landscape setting exerts a regional control on river health (Figure 11).

In the mountainous stretch, the RHCs show a very distinct trend. Out of 34 reaches, the first 26 reaches (Gomukh to

Rishikesh u/s) fall in the near-pristine class, and all these reaches are characterised by a Himalayan bedrock landscape setting (Class I; Sinha et al. 2017). Steep Himalayan slopes provide the necessary stream power and maintain longitudinal connectivity, while monsoonal discharges provide high lateral connectivity. The narrow and sinuous reaches have a patchy floodplain when the river valley widens. Downstream of

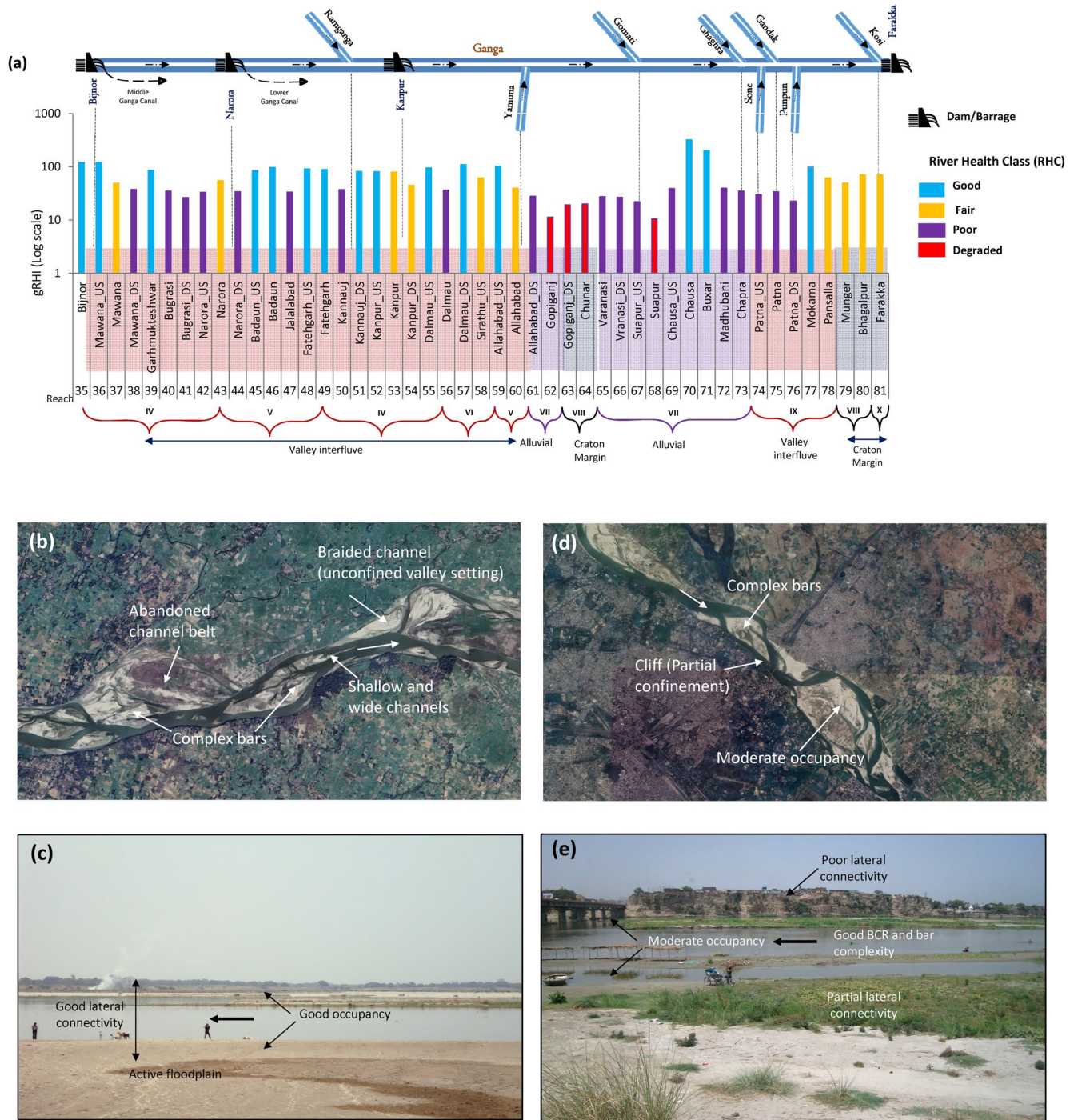


FIGURE 10 | (a) Distribution of river health classes (RHC) in the alluvial reaches; (b) satellite image and (c) field photo showing the reach at Dalmau (reach 57) classified as 'good' with good lateral connectivity, good occupancy, good BCR and bar complexity; (d) satellite image and (e) field photograph of a 'fair' RHC at Jajmau (reach 54) with good lateral connectivity, good BCR and bar complexity; (f) satellite image and (g) field photograph of a 'poor' class at Dubepur (reach 59) with poor lateral connectivity because of low floodplain development, low BCR; (h) satellite image and (i) field photograph of a 'degraded' RHC at Gopiganj (reach 63) with low lateral connectivity, low BCR and high BD because of significant flow reduction. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rra.70195)]

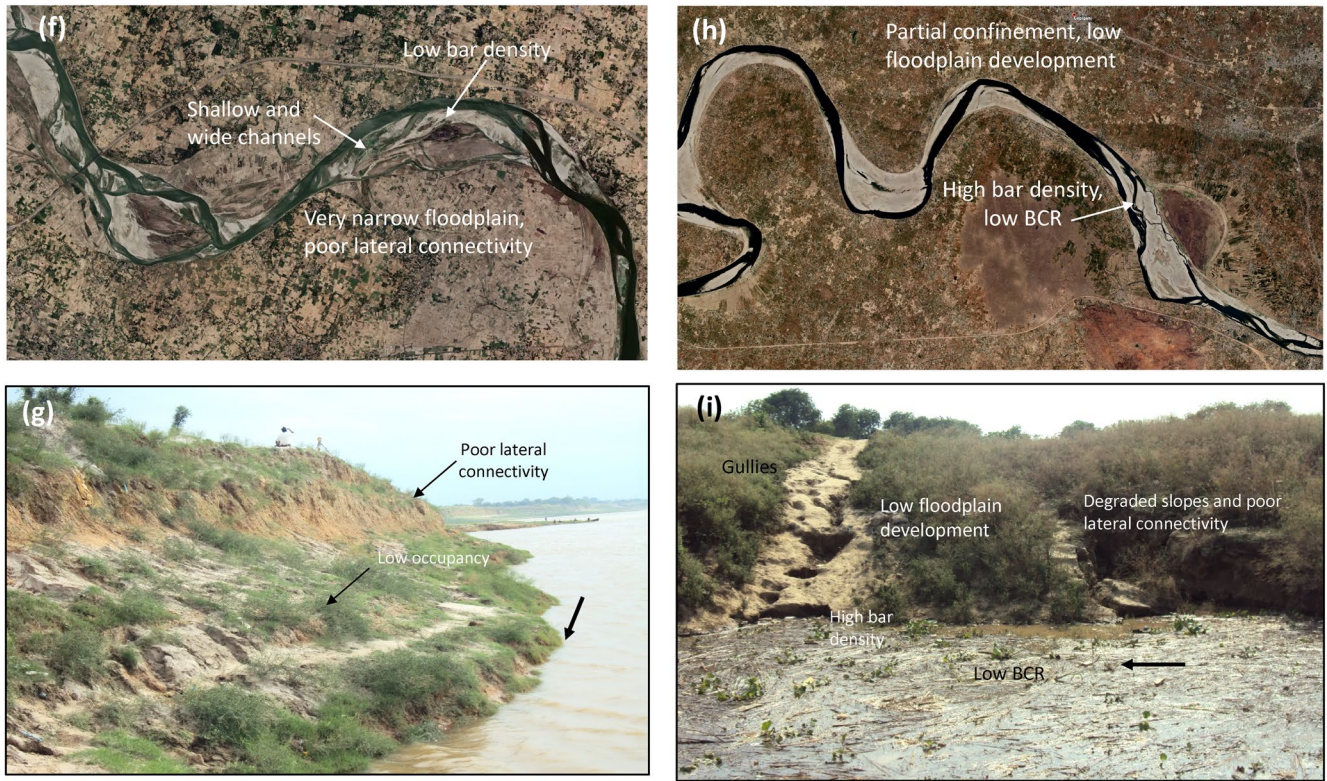


FIGURE 10 | (Continued)

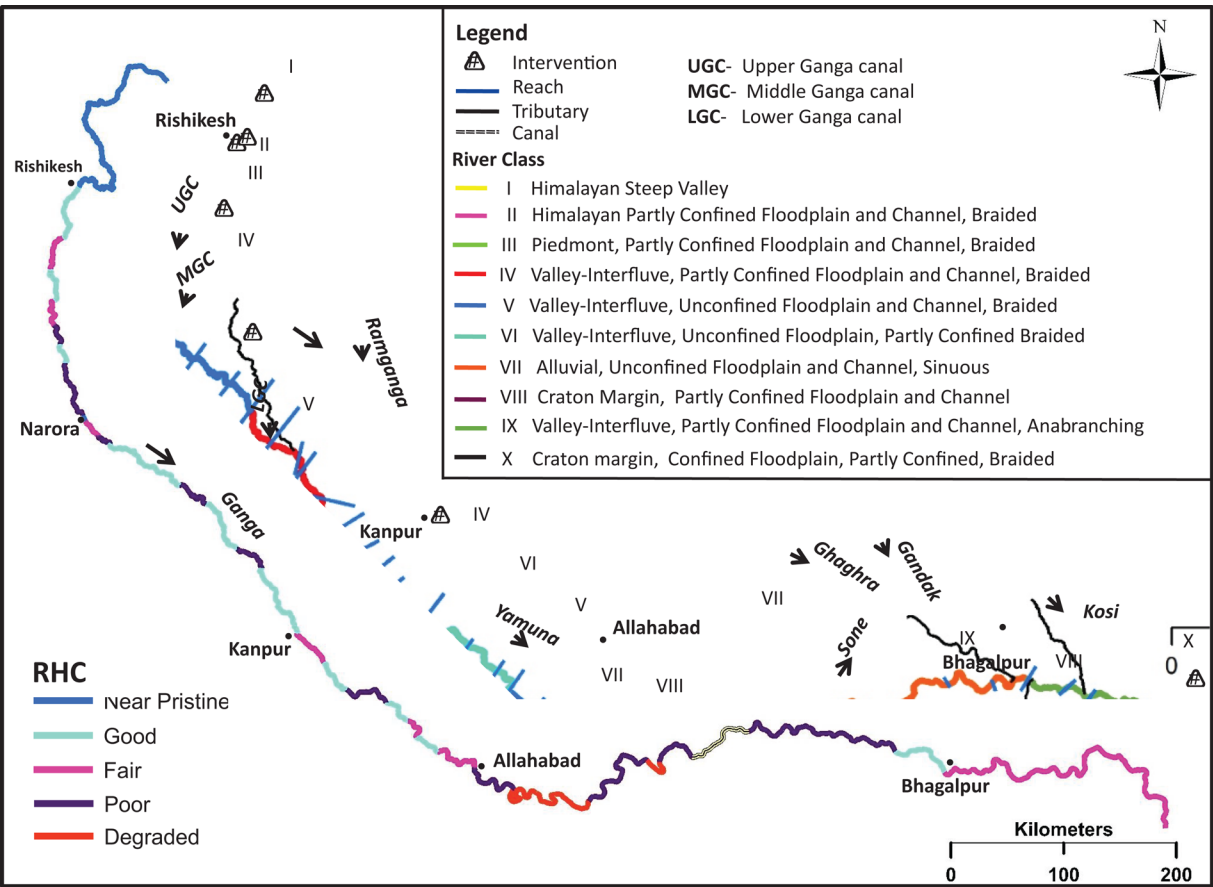


FIGURE 11 | River Health Classes (RHC) in comparison to the Geomorphic Classes of Sinha et al. (2017), along with a line diagram of the Ganga River, tributaries, canals and interventions. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/ra.20195)]

Rishikesh, the river reaches 27–34 from a piedmont landscape setting (Class-II, Sinha et al. 2017), which provides enough slope to generate moderate stream power but triggers a significant change in river morphology from sinuous to braiding. Most of these reaches were classified in Good RHC (Figures 9 and 11). The last two reaches (33 and 34) in the mountainous stretch fall in 'Fair' RHC. These reaches are transitional zones between the piedmont and valley-interfluvial setting, where the slope significantly reduces, thereby lowering stream power. Floodplain development and occupancy remain low because of the limited valley width.

In alluvial reaches (35–81), the distribution of RHCs shows no systematic trend, and they appear to be randomly distributed. It is equally important to note that these reaches are also very diverse geomorphologically, falling in 7 River Classes (Sinha et al. 2017). However, we still find a strong control of landscape setting on morphological attributes and hence on river health (Figure 11). For example, all reaches, except reaches 70–71 around Buxar, classified as 'Good', correspond to valley-interfluvial landscape setting (Class III, Sinha et al. 2017). The valley-interfluvial setting allows the rivers to develop good occupancy and facilitates lateral connectivity. The channel slopes and stream power are low, which allows bar development and multiple channels, improving flow efficiency. Reaches 70–71 are the only exceptions that fall in an alluvial setting where the river is confined with high discharges and therefore classified as good RHC.

The reaches of fair RHC fall in two landscape settings, namely the valley interfluvial and Craton (reaches 78–81) landscape setting (Figure 11). In certain reaches in the valley interfluvial setting, occupancy decreases due to partial confinement either because of asymmetric incision (caused by flow concentration along one bank) or anthropogenic interventions such as barrage or bridge, which also results in impoundment and therefore decreases BCR values. This leads to their classification in fair RHC. A similar process operates in the other fair reaches falling in a cratonic landscape setting, except that the confinement here comes from the bedrock as the river flows close to the southern edge of the basin.

The major factors that contribute to the change of RHC from fair to poor/degraded include occupancy (changes from moderate to either high or low), W/D ratio (changes from high to moderate), while bar density and bar complexity remain low to moderate. Poor and degraded reaches are distributed in three stretches. The first stretch between Mawana (D/s) (Reach No. 38) and Dalmau (Reach No. 56) is discontinuous, in which 7 reaches have poor RHC (Figure 10a). All these reaches fall in a valley-interfluvial landscape setting but in different geomorphic classes (Figure 11) based on channel/floodplain confinement and other morphological attributes (Sinha et al. 2017). We argue that local geomorphic conditions and anthropogenic factors contribute to the classification of these reaches into poor RHC. There are three major interventions in this stretch, namely the Narora barrage (reach 43), two close rail and road bridges at Fatehgarh (reach 49) and the Kanpur barrage (reach 53). Most of these reaches are close to these interventions, which have affected geomorphic attributes such as floodplain development and lateral connectivity through stabilised banks (Jiao et al. 2023) and, in turn, river health.

A second continuous stretch of poor/degraded reaches (61–69) is downstream of Allahabad, where the Ganga River meets another major river, the Yamuna. In this stretch, the Ganga River undergoes a rapid transition in the landscape setting from alluvial to cratonic margin and then to alluvial. We document a sharp change in river morphology from multithread to strongly sinuous downstream of the Ganga-Yamuna confluence. These transformations are manifested in moderate values of occupancy and W/D ratios but low values of bar density, bar complexity and stream power. Another major transformation in the landscape setting occurs downstream of Buxar (reach 71) from alluvial to valley interfluvial and then to the craton margin. Five reaches (72–76) in this stretch are classified as poor RHC because of a sharp increase in valley width and floodplain width, but not in channel width. We note that occupancy and FD increase, BD and BC are variable, the W/D ratio is moderate and stream power improves slightly in this stretch. We attribute this to confluences of two major rivers, the Ghaghra and Gandak, from the north and the Sone River from the south, which add significant discharges and sediment flux into the Ganga in this stretch (Sinha et al. 2023).

6.2 | RHC Versus Ecological Attributes

Unlike the geomorphological data, the ecological datasets for the Ganga River are very scarce, and therefore, the assessment of ecological integrity (Boulton 1999) and incorporating this in RHA is far-fetched at this stage. The Ganga River has been classified into 3 broad ecological segments: Upper Ganga (UG), Middle Ganga (MG) and Lower Ganga (LG), and further subdivisions were made based on the biological profiling (Mathur and Kapoor 2019a, 2019b). Here we make an attempt to establish a broad correlation between geomorphological and ecological attributes based on limited datasets. The stretch from Gomukh to Haridwar (reaches 1–30) was classified as Upper Ganga in the Ecological class, where water was considered pristine to near-pristine in these reaches. The upper stretch of the Upper Ganga between Gomukh and Gagnani (UG1, reaches 1–5) was classified as near-pristine, but very limited biota exists because of low temperature, high velocity and ultra-oligotrophic conditions (Mathur and Kapoor 2019a, 2019b). The stretch between Gagnani and Devprayag (UG2, reaches 5–20), also classified as near-pristine RHC, has been reported to be more productive in terms of algae and fish, including the Snow Trout, which is often considered a keystone species for this stretch (Mathur and Kapoor 2019a, 2019b). In these reaches, the river flows on a steep bed and narrow terrain where the substrate is mostly bedrock, boulders and cobbles. From an ecological point of view, rapids were recorded as the main habitats for aquatic biota. In some of the reaches, riffles and deep pools were identified as healthy aquatic habitats. However, there are major hydroelectric projects at Maneri Bhali, Tehri and Koteswar in this stretch that have impacted the river flows, which changed the habitat conditions as some fishes usually move upstream for breeding (Mathur et al. 2019). Our gRHI scores show some variability around these interventions but are not enough to change the RHC.

Further downstream, the stretch between Devprayag and Haridwar (UG3, reaches 21–30) is also classified as near pristine

except for a few downstream reaches (27–30), which fall in good RHC. In this stretch, the river flows through a deep gorge, and while a general reduction in producers has been reported, this stretch is still quite rich in fish population, including the Golden Mahseer, which is the keystone species here (Mathur and Kapoor 2019a, 2019b). The flows between Rishikesh and Haridwar are substantially fluctuating, and the geomorphic setting changes to piedmont, thereby affecting the habitat conditions as well. This leads to the deterioration of both river health and ecological abundance around Haridwar.

Further, the stretch between Haridwar and Varanasi (reaches 31–65) has been categorised as Middle Ganga from an ecological perspective and has been reported to be very productive biologically. Higher concentration of nutrients, warm water, reduced velocity and a meandering river with floodplains promoted this stretch as a good habitat, resulting in a very conspicuous fish population, including Indian Major Carps and Catfish (Mathur and Kapoor 2019a, 2019b). The Middle Ganga is also characterised by the presence of three major groups of higher aquatic vertebrates, including the Gangetic Dolphin, Gharials and Turtles. The Gangetic Dolphin (Jhingran 1991; Jhingran and Ghosh 1978; Sinha et al. 2010) has been identified as an indicator species of the middle Ganga stretch (Figure 11). It is important to note that these species inhabit reaches with soft strata, so the alluvial reaches of the middle Ganga with wide valleys and sandy substrate provide the ideal habitat for them. Our river health assessment broadly corresponds to the ecological status, as several of these reaches fall in good RHC. However, several reaches in this stretch have been reported as disturbed from an ecological integrity point of view due to human interventions (i.e., Ganga barrage at Narora, Luv-Kush Barrage at Kanpur), modifications in river morphology and flow of uncontrolled effluents into the channel. As a result, the population of Ganga Dolphins and Gharials has gone down significantly in recent years (Rao 1995; Sinha et al. 2010). Several of these reaches have been classified as poor or degraded RHC (discussed above). Narora D/s (reach 43) and Allahabad D/s (reach 61) were reported as imbalanced habitats for having more effluents compared to freshwater (Sinha et al. 2010; Mathur and Kapoor 2019a). These two reaches were classified as poor RHC (Figures 10a and 11).

Like the Middle Ganga, the Lower Ganga (Varanasi to Farakka, reaches 65–81) was also reported as a productive stretch for the growth of the biological community due to the presence of nutrients, high temperature, clean water and high-water discharge (Mathur and Kapoor 2019a, 2019b). The confluence of several major tributaries such as Ghaghra, Gandak and Kosi in this stretch brings large sediment flux (Sinha et al. 2023), producing a soft riverbed consisting of silt over sand (Mathur 1991). Such conditions have allowed the biological communities to be well represented in this stretch, which is a repository of a wide range of zoobenthos and macro-invertebrates that play an important link between food chains (Mathur and Kapoor 2019a, 2019b). This is also one of the largest productive stretches for the inland fisheries, which has been commercially exploited for a very long time. However, the situation has changed drastically in recent years. One of the most important species, the Hilsa, which accounted for over 90% of the fish catch in this stretch, has completely disappeared after the construction of the Farakka barrage and

is now mostly found downstream of the barrage (Mathur and Kapoor 2019a, 2019b). Also, the phenomenal growth of exotic fishes in this stretch has outnumbered the native fishes such as Hilsa, Indian Major Carps and Catla. In this work, this segment from Varanasi (D/S) to Patna (D/S) (reaches 65–75) was categorised in the Poor RHC except for two reaches (70–71) because of local hydrogeomorphic controls (discussed above). The reaches from Bhagalpur to Farakka (78–81) are mainly characterised by silty substrate, which is considered healthy for aquatic diversity. These reaches were also classified as Fair RHC in this work.

6.3 | Drivers of RHC and Associated Geomorphic Processes

Despite high complexity and diversity in the Ganga River, we note significant correspondence among landscape setting, RHC and overall ecological attributes. Figure 12 shows an infographic of major geomorphological attributes and associated processes that drive the river health assessment in this study. We have categorised the geomorphic attributes of river health assessment into three major pillars: (1) channel geometry and planform complexity comprising sinuosity, braid-channel ratio and W/D ratio, (2) energy dynamics represented by stream power and sediment bar metrics such as bar density and bar complexity and (3) ecological habitat or connectivity, which is represented by floodplain development and occupancy.

In mountainous reaches, stream power was considered the most important driver, which influences the longitudinal connectivity and erosion/deposition pattern, thereby affecting several morphological attributes considered for gRHI. Further, except for certain reaches where deep gorges have formed, a moderate W/D ratio with shallow channels provides enough turbulence and oxygenation, whereas moderate occupancy maintains channel-floodplain equilibrium. These conditions favour pristine or good RHC.

In alluvial reaches, stream power is generally low, and therefore occupancy, floodplain development, channel multiplicity, bar density and bar complexity were prioritised for gRHI computation. The valley interfluvial landscape setting provides the optimal conditions for a good RHC. The reaches falling in the Ganga-Ramganga interfluvial and Ganga-Yamuna interfluvial have high to moderate occupancy and variable floodplain development, which maintain the channel-floodplain equilibrium and lateral connectivity. Low to moderate stream power and moderate braiding maintain channel efficiency and allow the formation of diverse sandy bars that provide good nutrients for the aquatic biota, and a healthy habitat is established (Figure 12). In some reaches where major confluences with sediment-charged tributaries occur, excessive sedimentation reduces the occupancy and increases the bar density, thereby impacting channel-floodplain equilibrium and lateral connectivity, which degrades the RHC. However, some of these reaches have been reported as biologically productive due to the soft substrate of silt over sand (Mathur 1991). Anthropogenic interventions such as barrages, closely spaced bridges and water extraction through canals also emerge as

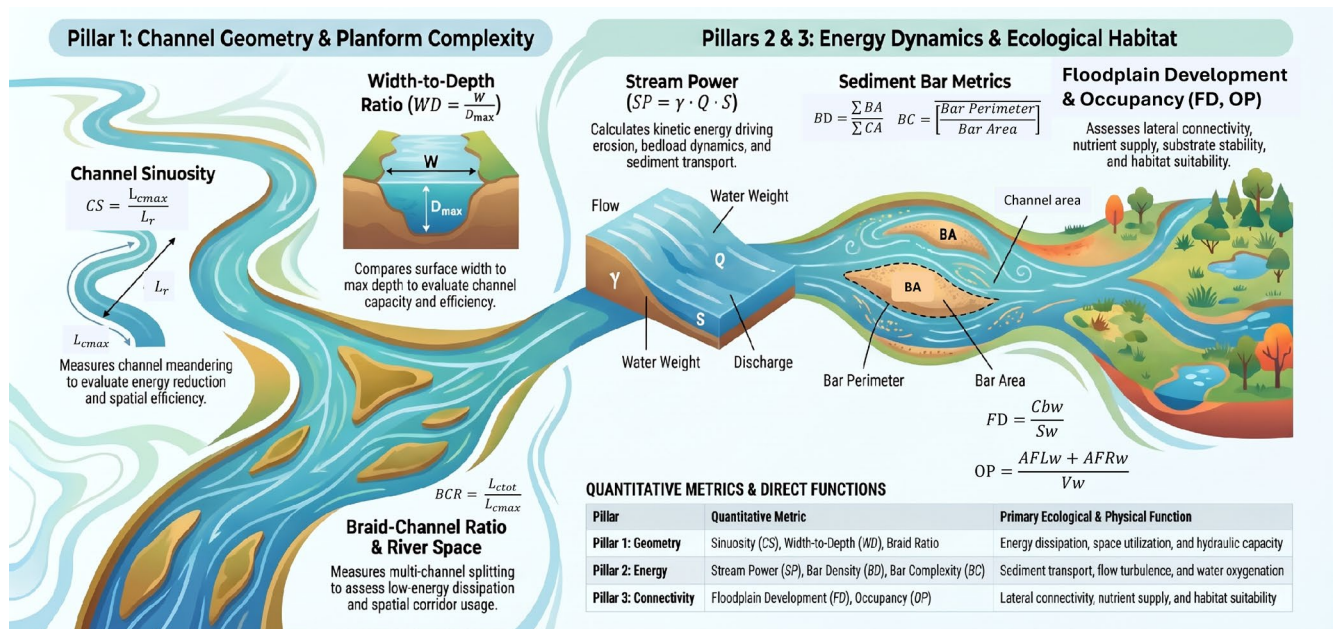


FIGURE 12 | Infographic showing major geomorphic drivers of river health and associated geomorphic processes used for the quantification of river health; it illustrates conversion of measurable physical geometry into functional indicators of river stability, hydraulics and habitat quality. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

important drivers that impact the morphological attributes in the vicinity of these structures and hence RHC. However, these interventions are now an integral part of most river systems, and they serve important socio-economic functions. Although there is an emerging view that river health cannot be solely dependent on physical or ecological attributes but must include socio-economic factors (Meyer 1997; Fairweather 1999; Jiao et al. 2023), some efforts must be made to create a balance between the two.

6.4 | Implications for River Management

Against the backdrop of the concepts of river science and a first-order RHA of the Ganga River, several management strategies can be planned through the extensive use of state-of-the-art datasets and IT tools. The first step in this direction should be to recognise and appreciate the morphological diversity of the Ganga for developing a sustainable river management strategy. Based on the process-based typologies and gRHI scores, hotspots of river degradation should be identified and prioritised for rehabilitation. One of the most important steps is to restore the river space, which plays a crucial role in maintaining river health. Severe population pressure and lack of any floodplain zoning policy for the Indian rivers have resulted in the loss of river space. This has, in turn, disrupted river-floodplain connectivity, impacting surface-subsurface interactions of river flows and has also contributed to river pollution and increased vulnerability to floods. In reaches of poor floodplain development and occupancy along the Ganga River, the next step should be to map the active and lost floodplains using multitemporal satellite images (optical/microwave) to define the reference state of the river system. Floodplain zonation based on geomorphic mapping should be integrated with the hydraulic models to define and restore the 'river space'. Additional information, such as ecological

hotspots, can be added to the GIS database so that an appropriate notification strategy can be planned.

Several water resource development projects in both mountainous and alluvial reaches of the Ganga and several rivers across the country have disrupted longitudinal connectivity. Some of the major impacts of this are a significant reduction in flows downstream, aggradation upstream of the interventions and mobility of aquatic life, impacting their habitat adaptation and loss of ecological services in many cases. Several alluvial reaches of the Ganga, such as those around Kanpur and Farakka, show 'fair' RHC because of such interventions, where we document moderate values of bar density because of excessive sedimentation. A complete review of the interventions along the rivers (both large and small) and their cost-benefit analysis (including ecological damage) should be undertaken. This should be followed by mitigative or adaptive strategies, for example, revision of barrage operation policies and desiltation activities.

Further, several reaches of the Ganga are embanked, and this has disconnected the channel from floodplains, thereby disrupting the nutrient supply, causing loss of riparian vegetation and degradation of the river. This has also caused a rapid buildup of sediments between the embankments. This is reflected in poor values of floodplain development and high values of bar density, resulting in 'poor' RHC in several reaches of the Ganga River, particularly around large cities such as Varanasi and Patna, where extensive embankments are present. It is recommended that the lateral connectivity between the channel and floodplain be restored in such reaches through innovative approaches, such as controlled flooding or even removal of embankments, where their efficacy is questionable. As a long-term strategy, an integrated assessment of land cover changes, erosion and sedimentation at the catchment scale is required—this will provide a better understanding of the cause-and-effect relationship

between different processes and will help in designing sustainable strategies for sediment management. In reaches with excessive sedimentation, such as the Lower Ganga, the government needs to conduct strategic dredging in downstream stretches and consider innovative approaches for promoting large-scale use of the dredged silt in road construction, embankment maintenance, agriculture, reclamation of low-lying and waterlogged areas, and so forth.

7 | Conclusions and Future Perspectives

Simple morphometric parameters were used to design a gRHI using maps and satellite images based on process-based understanding. This approach has provided a protocol for rapid, first-order assessment of a large and diverse river such as the Ganga and will help design sustainable river rehabilitation strategies. The major conclusions from this study are listed below:

1. A set of 8 geomorphic attributes was selected to design RHCs using a weightage system based on the AHP method. Keeping in view that different geomorphic processes operate in the mountainous and alluvial reaches, we prioritised the parameters differently and developed distinct weightage schemes for these two settings.
2. SP, along with CS and W/D ratio, was given higher weightage for the mountainous reaches as they influence the channel efficiency and longitudinal connectivity of the river. OP, FD and BCR were given higher weightage for the alluvial reaches as they maintain channel-floodplain equilibrium and lateral connectivity.
3. In the mountainous stretch, most reaches of the Ganga River are in 'near-pristine' condition. In a valley inter-fluve setting in alluvial reaches, several reaches fall in 'good' and 'fair' RHC. Several alluvial reaches exhibit 'poor' river health, primarily due to flow reduction and sediment accumulation, leading to morphological degradation. Tributaries and interventions such as barrages and embankments significantly influence river health in the alluvial reaches.
4. We document a broad correspondence between RHC and landscape setting. Most mountainous reaches forming steep valleys (Class I) are 'near-pristine', whereas transitional (piedmont) reaches (Classes II and III) fall in 'good' and 'fair' classes. Even though the alluvial reaches are very geomorphologically diverse, we note the first-order control of the landscape setting. The valley inter-fluve setting provides the optimal parameters for a good RHC, whereas the reaches in other settings are driven by second-order controls, including anthropogenic interventions, for their classification into fair, poor or degraded classes.
5. We also document a broad correspondence between RHC and ecological attributes of the Ganga River although based on very limited data.

While this work has primarily focused on geomorphic parameters, which are easy to estimate for large rivers using geospatial

datasets, a comprehensive RHA framework should recognise at least four interconnected dimensions: hydrological health, geomorphic health, ecological health and water-quality health. Hydrological health concerns the magnitude and variability of river flows and the degree to which natural flow processes are maintained. Geomorphic health considers channel morphology, sediment balance, erosion and deposition, channel stability and longitudinal and lateral connectivity. Ecological health evaluates habitat quality, biological diversity, community structure and ecosystem functioning. An ecosystem-based restoration proposed by Palmer et al. (2005) has strongly emphasised providing 'river space' and maintaining longitudinal and lateral connectivity of the river systems. In the case of the Ganga River, the recommendations for eco-restoration measures have included the maintenance of environmental flows by restoring connectivity, protection of floodplains and wetlands, among others (Mathur and Kapoor 2019b). This underscores the importance of geomorphic attributes in RHA.

Importantly, these components should not be considered as independent indicators. They are strongly coupled through river processes. For example, hydrological alteration can modify sediment transport and channel morphology, which in turn affects habitat availability and biological communities. Changes in sediment supply can alter channel-bed characteristics, turbidity, habitat structure and aquatic productivity. Pollution can interact with reduced discharge to increase ecological stress, while loss of floodplain connectivity can alter nutrient exchange, habitat availability and flood regulation. River health is therefore an emergent property of interactions among water, sediment, channel form, habitat, biota and human interventions.

Furthermore, most large rivers are complex and dynamic; therefore, morphological attributes change over time, and so will gRHI. Therefore, a time-series analysis to understand the morphodynamics of the river, including additional parameters in RHA, would be extremely rewarding. In addition, human interventions, such as dams and barrages, affect the longitudinal connectivity of the river system and, therefore, the life cycles of aquatic biota. Normally, stream biota move upstream to breed, but dams/barrages create obstacles to their movement. Canals that abstract large volumes of water may change the water-sediment balance of the channel belt. Both pre-monsoon and post-monsoon analyses are required to establish the longitudinal and lateral connectivity of the river system.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table A1:** Saaty's fundamental scale for pairwise comparisons in the Analytic Hierarchy Process

(AHP) (Saaty 1980). **Table A2:** Reach-wise weighted contributions, Geomorphic River Health Index (gRHI) and river-health classes (RHC) for the mountainous reaches of the Ganga River. **Table A3:** Reach-wise weighted contributions, Geomorphic River Health Index (gRHI) and river-health classes (RHC) for the alluvial reaches of the Ganga River.