River health assessment of the Ganga River, India based on geomorphic attributes

Évaluation de la santé du fleuve Ganga, en Inde, sur la base d'attributs géomorphiques

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RÉSUMÉ

Les rivières, en particulier les grands réseaux fluviaux, constituent l'un des systèmes de survie les plus fondamentaux qui ont soutenu les civilisations et devraient jouer un rôle déterminant dans la survie future des civilisations humaines. Une rivière ne peut être qualifiée d'écosystème sain que lorsque toute la flore et la faune dans et le long de la rivière et les cultures dans les plaines inondables sont saines et que la forme de la rivière est en équilibre. Le système fluvial du Gange en Inde est un vaste système fluvial comprenant géodiversité et biodiversité, où environ un tiers de la population indienne dépend directement ou indirectement du fleuve Ganga. Cette étude se concentre sur le développement d'un indice de santé des rivières (RHI) basé sur des attributs géomorphiques, où les paramètres de santé des rivières sélectionnés sont analysés à l'aide d'une technique de prise de décision multicritère, le processus analytique hiérarchique (AHP), dans un cadre SIG. Nous avons adopté un système de classement en cinq classes (c'est-à-dire presque intact, bon, passable, pauvre et dégradé) pour l'ensemble du système du fleuve Ganga, de Gomukh à Farakka. Les résultats de l'estimation RHI indiquent que la plupart des tronçons du fleuve Ganga dans la partie montagneuse sont dans un état « quasi intact ». Dans le contexte de l'interfluve des vallées, plusieurs tronçons entrent dans la classe RHI « bon ». La plupart des tronçons de la partie alluviale présentent un état de rivière « mauvais », principalement en raison de la réduction du débit et de l'accumulation de sédiments entraînant une dégradation morphologique. Plusieurs « points chauds » de « mauvaise » santé fluviale dans le tronçon alluvial du fleuve Ganga ont également été identifiés. Le cadre géomorphique présenté dans cette étude peut être mis en œuvre pour comprendre et évaluer les scénarios spatio-temporels d'adéquation de l'habitat, de débits environnementaux et de risque d'inondation associés à tout système fluvial.

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 as a healthy ecosystem only when all flora and fauna in and along the river and the cultivation in flood plains are healthy, and the river form is in equilibrium. The Ganga River system in India is a large river system comprising geodiversity and biodiversity, where about one-third of the population of India depends on the river directly or indirectly. This study focuses on the development of a River health index (RHI) based on geomorphic attributes, where the selected river health parameters are analysed using a multi-criteria decision-making technique, the Analytical Hierarchical Process (AHP), in a GIS framework. We have adopted a five-class (i.e., near pristine, good, fair, poor and degraded) ranking system for the entire Ganga River system from Gomukh to Farakka. Results of the RHI estimation indicate that most of the reaches of the Ganga River in the mountainous stretch are in 'near pristine' condition. In the valley interfluve setting, several reaches fall in the 'good' RHI class. Most reaches in the alluvial part show 'poor' river health, primarily because of flow reduction and sediment accumulation leading to morphological degradation. Several 'hotspots' of 'poor' river health in the alluvial stretch of the Ganga River are also identified. The geomorphic framework presented in this study can be implemented to understand and evaluate the spatio-temporal scenarios of habitat suitability, environmental flows, and flood risk associated with any fluvial system.

KEYWORDS: Analytical Hierarchical Process, Ganga River, geomorphic diversity, river health parameters, river management.

Processus analytique hiérarchique, fleuve Ganga, diversité géomorphique, paramètres de santé des rivières, gestion des rivières.

1. INTRODUCTION

A river can be termed as a healthy ecosystem only when all the flora and fauna in and along the river and the cultivation in flood plains are healthy and river form is in equilibrium. River health assessment generally focuses on integrating 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 and energy exchange, support for riparian vegetation and ecosystem (in-channel and floodplain), maintaining longitudinal and lateral connectivity, and maintaining geodiversity and biodiversity.

River health assessment has several connotations as perceived by scientists from different disciplines such as geomorphologists, ecologists, hydrologists and water quality experts. In a geomorphic context, the quantification of geomorphic change (Norman et al., 2017) provides a useful platform for River Health Indices (RHI) whereas biological monitoring of river health (Karr, 1999) has often been used to assign the health status in ecology. In large rivers exhibiting significant geomorphic diversity, it is important to design the criteria for river health assessment separately for different geomorphic settings.

The Ganga River in the Himalayan foreland (Figure 1) flows through a diverse climatic and geomorphic setting, and our earlier work highlighted this diversity, which has significant implications for river management (Sinha et al., 2017). The present study takes this work forward and uses a set of geomorphic indices integrated into a GIS framework to develop a River Health Index (RHI) that is (a) process-based, (b) framed in terms of the type of river (geomorphic diversity), and (c) framed in terms of river change (morphodynamics). We then integrate the river health assessment with the river classes proposed by Sinha et al. (2017) to investigate the controls on river health parameters.

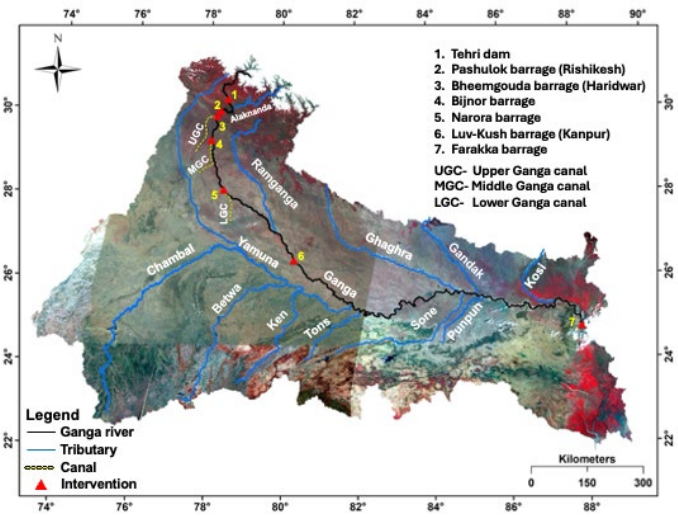

Figure 1. The Ganga basin in the Himalayan foreland.

2. METHODS

We have designed a set of river health parameters for this study (see Table 1 for their definitions and expressions. ‘Sinuosity’, ‘Braid channel ratio’, 'Bar density' and 'Bar complexity' are the important channel belt parameters focused on the morphometric attributes of bars and channels. ‘Occupancy' and 'Floodplain development' indicate the lateral connectivity component, where active floodplain width and valley width are considered. In addition, the width/depth ratio representing cross-sectional form and stream power integrating hydrology and longitudinal slope were also used for RHI calculation.

We have integrated several geomorphic parameters for river health assessment using the spatial-AHP method which is centred on a 9-point scale (Saaty, 1980; Siddique et al., 1996). The mountainous and alluvial reaches are characterized by very different geomorphic settings, and therefore, we designed different weightage schemes (decision matrix) of the RHI parameters for them.

3. RESULTS AND DISCUSSION

In the mountainous reaches, a total of 34 reaches between Gomukh (reach 1) to 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. Here, reaches were classified into four classes according to their desired values in the RHI parameters (Figure 2).

(a) Near Pristine: Reaches having RHI values of more than 45,000 were recorded in the Near Pristine class. In the Himalayan bedrock region, all the reaches from Gomukh (Reach no. 1) to Rishikesh (U/s) (Reach

no. 26) show distinct RHI values. All these reaches show balanced natural sinuosity. No active floodplain is present in these reaches. Hence, the channel touches directly into the valley margin, resulting in good Occupancy and lateral connectivity.

(b) Good: Reaches having RHI values in between 1500 to 15,000 were classified in Good class. Between Rishikesh (Reach no.27) to Balawali (Reach no. 32), 5 reaches fall in this Class. This stretch is in the transition zone between the hill and the plain. Here, the Ganga River enters into the plain, and the landscape setting is Piedmont. All these six reaches show better lateral connectivity between the channel belt and the active floodplain. Heterogeneity is maintained here with a healthy Braid channel ratio.

(c) Fair: Reaches having RHI values less than 1500 were categorized in Fair class. Shivpuri (Reach no. 33) and Chandok (Reach no. 34) fall in this class. These two reaches show relatively low but considerable occupancy, lateral connectivity and Braid channel ratio. Good to moderate sinuosity was documented in this stretch and moderate stream power was computed

Table 1: Parameters for the River Health Index.

Term	Expression	Remarks
Sinuosity (P)	Lcmax/Lr	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 (B)	Lctot/Lcmax	Higher values are good for biota
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 good for biota as it would indicate the presence of ample substrate for biological activities.
Bar Complexity (Bc)	$Bc = \overline{\left[\frac{Bar\ Perimeter}{Bar\ Area}\right]}$	Measures complexity of the bar margins. Higher values indicate presence of bars of varied sizes. Good for biota.
Occupancy	$Occupancy = \frac{AFLw + AFRw}{Vw}$ 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.
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/dmax where w is bankfull width and dmax is maximum depth	Low to moderate w/d ratios favor turbulence and oxygenation; increased w/d ratio results in less canopy cover
Stream power	Energy dissipation rate per unit downstream length of a stream	Low to moderate stream power is just enough to maintain the present morphology should favor good river health

(a) Good: Reaches having RHI values between 50 and 75 were categorized in the Good class. Among these 13 reaches, 12 were above the Ganga-Yamuna confluence. Reach no. 77 (Mokama), reported in this class, is located downstream of the Ganga-Gandak confluence. While all these reaches showed high RHI scores in 6-7 of the 8 parameters, they exhibited comparatively higher RHI values in the first 4 parameters (i.e., Occupancy, Floodplain Development, BCR, and Bar Density).

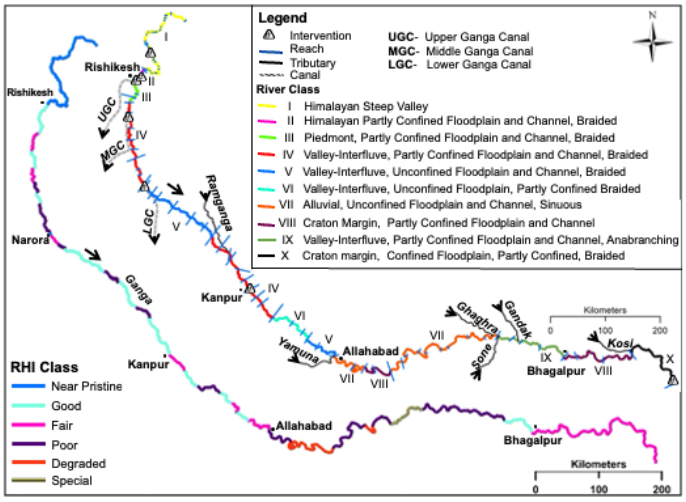

Figure 2. RHI classes for the Ganga River vis-a-vis River Classes (Sinha et al., 2017) along with tributaries, canals and interventions.

(b) Fair: Reaches having RHI values between 25 and 50 were classified in the Fair class. Among these 10 reaches, 5 were above the Ganga-Yamuna confluence, 4 were near the Pansalla to Farakka stretch (Craton margin), and the other was located at the meeting point of the Ganga-Yamuna. For these reaches, low to moderate values were calculated for various parameters.

(c) Poor: Reaches having RHI values between 10 and 25 were recorded in the Poor class. this class, the reaches were distributed almost throughout the entire Ganga River, starting from Mawana (D/s) to Patna (D/s).

(d) Degraded: Reaches having RHI values between 10 and 25 were recorded in the Degraded class. All these four reaches were located between the Ganga-Yamuna confluence and the Ganga-Ghaghra confluence. Low to very low values were reported in these reaches.

Despite the high complexity and diversity in the Ganga River, some identical controlling factors were identified for River class, Ecology and RHI assessment in some of the reaches. Reaches in the hilly area were more balanced compared to the plain reaches, which was reflected in the driving parameters of these stretches. But, in most of the reaches, unique controlling factors were reported for each of the above-mentioned assessments.

In the Himalayan hinterland, Stream power was considered as the main controlling factor. Stream power influences the channel morphology for River Classes as well as contributes to the major portion of the RHI values in the Near Pristine Class from Gomukh to Rishikesh. In Plains, all the reaches with Good RHI class were identified in the valley interfluve landscape setting. Ganga-Ramganga interfluves and Ganga-Yamuna interfluves produces Good RHI reaches. This is due to the transportation of more water and sediment loads from these large tributaries, which enhances the multiplicity of the river. Thus, a wide range of bars with diverse sizes formed, and a balanced RHI value was maintained with a high BCR and Bar complexity value. The Ecological reports suggest that these sandy bars provide good nutrients for the aquatic biota, and a healthy habitat was established. In the interfluve reaches, wide active floodplains were encountered, which adds more 'Occupancy' value in the River Health assessment. In this way, lateral connectivity was maintained in these reaches.

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