



Multifunctional resilience of river health to human service demand in an alluvial quarried reach: a comparison amongst fuzzy logic, entropy, and AHP-based MCDM models

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Abstract

Riverine ecosystem services to human beings are dynamically evaluated by harmonic relationships; however, over growing human service demands (HSDs) are leading to deteriorate the river health resilience. In this study, an assessment index system of river health involving pressure-state-response (PSR) based on twenty indicators of riparian, channel geomorphic, hydroecological, and social attributes was developed to detect the multifunctional reliability and resilience of river system integrity for HSDs at upper (US), middle (MS), and lower segments (LS) of Kangsabati River using fuzzy logic, analytical hierarchical process (AHP), and entropy weight-based multi-criteria decision matrix (MCDM) methods. Borda integrating MCDM results revealed that overall indicator performance is high health score in US (77), medium score in MS (69), but mostly unhealthy score in LS (34); thus, entropy-MCDM models give highest rank to US, medium rank to MS, and least rank to LS, while AHP and fuzzy MCDM models assigned as high priority rank to MS, medium rank to US, and least rank to LS, respectively. According to model validation performances, entropy-MCDM models (RMSE < 2.48) are rationalized to the harmonic relationship of riverine system, whereas fuzzy and AHP-MCDM models (RMSE < 2.79) are signified to HSDs, and these results are closer to real problems. With the acceptability of AHP-MCDM models through the percentage change (73.89%) and intensity change (17.16) assessment, it points that over HSDs are crucial factors for river health degradation. Moreover, final outcome of the present research helps to find out the sick river health sites for ecological restoration.

Keywords Harmonic relationship · Human service demands · River health resilience · Multifunctional reliability · Multi-criteria decision matrix

Introduction

River health is one kind of metaphor like human health and veterinary health, which indicates the overall status of a river particularly ecological function and biodiversity as required enough expectation of burgeoning human social needs and enriching the sustainable development (Ma et al.

2019; Zeng et al. 2020). Contrastingly, human satisfaction and response along with physical, chemical, and biological resilience capacities controlled the river's well-being state (Sadat et al. 2020; Zhao et al. 2019; Shan et al. 2021). During the twenty-first century, river health including the ecological environment has become a prime concern caused by abruptly socio-economic development and several constructions across the river for flow regulation like dams, reservoirs, barrages, bridges, and weirs (Gain and Giupponi 2015; Restrepo et al. 2018). Thus, river health resilience (RHR) (ecosystem ability to improve its original structure and function after the harmful disturbance) has become more speed up from the river ecosystem to socio-economic and cultural realms with the following ecosystem integrity and human service demand (HSD) (Von Schiller et al. 2017; Cheng et al. 2018). Many research works have been already done about the RHR which indicates river ecosystem as a more dynamic process involving constant changes

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after the crossing of the autogenic level (Liu et al. 2019) and then turning to socialize with the corresponding of HSDs (Luo et al. 2018). With the understanding of the harmonious relationship between dynamic river ecosystem and HSDs, assessment techniques play a big role to determine the resilience of river health ensuring scientific management of rivers. In this context, several theories and methods are employed with continuously revised and enriched to measure the RHR (Alemu et al. 2018; Yang et al. 2018). Entire assessment approaches are based on three different studies, i.e. (1) single-based studies like biological, floral species, and faunal species (Zhao et al. 2019); (2) river ecological function related studies like plant respiration, evapo-transpiration, and photosynthesis rates (Ma et al. 2019); and (3) composite index-related studies like water quality index and macro-invertebrate indices (Singh and Saxena 2018; Sadat et al. 2020). Recently, several indices like biological integrity (Petesse et al. 2016; Su et al. 2021), pollution overall index (Sargaonkar and Deshpande 2003), river pollution index (Mupenzi et al. 2017), multi-metric assessment index (Shi et al. 2017), and ecological quality index (Singh and Saxena 2018) are widely used to assess the river health.

Henceforth, several mathematical approaches like multivariate analysis (Ustaoglu et al. 2020), analytic hierarchy process (Wu and Chen 2020), artificial neural network (Kadam et al. 2019), and fuzzy comprehensive assessment (Deng et al. 2015) are already applied for river health assessment. It points that all of these methods have such significant role in evaluating the multi-dimensional diversity, reliability, structural, and functional complexity of the river ecosystem. However, these methods could not be effectively determined the multi-index assessment and multi-object decision-making for RHR (Deng et al. 2015; Su et al. 2021). Thus, due to the complex multifunctional threshold state of resilience factors of the river health, a single evaluation method cannot be trustfully performed as well as does not provide effective results. Consequently, RHR approach has been integrated with multi-dimensional human demands; hence, nonlinear and indeterminate methods are applied to measure this obscure multifunctional relationship (Karr 1999; Zhao et al. 2019). Thereafter, application of fuzzy membership function with its assessment evaluation method has now been used in different perspectives such as comprehensive evaluation, scientific decisions, and pattern recognition (Zhu et al. 2019) that help for scientific and rational utilization to get more effective evaluation results (Feng et al. 2021). Based on fuzzy membership function, fuzzy matter element method (FME) for scientific and comprehensive decision making, combining grey relational analysis method (GRA) for theoretical explanation of uncertain information and incomplete data samples (Deng et al. 2015; Shan et al. 2021), and harmony degree evaluation method (HDE) for the analysis of dynamic equilibrium in between HSDs and river ecosystem

integrity (Zuo et al. 2016; Luo et al. 2018) are successively used for achieving the different goals, i.e. analysis of the overall performance of every attributes under river health and comparison and validation amongst the models (Sadat et al., 2020; Xue et al. 2020).

Nevertheless; fuzzy membership functions could not be significantly determined the attribute performance of RHR against the various environmental stresses in particular river ecosystem integration. Moreover, fuzzy assignments are incorporated either various uncertainties of criteria performance values or uncertainties of criteria weights for river health assessment. With the comparison approach, no one fuzzy function is not properly detected in the multifunctional threshold state of RHR attributes with respect to HSD. In this regard, this research has tried to evaluate several hydroecological and social river health assessment criteria and their indices in Kangsabati River using comparison amongst five multi-criteria decision making (MCDM) methods, i.e. VIKOR, TOPSIS, SAW, CORPAS, and WASPASS under fuzzy membership function, AHP, and entropy evaluation environment.

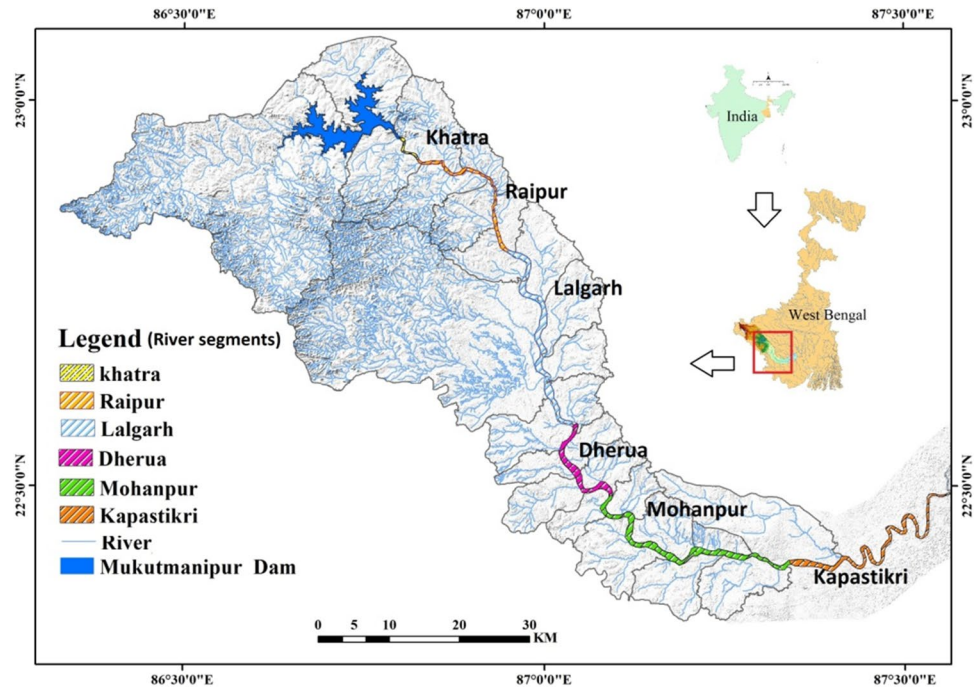
AHP and entropy weight-based MCDM models integrated with fuzzy membership function can perform well to evaluate the multifunctional RHR of the riparian, channel geomorphic, planform, hydroecological, and social attributes as well as to detect the healthy and sick sites in the entire Kangsabati River. Moreover, AHP weight assigning MCDM methods helps to detect the resilience capacity of health indicators, whereas entropy MCDMs find out the harmonic relationship amongst indicators. The objectives of this study are (1) to assess the reliability-resilience of riparian, channel geomorphic, hydroecological, and social dimensions on RHR with respect to HSD; (2) to quantify the multifunctional threshold state amongst the health indicators at different segments; (3) to validate and compare of twelve MCDM models as well as identify the best-fit methods for assessing the overall RHR status; and (4) to find out the sick health sites for ecological restoration strategy and environmental management policy.

Materials and methods

Study area

The Kangsabati River (21°45'N–23°30'N, 85°45'E–88°15'E) is originated from south-east of Chhota Nagpur plateau fringe in Jharkhand and then feeds its water to the Rupnarayan River and Kheliaghai River in lower Gangetic basin. The Kangsabati River has a basin area of 9658 km² (Fig. 1). The main stream length of this seasonal alluvial river is approximately 465.23 km, and the average width-depth ratio in this river ranges from 35.61 to 1208.01 m under the

Fig. 1 Location and segment sites of the study area



significant changes of elevation as 2–656 m above mean sea level (MSL). Maximum rainfall occurred mainly monsoon season (June to October) with an average of 1200 mm/year. In recent past, Mukutmanipur dam construction near confluence point at Kansai and Kumari River, built up of barrages, artificial embankments, weirs, cross bridges, intensive instream, and floodplain sand mining, changed several surface characteristics and altered the riverine land cover and land use. Therefore, human beings have strongly interrupted many aspects of Kangsabati River, i.e. flow regime, sediment inflow and outflow, channel morphology, and habitat degradation (Mura and Gope 2020).

Since the construction of Mukutmanipur dam (1956), sand mining is one of the prime anthropogenic activities removing a huge volume of sand (588,155 ton/year) than natural replenishment (1,413,112 ton/year) from Kangsabati River (2002–2016) (District Land and Land Reforms office of Paschim Midnapore and Bankura, India 2002–2016) (Bhattacharya et al. 2019a). In terms of sand mining in Kangsabati River, natural replenishment (76,644 ton/year) is far better than mining (13,956 ton/year) in Dherua segment, but the rate of mining (161,308 ton/year) exceeds replenishment (20,096 ton/year) in Kapastikri segment. In Lalgarh segment, annual replenishment (529,325 ton/year) always crossed the over-growing sediment removal (75,058 ton/year) (Bhattacharya et al. 2019a, b). As a result, maximum water quality deterioration, channel wideness, bed level lowering, reduction of channel meandering, habitat destruction or transformation, and fragmentation of biodiversity indices occurred in the entire Kapastikri segment,

while these consequences are restricted in mining and pit sites but sandbar sites are fully free from those affects in Dherua and Lalgarh segments (Bhattacharya et al. 2019a, b, c; 2020a).

Selection of river health indicators and indices

In this study, the river health estimation procedure comprises mainly twenty indicators under five attributes, i.e. riparian zone feature (A), river water condition (B), morphology and its planform (C), ecological structure (D), and social structure, and (E) based on their relative importance on RHR and HSDs. All corresponding assessment criteria and estimation techniques are defined and presented in Table 1. Twenty health indicators were taken from three different segments, i.e. Lalgarh (upper), Dherua (middle), and Kapastikri segments (lower) of Kangsabati River. With the understanding of the multifunctional RHR attributes, three sections were taken from unstable mining sites, abandoned mining or pit sites, and stable sandbar sites of Lalgarh, Dherua, and Kapastikri segments (Fig. 2a, b, c).

Assessment indicator system

Determination of assessment criteria has a more significant role to find out the influence intensity of indicators on river health (Deng et al. 2015). However, human demand changed the assessment criteria day by day, and no one consistent standard has been properly set up (Karr 1999). Several typical methods including field surveys, ground truth

Table 1 Estimation methods and the corresponding data resources for the different assessment criteria

Health indicators/indices	Estimation	Reference	Data sources
Human encroachment in riparian site (A1)	Encroachment activities along the left and right riparian sites up to 25–50 m width	Zheng et al. (2007); Ding et al (2015), Yang et al (2018)	Estimated the areal coverage of encroachment activities along the riparian corridor of Kangsabati River using Google Earth Image (2017)
Vegetation buffer width (A2)	$VBW = \left\{ \left(\frac{\text{Riparian width}}{\text{River width}} \right) \times \text{Tree and shrubs coverage} \times \text{vegetation level} \right\}$	Zhao et al. (2019)	Vegetation buffer width (VBW) is considered up to 200 m across the right and left riparian zones from thalweg line of Lalgarh, Dherua, and Kapastikri
Bank erosion degree (A3)	$BED = \left\{ \frac{(PSBL - PVBL)}{PVBL} \times 100 \right\}$ where BED means bank erosion degree, PSBL means present bank line, and PVBL means present bank line	Yang et al. (2017); Yang et al. (2018)	Extraction of bank line from Google Earth Image in the year of 2016 and 2017
Water flow condition (B1)	$WFC = \left[\frac{Q_d}{Q_{avg}} \right]$ Q_d denotes daily runoff and Q_{avg} indicates average annual runoff	Sadat et al. (2020)	Nine cross profiles from sandbar, mining, and pits at Lalgarh, Dherua, and Kapastikri were taken to determine the indicators of river water condition following the flow regime and sediment transport during pre monsoon, monsoon, and post monsoon (2016–2017)
Mean flow velocity (B2)	$v = \frac{Q}{A}$ Q mean discharge and A mean cross section area	Julien (2002); Dutta et al. (2017)	Mean flow velocity was estimated from nine cross sections at AB, CD, EF, GH, IJ, KL, MN, OP, and QR
Water quality index (B3)	$WQI = \left[\frac{SI}{SI} \right]$ $SI = R_w \times Q_{rs}$ R_w means relative weight, Q_{rs} denotes quality of rating scale, and SI means sub-indices of water samples	Alobaidy et al. (2010); Sharma et al. (2014)	Nine water samples from sandbar, mining, and pits of three segment were collected for measuring the water quality index (WQI) using the assigned weight value of conductivity (5), DO (5), TDS (4), pH (4), salinity (4), BOD (2), and Mg^{2+} (2)
Pollution index (B4)	$P = \frac{1}{n} \sum_{i=1}^n \frac{C_i}{C_o}$ C_i denotes concentration amount of i th pollutant (mg/L) and C_o indicates evaluation standard value of i th pollutant (mg/L)	Yang et al. (2018)	Nine water samples were taken from three segment during premonsoon, monsoon, and postmonsoon
Substrate compositions (C1)	Graphic mean $(M_z) = \frac{Q_{i,c} + Q_{st} + Q_{sl}}{3}$ ϕ means phi value of sediment	Folk and Ward (1957)	Thirty sediment samples were collected from sandbar, mining, and pits during premonsoon, monsoon, and postmonsoon
Average channel width (C2)	$W = \frac{W_{bed} + W_{bank}}{2}$ where W means average channel width, W_{bed} means average bed width, and W_{bank} means average bank width	Julien (2002)	Nine cross sections
Average channel depth (C3)	$D = \frac{D_{si}}{N_i}$ D means average channel depth, D_{si} means sum of interval depths, and N_i means number of intervals	Julien (2002)	Nine cross sections
River meandering degree (C4)	$P = \frac{L_R}{L_{conv}}$ L_{conv} states curvature distance along the thalweg line and L_R indicates the straight distance in measuring segment following the thalweg line	Friend and Sinha's method (1993)	Taken of nine cross section from sandbar, mining and pit sites of these three segments of Kangsabati River

Table 1 (continued)

Health indicators/indices	Estimation	Reference	Data sources
Simpson index of biodiversity (D1)	Simpson's index of diversity = $1 - D$	Shannon (1949)	Total one hundred fifty-four species were collected from nine cross sectional sites
Simpson index of dominance (D2)	$D = \frac{[N(n-1)]}{[N(n-1)]}$ <i>N</i> denotes total number of all species within a living organism and <i>n</i> indicates entire number of organisms in each species $H = - \left\{ \sum \frac{S}{N} \ln \frac{S}{N} \right\}$ <i>S</i> indicates individual number of specific species, <i>N</i> denotes to total number of all individuals in each sample site, and <i>IN</i> stated logarithm to base <i>e</i>	Shannon (1949)	154 species from sandbar, mining, and pits sites
Shannon–Wiener index (D3)		Shannon (1949)	154 species from sandbar, mining, and pits sites
Species richness index (D4)	Margalef's index = $\frac{S-1}{n/N}$	Margalef (1958)	154 species from sandbar, mining, and pits sites
Habitat complexity (D5)	Number of small habitat in defined area	Yang et al. (2018); Wang et al. (2020)	Field observation in nine sites
Species evenness (D6)	$e = \frac{H}{\ln S}$	Pielou (1966)	154 species from sandbar, mining and pits sites
Land use density (E1),	= $\frac{\text{Land use area}}{\text{Basin area}}$	Cheng et al. (2018); Luo et al. (2018)	Extraction of human induced land use area from Google Earth Image
Groundwater depletion level (E2)	= $\frac{\text{Present year Ground water level} - \text{Previous year Ground water level}}{\text{Basin area}}$	Bhattacharya et al. (2020c)	Groundwater recharge level during 2016 (pre-monsoon) and 2017 (premonsoon)
Developmental density (E3)	= $\frac{\text{Development area in riparian site}}{\text{Basin area}}$	Luo et al. (2018)	Extraction from Google Earth Image during 2017

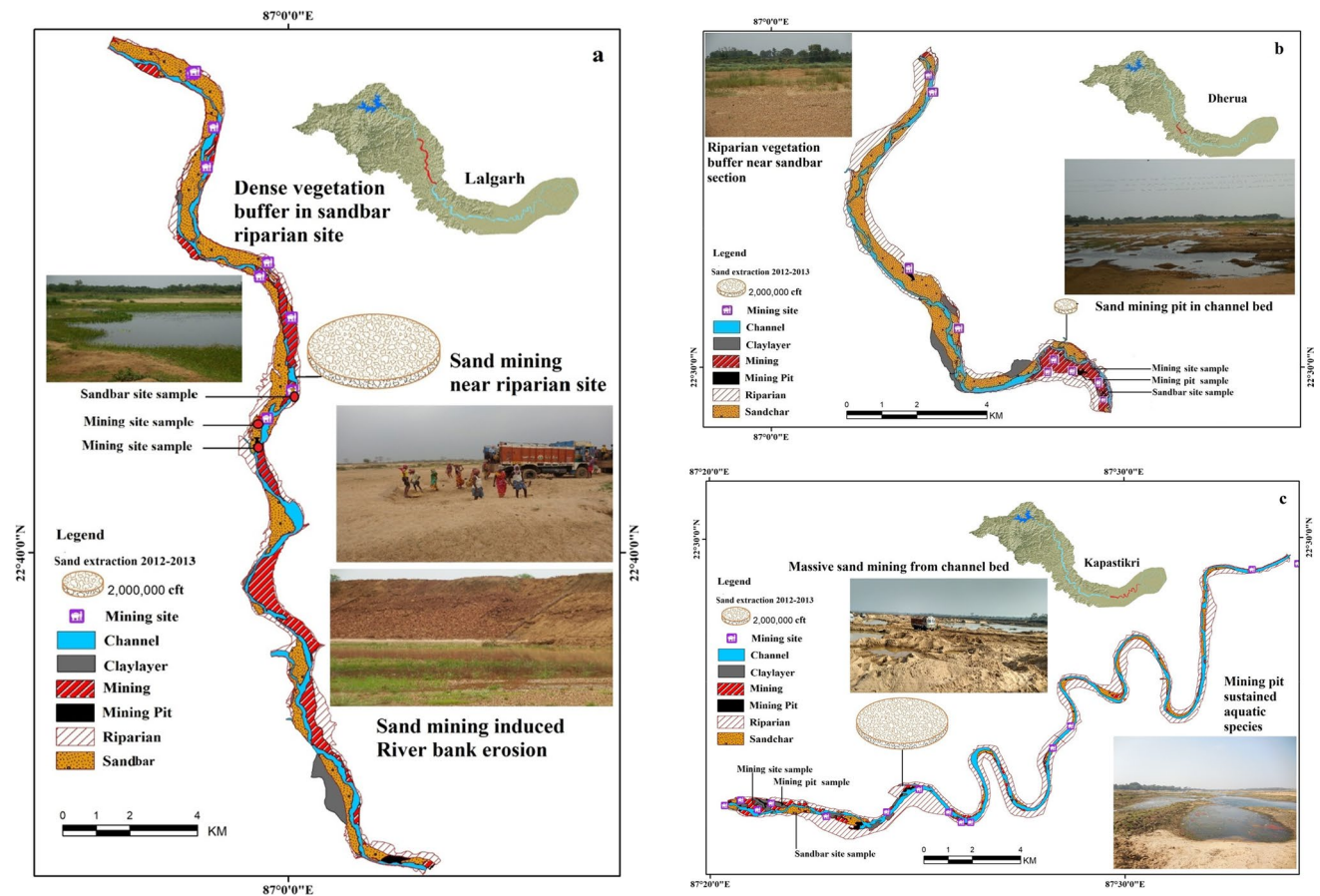


Fig. 2 Riverine land use patterns including sand mining, mining pit and sandbar sites in three segment sites. **a** Lalgar (upper course), **b** Dherua (middle course), and **c** Kapastikri (lower course)

verification, comparative analyses, reference system for relevant research results, and national standards have been used to determine the river health assessment (Zhao and Yang 2009; Sadat et al. 2020). With the assignment of different criteria assessment, threshold ranges of physical, ecological, and social indicators are easily determined amongst different river sites. In this study, standard evaluation methods, expert consultation method, surface water quality index (WHO 2011), overall pollution index (Yang et al. 2018), and biodiversity indices, were used to find out the threshold limit in each indicator for classifying their range, i.e. very well, well, critical, poor, and very poor, respectively (Table 2).

Human encroachment in riparian site (A1)

Trends of several encroachment activities including fishing, sand mining, vegetation depletion, and domestic waste stacking along the riparian sites are considered of human encroachment intensity (Yang et al. 2018). Very poor encroachment category is regarded when losses of biotic habitat diversity, degradation of structure and function of the river ecosystem, and cut off of the connectivity of river

channel-floodplain mostly occurred near 5 m from the active channel. Very well encroachment category is considered when all of those human activities have not been found up to 25–50 m from active channel to riparian sites (Zheng et al. 2007; Yang et al. 2017).

Riparian vegetation buffer width (A2)

With the following vegetation protection conditions, large volume of riparian vegetation coverage not only initiated the habitat potentiality for organisms but is also favourable for biological diversity formation to conserve the vegetation water as well as to protect the bank erosion (Yang et al. 2018). Human activities can threaten as more hindrances for disturbing the native species in the riparian vegetation zone where production modes are directly reflected by various land use types. In Kangsabati River, sand mining and agricultural practices in riparian zone cause an adverse impact on changing the vegetation composition and structure; as a result, hence, the intensity of erosion highly increases (Bhattacharya et al. 2019a). Therefore, good buffer width

Table 2 Assessment criteria of river health evaluation indicators

Indicators	Attribute role	Unit	Very well	Well	Critical state	Poor	Very poor
A1	ve +	Meter	< 25	15–25	10–15	10–5	< 5
A2	ve +	Meter	< 200	100–200	50–100	0–50	0
A3	ve –	%	< 10%	10–30%	30–45%	45–60%	> 60
B1	ve +	/	< 0.8	0.8–0.6	0.6–0.4	0.4–0.2	> 0.20
B2	ve +	m/s	0.60–0.75	0.40–0.50	0.30–0.40	0.20–0.30	> 0.20 to < 0.75
B3	ve –	%	< 25	25–50	50–70	70–100	> 100
B4	ve –	/	< 0.9	0.9–1.0	1.0–1.1	1.1–1.2	> 1.2
C1	ve +	Millimetre	< 0.50	0.25–0.50	0.10–0.25	0.05–0.10	> 0.05
C2	ve +	Meter	< 500	500–400	400–300	300–200	> 200
C3	ve +	Meter	< 1.7	1.7–1.5	1.5–1.3	1.3–1.0	> 1.0
C4	ve +	Number	< 2.00	1.60–2.00	1.40–1.60	1.20–1.40	> 1.20
D1	ve +	Number	< 0.8	0.8–0.6	0.6–0.4	0.4–0.2	> 0.20
D2	ve +	Number	< 10	10–8	8–6	6–4	> 4
D3	ve +	Number	< 1.8	1.8–1.6	1.6–1.4	1.4–1.2	> 1.2
D4	ve +	Number	< 4.5	4.5–3.5	3.5–2.5	2.5–1.5	> 1.5
D5	ve +	/	< 0.8	0.8–0.6	0.6–0.4	0.4–0.2	> 0.20
D6	ve –	Number	< 0.8	0.8–1.0	1.0–1.2	1.2–1.5	> 1.5
E1	ve –	/	< 0.1	0.1–0.3	0.3–0.6	0.6–0.8	< 0.8
E2	ve –	Meter	< 0.5	0.5–1	1–1.5	1.5–2	< 2
E3	ve –	/	< 1	5–1	10–5	15–10	> 15

Where ve + mean positive attribute role, ve – mean negative attribute role, / mean normal value

is considered of > 200 m, and poor buffer width considered of < 50 m, respectively (Table 2).

Bank erosion degree (A3)

Degradation of river habitat, estuary silting, and riverbed emerging occurred by prime ecological factors such as bank erosion, soil erosion, and water loss (Yang et al. 2018). Bank erosion is one of them that degrade the riparian habitat and biodiversity. Maximum bank erosion and bank line shifting in Kangsabati River progressively grew up near the higher bank slope along the upper course, but it becomes accelerated in sand mining sites along the middle and lower courses. Contrastingly, sediment accumulation across the riparian zone can restrict the bank erosion; as a result, minimum erosion observed in sandbar sites but erosion expanded in mining and pit sites. So, assessment level is inversely related between bank erosion and river health connotation which means the very well level assigning to < 10%, and the very poor level assigning to > 60% (Zheng et al. 2007; Yang et al. 2017).

Water flow condition (B1)

Water flow in the channel is the most effective indicator for preserving the basic ecological process of key species along with maintaining the entire river ecosystem structure and function, i.e. biotic and energy exchange, biotic

spawn, sediment cycle, and pollution dilution (Yang et al. 2013, 2018). In this study, flow condition for river health connotation is determined with the taken of daily and annual discharge measured by acoustic Doppler current profiler (ADCP) across the nine cross profiles. In Kangsabati River, poor flow condition is highly dominated in mining and pit sites than sandbar sites.

Mean flow velocity (B2)

Flow velocity is an important physiographic indicator to develop the particular habitat potentiality at the channel segment scale (Dutta et al. 2017). High-flow velocity can significantly disturb the biological community; consequently, river habitats changed into red zones caused by sudden increases in water discharge especially middle and downstream. Contrastingly, low to moderate flow velocity of upstream sites supported the maximum diversity for providing the good health connotation. In Kangsabati River, the maximum flow velocity is observed in pit pool sites along the middle and lower course during monsoonal flow, while minimum flow velocity is observed along the upper course (Mittal et al. 2014).

Substrate compositions (C1)

River substrate characteristics and structure both depend on substrate composition to provide the diverse habitat

complexity, especially aquatic organisms through the sheltering for benthonic organisms, which also offered the vast spawn site for fish species (Dutta et al. 2017; Yang et al. 2018). Based on sediment grain size, substrate composition in Kangsabati River is classified into four classes, i.e. boulders ($\phi > 60$ mm), gravel ($\phi = 3\text{--}60$ mm), sand ($\phi = 3\text{--}0.25$ mm), and mud ($\phi < 0.25$ mm), respectively (Kristensen et al. 2011; Wang et al., 2020). In addition, the finer grain size of hard clay and peat both are included under the substrate category.

Average channel width (C2)

Channel width is determined by quantitative analysis of hydraulic geometry to use for identifying the morphological attributes of river segments namely routine of sediment, flow regime, physical habitats, and interaction between channel and floodplain (Stewardson 2005; Yang et al. 2013). A wide channel always provided extensive physical habitat potentiality than a narrow channel (Maddock 1999). In Kangsabati River, channel width including the riparian zone has more extensive along with the middle course segments, but the width becomes narrowing along with the upper and lower segments (Bhattacharya et al. 2019a). So, the riparian vegetation buffer has progressively grown up in a wide channel.

Average channel depth (C3)

Water depth in an open channel, shallow water, and deep pools sustained primary habitat potentiality of the river ecosystem on one hand and successively contributed to habitat complexity including maximum diversity on the other hand (Dutta et al. 2017). Maximum aquatic species diversity including fish community has been observed in more deep pools with moderate to low velocity of the alluvial channel, but water depth (< 1 m) has negatively affected on species diversity. Channel depth in Kangsabati River has been drastically reduced after the construction of the Mukutmonipur dam (1956); consequently, minimum flow discharge is now observed over the season (Mittal et al. 2014). Recently, massive sand mining in this alluvial river increases the channel depth to form numerous pit pools that have positively influenced on flora and fauna composition to survive the ecological richness (Bhattacharya et al. 2019b).

Habitat complexity (D5)

Habitat complexity indicates the characteristics and composition of river habitat along with microhabitat and biotic habitat associations which are grown up in gravel river beds and shrinking holes across the bank margin, pool, riffle, dry branches, embankment, natural leaves, and hydrophytes,

respectively (Yang et al. 2018; Wang et al. 2020). Habitat complexity hurts species competition but can generate suitable space for all living species. Based on substrate composition, sand and mud composed habitat has zero complexity, while gravel composed habitat has maximum complexity. In this study, maximum habitat complexity is concentrated in coarse grain river beds along the upper course, but complexity has declined in finer grain beds along the lower course, respectively.

Land use density (E1)

Land use has a great impact on river health through the controlling of river ecosystems like altering water flow, degradation of river habitat, and biotic condition (Aazami et al. 2015). Various riverine land use patterns can change the hydrological systems, stream water quality, and structure of flora and fauna assemblages in the entire course (Shi et al. 2017; Cheng et al. 2018). In Kangsabati River, sand mining, channelization, urban expansion in the floodplain and bank margin, and inverse riverine land use change are declined the river health over the years (Bhattacharya et al. 2019a). Therefore, high land use density is given as poor health class, whereas low density is assigned to well health class.

Groundwater depletion level (E2)

Groundwater hydroecology has a great impact on river ecosystem function; however, over exploitation and surface water intrusions are depleting the groundwater level over the last decade (Boulton 2000). In addition, most of the exchange occurred in hyporehich zone situated in the bottom layer of saturated sediments and river banks. So, hyporehich zone alters the water flow, microbial and chemical processes through the transformation of the decomposed organic matter, consuming oxygen, nutrients, and other activities (Boulton 1993). Over exploitation of groundwater can hamper the hyporehich zone, algal growth, and invertebrate composition. In this study area, groundwater health has been more depleted caused by over water utilization and the presence of recharge resistance such as dense settlement sites and crop land sites across the river bank (Bhattacharya et al. 2020b). Land use change and land cover alteration have negative impacts on groundwater potentiality in mining sites, which causes the degradation of hyporehich zone as well as river health.

Developmental density (E3)

The dynamic process has been identified in the entire evolution of the river ecosystem, which is observed as the regular process for achieving a dynamic balance between river ecosystem protection and human development (Luo et al.

2018). Socio-economic development density is to be a key hindrance to river health as determined by a contradiction between the protection of riverine ecosystem and human activities. In respect of human service demand, long-term harmonious relationships depicted the generation of several problems from the ongoing human development and river health. In Kangsabati River, the construction of Mukutmonipur dam and Anicut dam, six bridge construction, weirs, rapid industrial development, and urban pollution are causes of the gradually deteriorating river ecosystem and basin water environment (Mura and Gope 2020).

Assessment index system

Water quality (B3) and pollution level (B4)

Interaction amongst the chemical, biological, and physical components helps to comprehensively determine the various attributes like water quality (Yang et al. 2018). Physicochemical parameters (PPs) i.e. salinity, dissolved oxygen (DO), electric conductivity (EC), total dissolved solids (TDS), and pH along with major cations (Mg^{2+}) and anions (NO_3^-) are controlled the composition of surface and groundwater water quality (Sharma et al. 2014; Bhattacharya et al. 2019c). Moreover, PPs like DO, P^H , and NH_3^- are used to measure the pollution index for detecting the intensity of pollution level and the ratio of major pollutants (Yang et al. 2018).

River meandering degree (C4)

The meandering degree reflects the natural curvature of the river as well as the flow continuity of different structures and functions; however, channel meandering has been intensively modified caused by navigation, flooding, over agricultural irrigation, and straightening construction for railways and roads (Yang et al. 2018). Meandering does not only demonstrated the channel planform change but also reveals the entire morphological responses name as sediment transition, biotic and energy exchange, longitudinal connectivity, and aquatic habitat diversity. The meandering degree is measured by taking two points from the channel of the bed along the straight and middle lines (Friend and Sinha 1993). In this study, the maximum meandering degree is concentrated along the middle and lower course than the upper course. Nonetheless, intensive sand mining can inversely change of meandering degree to interrupt the erosion and deposition sequences.

Biodiversity index (D1, D2, D3, D4, D6)

River ecosystem health is effectively determined using biological indices especially aquatic organisms, i.e. micro

invertebrates (Smith et al. 1999), algae (Poikane et al. 2016), fish (Karr 1981), and plankton (Reynolds 2003). These indices are considered as crucial indicators for accessing or evaluating the health connotation (Cheng et al. 2018). Micro invertebrates are important biological indicators due to providing their sedentary behaviour, ubiquitous nature, quick sampling, identification, and long life cycle (Birk et al. 2012). In the present study, species diversity and richness in the aquatic community have been deteriorated caused by massive instream sand mining. Thus, maximum habitat degradation occurred in mining sites than in sandbar sites over the course.

Weight assignment of the river health indicators

AHP-based weight assignment for MCDM

AHP is a more effective practical cum quantitative and qualitative analysis-based multi-criteria decision-making method as developed by Saaty (1977) to significantly explain the non-sequential relationship amongst the target criterion. In this study, a pair-wise comparison was greatly supported to conduct the AHP process with the taking of the overall goal from twenty RHR criteria, sub-criteria, and a judgment matrix. Therefore, $Wn \times n$ is expressed as follows:

$$W = \begin{bmatrix} \mathcal{O}_{11} & \mathcal{O}_{12} & \mathcal{O}_{1n} \\ \mathcal{O}_{21} & \mathcal{O}_{22} & \mathcal{O}_{2n} \\ \mathcal{O}_{n1} & \mathcal{O}_{n2} & \mathcal{O}_{nn} \end{bmatrix}_{n \times n} \tag{1}$$

where \mathcal{O}_{ij} states the relative importance between two indicators following linguistic term-based fuzzy number, i.e. equal important (1), weakly more important (3), strongly more important (5), very strongly more important (7), absolutely more important (9), and median value between two adjacent judgments (2, 4, 6, 8).

Finally \mathcal{O}_{ij} was secured the following conditions according to Eq. 2.

$$X(x_{ij}) = \begin{cases} x_{ij} > 0 & (i, j = 1, 2, \dots, n) \\ x_{ii} = 1 & (i = 1, 2, \dots, n) \\ x_{ij} = 1/x_{ji} & (i, j = 1, 2, \dots, n) \end{cases} \tag{2}$$

Then, maximum eigenvalue and eigenvector of matrix were calculated after the computation of root mean square as follows:

$$y_j = \left(\prod_{j=1}^n \mathcal{O}_{ij} \right)^{\frac{1}{n}} \quad (i, j, = 1, 2, \dots, n) \tag{3}$$

$$W_j = \frac{b_j}{\sum_{k=1}^n b_k} \tag{4}$$

Therefore, it can be said that the judgment matrix is greatly influenced by expert knowledge and performance (Si et al. 2020), whereas the consistency test is most effectively used to check the matrix for ensuring the credibility of each indicator according to Eq. 6. In the case of C.R. < 0.1, the judgment matrix is more acceptable, while in the case of C.R. > 0.1, the judgment matrix must be needed to reassign until the passing of the consistency check. The following equation was used to calculate consistency ratio (C.R.):

$$C.R = \frac{\lambda_{max}}{(n - 1)R.I} \tag{5}$$

where C.R. means consistency ratio, λ_{max} denotes maximum eigenvalue of the judgment matrix, n states order number of matrix, and R.I. indicates average value of random consistency indicator ranges of 0, 0.513, 0.893, 1.119, 1.249, and 1.345 as corresponded with order number of 2, 3, 4, 5, 6, and 7, respectively. The specific calculated equation of eigenvalue is as follows:

$$\lambda = \frac{1}{n} \sum_{i=1}^n \left(\sum_{j=1}^n \frac{Q_{ij} W_j}{W_i} \right) \quad (i, j = 1, 2, \dots, n) \tag{6}$$

Entropy-based weight assignment for MCDM

Entropy evaluation process was adopted for accurately assigning the weight of each indicator based on their relative importance and functional role (Zou et al. 2006; Zhu et al. 2020). In present research, entropy weight assignment for twenty indicators has been calculated within three steps for finding their harmonic relationship as follows:

(1) Relational matrix normalization.

At first, relational matrix normalization was calculated through the transformation from analogous to normalization and then conducted the process of entire performance values for ensuring the conversion from every alternative into a specific comparability sequence (Kuo et al. 2008). Thus, relational matrix (R_{mn}) was converted into comparability sequence matrix (Q_{mn}) by the following equation:

$$R_{mn} = (A_{ij})_{(m \times n)} \text{ converted to } Q_{mn} = (B_{ij})_{(m \times n)} \tag{7}$$

where $R_{mn} = (A_{ij})_{(m \times n)}$ denotes average indicator matrix; $Q_{mn} = (B_{ij})_{(m \times n)}$ indicates normalized matrix; i is considered as 1, 2, ..., n ; j is expressed as 1, 2, ... n

$$B_{ij} = \begin{cases} \frac{A_{ij} - \min(a_j)}{\max(a_j) - \min(a_j)} & \text{for efficiency indicator} \\ \frac{\max(a_j) - A_{ij}}{\max(a_j) - \min(a_j)} & \text{for cost indicator} \end{cases} \tag{8}$$

(2) Entropy computation of each indicator.

Based on entropy information analysis, value of m indicators and n assessment was calculated for assessing the entropy information (Sadat et al. 2020) as follows:

$$H_j = -\frac{1}{\ln(n)} \sum_{j=1}^m f_{ij} \times \ln(f_{ij}) \tag{9}$$

where H_j means entropy value of j th indicator and $f_{ij} = \frac{B_{ij}}{\sum_{j=1}^n B_{ij}}$ (Qiu, 2011).

If $f_{ij} = 0$, $\ln(f_{ij})$ is regarded as no mathematical meaning; therefore, f_{ij} can be redefined after rearrangement as follows:

$$f_{ij} = \frac{B_{ij} + 0.0001}{\sum_{j=1}^m (B_{ij} + 0.0001)} \tag{10}$$

(3) Weight assessment of each indicator.

Equation 12 was used to determine the entropy weight of j th as follow:

$$W_j = \frac{1 - H_j}{m - \sum_{i=1}^m H_j} \quad (0 \leq W_j \leq 1) \tag{11}$$

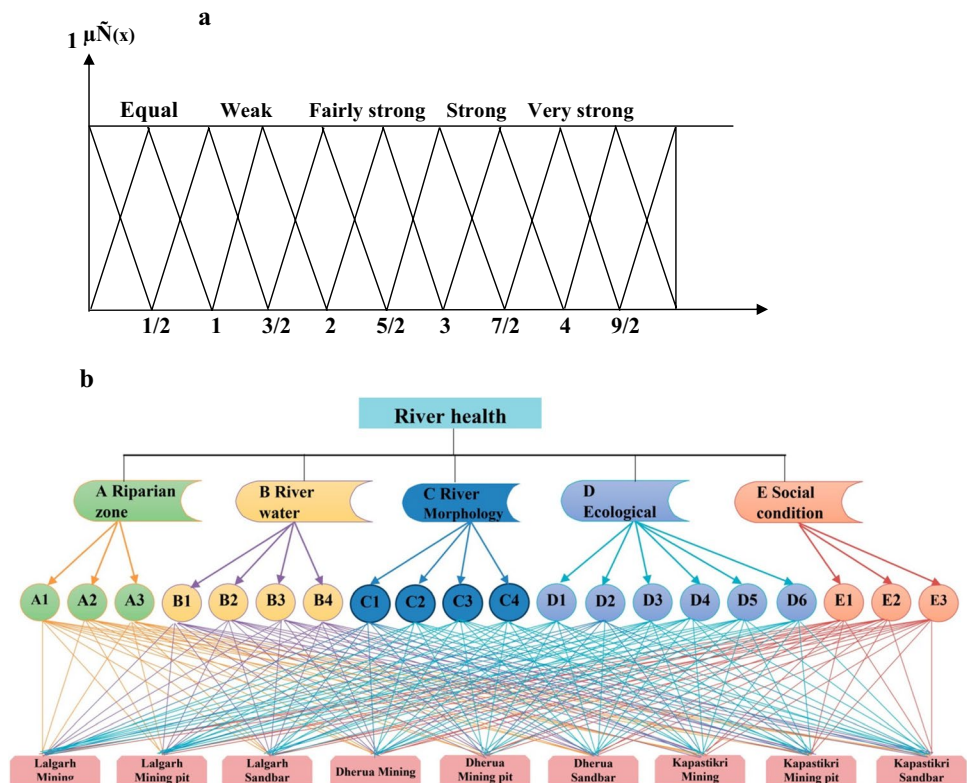
where $\sum_{j=1}^m W_j = 1$, W_j denotes weight of j th indicator, and m means number of the indicator.

River health assessment methods

Fuzzy set theory for river health assessment

Fuzzy set theory was applied to get a decision about multi-functional RHR through solving several problems like uncertain knowledge about the indicators. This theory is originally arranged as a crisp setup where considerable value ranges of 0 and 1 (Wang et al. 2020). In this setup, 1 denotes the full membership function, whereas 0 indicates the non-membership function. With the understanding of fuzzy situation, triangular fuzzy number (TFN) was employed to take a decision for multiple purpose and situation of health indicators (Shukla

Fig. 3 Fuzzy structure. **a** Fuzzy membership functions for linguistic values and **b** decision hierarchy for river health selection criteria at nine sites



et al. 2014). Subsequently, a linguistic scale of importance was used to assign the TFN rating scale in multi-criteria decision making (MCDM) problems as follows equal (1, 1, 1), weak (1/2, 1, 3/2), fairly strong (3/2, 2, 5/2), very strong (5/2, 3, 7/2), and absolute (7/2, 4, 9/2), respectively (Fig. 3a). Generally, the fuzzy number \tilde{a} is expressed through trio $X=(x, y, z)$. Therefore, the membership of TFNs was calculated according to this equation (Kaganski et al. 2018).

$$\mu_x(X) = \begin{cases} 0, & x < 1 \\ \frac{x-x}{y-x} & x \leq x \leq y \\ \frac{z-x}{z-y} & y \leq x \leq z \\ 0, & x > 0 \end{cases} \quad (12)$$

(1) Fuzzy analytical hierarchy process (FAHP)

Fuzzy-AHP is a very effective comprehensive MCDM evaluation approach for spoiling the decision problem and then converted into a very small problem using a sophisticated comparison matrix on the basis of TFNs (Solangi et al. 2019). So, TFN was constructed for making a pair-wise comparison matrix to determine the multifunctional threshold state amongst the river health indicators at different segments (Fig. 3b). With the following qualitative health indicators, four

different levels were considered, i.e. very high, high, general, and low as the corresponding value of $f(1)=1, f(2)=0.75, f(3)=0.5,$ and $f(4)=0.25$. According to expert feedback, all those values were converted into fuzzy numbers as follows:

$$y_{ij} = [d(1)_{ij}, d(2)_{ij}, d(3)_{ij}, d(4)_{ij}, d(5)_{ij}] \quad (13)$$

where $d(x)_{ij}(x=1, 2, 3, 4, 5)$ denotes to the expert feedback proportion at different levels. Qualitative health indicator value was determined based on the weighted average method as follows:

$$r_{ij} = \sum_{a=1}^5 [d(X)_{ij}f(X)] (i = 1, 2, \dots, n) \quad (14)$$

TFN was employed to measure the membership function of the twenty river health quantitative indicators according to this equation. Subsequently, fuzzy relation matrix (W) was computed as follows:

$$R = \begin{bmatrix} RIX_1 \\ RIX_2 \\ RIX_3 \end{bmatrix} W = \begin{bmatrix} r_{11} & r_{12} & r_{1p} \\ r_{21} & r_{22} & r_{2p} \\ r_{n1} & r_{n2} & r_{np} \end{bmatrix}_{n \times p} \quad (15)$$

where r_{ij} denotes the membership degree of every evaluated object in respect to fuzzy subset from indicators X_i .

Then, W and R , both matrixes, were combining used to evaluate the vector B with the following of appropriate fuzzy operator as:

$$B \triangleq (b_1, b_2, \dots, b_p) = W \circ R = (w_1, w_2, \dots, w_n) \circ \begin{bmatrix} r_{11} & r_{12} & r_{1p} \\ r_{21} & r_{22} & r_{2p} \\ r_{n1} & r_{n2} & r_{np} \end{bmatrix} \quad (16)$$

At the final stage, best alternative was selected based on maximum membership principle as follows:

$$b_r = \max_{1 \leq k \leq p} \{b_k\} \quad (17)$$

(2) Fuzzy TOPSIS

To detect the multifunctional threshold state amongst the health indicators, Fuzzy TOPSIS was constructed to easily solve the problems of decision making in uncertain data using the fuzzy number from the triangular membership function (Krohling and Campanharo 2010; Nadaban et al. 2016). With the following fuzzy set in the weighted normalized fuzzy-decision matrix of $\hat{P} = [\hat{P}_{ij}]_{m \times n}$, $i = 1, \dots, m$ and $j = 1, \dots, n$ both were generated by the multiplying of a normalized fuzzy-decision matrix with its associated weights. Therefore, the weight of the fuzzy normalized value as \hat{P}_{ij} was computed according to this formula as follows:

$$\hat{P}_{ij} = w_i \times P_{ij} \quad (18)$$

F-TOPSIS was formulated with six steps by the following equations:

Step 1: This step has been involved to identify the positive ideal solution A^+ (benefits) and negative ideal solution A^- (cost) as given by:

$$A^+ = \left(P_{1_1}^+, P_{1_2}^+, \dots, P_{1_m}^+ \right) \quad (19)$$

$$A^- = \left(P_{1_1}^-, P_{1_2}^-, \dots, P_{1_m}^- \right) \quad (20)$$

where $1_{\hat{P}_{ij}^+} = (\max 1_{\hat{P}_{ij}^+} \in J_1; \min 1_{\hat{P}_{ij}^+} \in J_2)$ and $1_{\hat{P}_{ij}^-} = (\min 1_{\hat{P}_{ij}^-} \in J_1; \max 1_{\hat{P}_{ij}^-} \in J_2)$, and J_1 and J_2 represent the criteria benefit and cost, respectability.

Step 2: Second step was comprises to calculate the distance of every alternative in respect to various members. To identify the distance of A_i alternative from the positive ideal solution of the group member M_1 , $1d_1^+$ was obtained by:

$$1d_1^+ = \sum_{j=1}^n d(1_{\hat{P}_{ij}^+}, 1P_j^+), \text{ with } i = 1, \dots, m; l = 1, \dots, L \quad (21)$$

Step 3: As like positive ideal solution distance, the distance of A_i alternative was obtained negative ideal solution of member M_1 , $1d_1^-$ was obtained by:

$$1d_1^- = \sum_{j=1}^n d(1_{\hat{P}_{ij}^-}, 1P_j^-), \text{ with } i = 1, \dots, m; l = 1, \dots, L \quad (22)$$

where distance of $d(\hat{P}_{ij}, \hat{P}_j^+)$ in between two fuzzy members was measured as follows:

$$d(\hat{a}, \hat{b}) = \sqrt{\frac{1}{3} [(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2]} \quad (23)$$

Step 4: To determine the relative closeness for every alternative A_i based on positive ideal solution as follows:

$$\delta_i = \frac{di^-}{di^+ + di^-} \quad (24)$$

Step 5: Relative closeness was used to assign the rank of alternatives; hence, higher value of δ_i is selected for best alternative. Moreover, this alternative selection is based on closing distance to the positive ideal solution.

Step 6: Final step was comprises to priority the rank amongst the entire health indicators for selection of the best indicator according to the order of δ_i value.

AHP and entropy weight-based MCDM models

(1) VIKOR method

Vise Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) is a crucial approach for multi-criteria decision making through the solving of problems with the associating of incompatible and incompatible standards (Opricovic and Tzeng 2004). With the application of VIKOR, health indicators were assigned in ranking order, and then the best indicator was selected to fulfil the aim using this equation (Bhattacharya et al. 2020b).

$$Q_j = V \times \frac{(S_j + S^+)}{(S^- + S^+)} + (1 - V) \times \frac{(R_j - R^+)}{(R^- - R^+)} \quad (25)$$

where S^+ means minimum value, $\text{Min}_j S_j$; S^- means maximum value, $\text{Max}_j S_j$; R^+ means minimum value, $\text{Min}_j R_j$; R^- means maximum value, $\text{Max}_j R_j$; and V means weight which is measured by the maximum agreement of the group.

(2) SAW method

Simple additive weighting (SAW) is an effective MCDM method to assign the score in every health indicator obtained by aggregating values in different criteria. After the construction of decision matrix, every criteria score was assigned with the taken relative weights (Sargaonkar et al. 2011). Then final data integration process was completed by acquiring from final score value of every option (K_i) as follows (Ameri et al. 2018; Bhattacharya et al. 2020b):

$$K_i = \sum P_{ij} \times W_j \tag{26}$$

(3) COPRAS method

Complex proportion assessment of alternatives (COPRAS) is regarded as a new effective MCDM technique, which was used to find out the superiority of one alternative over another along with making a comparison in the healthy alternatives based on their importance and utility degree (Zavadskas et al. 2009). Hence, COPRAS was applied to determine the maximum and minimum criteria assessment for considering one criterion (Hezer et al. 2021). To estimate the final weights of all alternatives, COPRAS was estimated according to this equation.

$$C_i = S_j^+ + \frac{S_{min}^- \sum_{j=1}^n S_j^-}{S_j^- \sum_{j=1}^n \frac{S_{min}^-}{S_j^-}} = S_j^+ + \frac{\sum_{i=1}^n S_j^-}{S_j^- \sum_{i=1}^n \frac{1}{S_j^-}} \tag{27}$$

where S_{min}^- means minimum value, S_j^- means maximum index, and S_j^- means minimum index.

(4) WASPAS method

WASPAS method is a new scientific method based on weighted sum model (WAS) and weighted product model (WPM), which was proposed by Zavadskas et al. (2012). To successfully establish a better accuracy in comparison to the accuracy of other MCDM methods, final calculation of WASPAS was computed for assessing and sorting of health alternatives as follows (Deveci et al. 2018):

$$WPS_i = 0.5 \sum_{j=1}^n \bar{x}_{ij} + 0.5 \prod_{j=1}^n \bar{x}_{ij} \quad i = \overline{1, m}; j = \overline{1, n} \tag{28}$$

In the supplementary section, VIKOR, SAW, COPRAS, and WASPAS methods are step-by-step detail explained along with presenting the output values of these MCDM methods in tabular form.

Integration of river health proposed methods

Borda was used for combining the proposed ranking method or integrating the proposed method. This method is implemented after the construction of diagonal matrix as $m \times m$ to express the row to column with respect to number of wires (Ghaleno et al. 2020). Based on matrix arrangement, boards are encoded with M if the number of this technique is high, while boards are encoded with X if number of votes is equal or column is in line. In this research, row number of boards in every row was assigned based on ranking order which means higher number belongs to win and higher rank was calculated using copy writing method following not only bets number but also taken of losses number for every indicator at segment level. Thus, ranking order can be reduced through the differentiation between boards (Opricovic and Tzeng 2004).

On the other hand, root-mean-square method was applied to obtain the closest MCDM method for getting the final result of health status as follows:

$$RMSE = \sum_{i=1}^n (y_i - f(x_i))^2 \tag{29}$$

y_i refers to the final rank; $f(x_i)$ is obtained through the applying of every multi-index decision-making method.

Performance of application MCDM models

In this research, percentage change and intensity change both were considered to validate the river health assessment methods as well as find out the best suitable method amongst them (Badri 2003; Ameri et al. 2018; Bhattacharya et al. 2020b).

(1) Percentage change

This method was employed for assigning rank order in different section of river segment with the respect of different methods as follows:

$$\Delta P = \frac{N - NN_{constant}}{N} \times 100 \tag{30}$$

where ΔP means percentage of changes, N indicates total alternative number, and $NN_{consistent}$ states the alternative numbers of same rank.

(2) Intensity change

To make a comparison amongst the using techniques, intensity change find out the actual rank of every indicator in different sections as obtained by following equation.

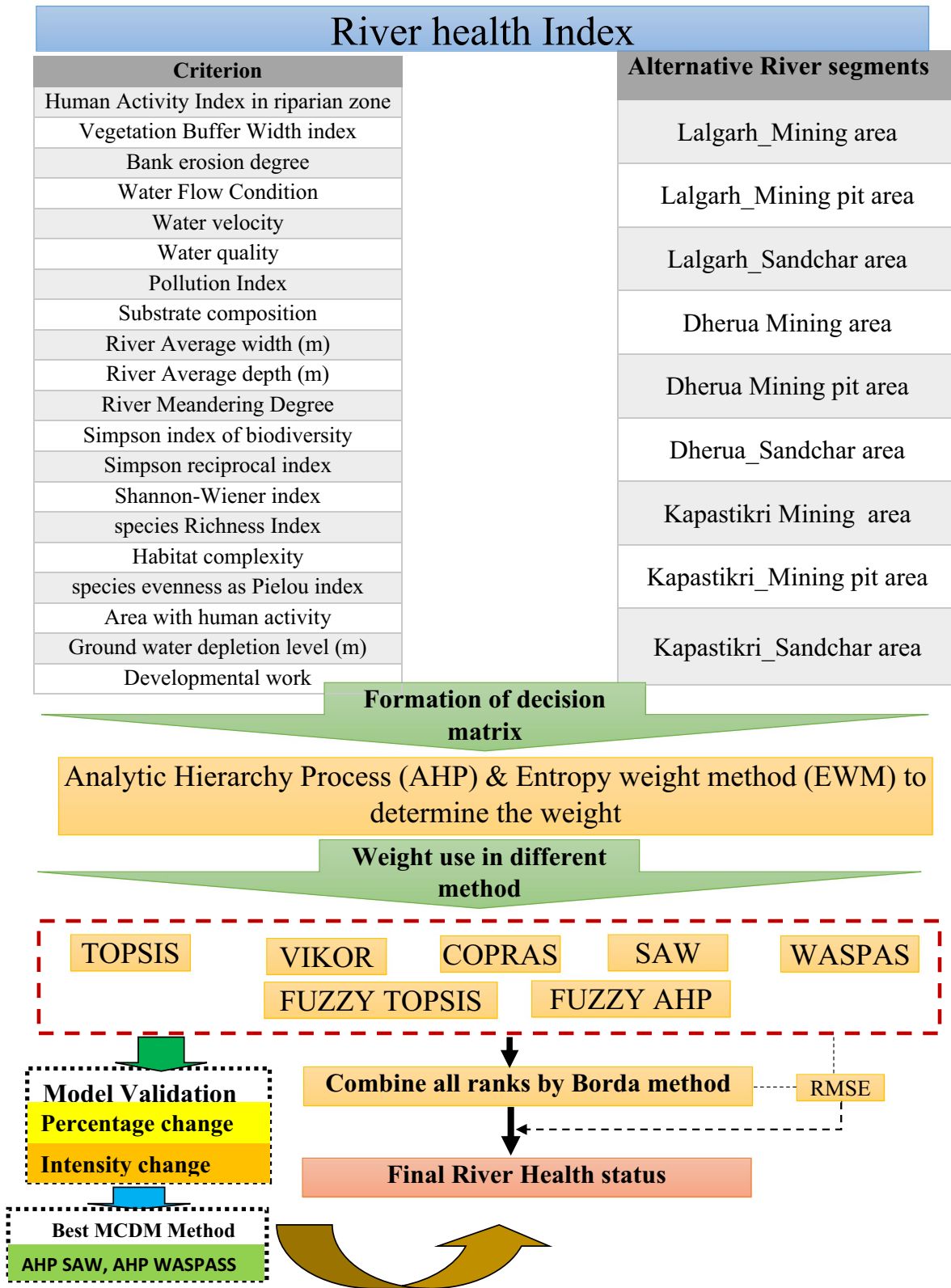


Fig. 4 Methodological framework for multifunctional resilience of river health assessment in Kangsabati River

$$\Delta I = \frac{\sum_{i=1}^N \frac{\text{rank } i (r1)}{\text{rank } i (r2)}}{N} \quad (31)$$

In this context, ΔI refer to intensity change, $r1$ represent 1st method of alternative rank, and $r2$ indicate 2nd method of alternative rank.

Finally, it can be stated that the entire methodological framework helps to determine the resilience capacity of river health in respect of HSDs (Fig. 4).

Result

Relative weight assignment of indicators

AHP weight method is adopted to determine the relative importance of each indicator in Fig. 5 where the weight scores of riparian zone feature (A), river water condition (B), river morphology and structure (C), ecological structure (D), and social structure (E) are given of 0.176, 0.333, 0.098, and 0.266, respectability. Consistency index (CI) in comparison matrix table of A, B, C, D, and E groups are 0.010, 0.020, 0.050, 0.000, and 0.010; however, incompatibility rate of final matrix in this study is acceptable for lowering value (0.090) than 0.1 (Saaty 1977). In line with results of Yang et al. (2018), Zhao et al. (2019), Sadat et al., (2020), and Wang et al. (2020), high weight score is assigned to water quality (0.163), bank erosion degree (0.111), and pollution index (0.102) for their intensive influences on river health, whereas low score is assigned to river meandering degree (0.015), groundwater level (0.015), and Simpson reciprocal index (0.019) for their least impact on health level (Fig. 5).

On the other hand, the entropy-based weight of twenty indicators for nine sample sites was estimated separately as shown in Fig. 5 which denotes every attribute significant role to the rivers. Maximum weight values are given to development density (0.091), groundwater level (0.0695), and land use density (0.0656) for their much-controlled role on health resilience (Table 3). On contrary, minimum values are considered as substrate composition (0.035), bank erosion degree (0.041), and Simpson reciprocal index (0.0413) for their less control capacity to health level. Therefore, it is interesting that AHP and entropy both weights have given contradictory scores for responsible indicators of river health. For this reason, AHP and entropy-based MCDM models including two fuzzy techniques were applied to estimate the proper rank of indicators along with finding out the threshold limit of these indicator responses.

Assessment indicator score

Score of riparian health indicators (A)

In riparian zone feature, maximum concentration of encroachment activity near riparian corridor (A1) observed in all mining Sections (9 m) causes for over growing poor to very poor health state, but encroachment activity is far away in sandbar Sections (11 m) which increases health potentiality. Although overall encroachment area in three segments has now reaches to unhealthy level, A2 reveals that vegetation buffer in riparian corridor of all sections has much lower except Kapastikri sandbar section with a low average value (36.25 m). In A3, all section of Dherua and Kapastikri segments faces a critical to unhealthy situation due to high magnitude bank erosion (Fig. 6a). Average value of erosion degree is highly dominated in mining and pit Sections (47%) than sandbar Sections (37%). It is a point that all indicators of riparian zone are more susceptible to healthy ecosystem in mining and pit sections of middle and lower segments.

Score of river water condition (B)

In river flow conditions, B1 ranges from 0.60 (Dherua sandbar section) to 0.15 (Kapastikri pit section) with an average of 0.32. Overall result of B1 indicates that poor flow condition is highly dominated in mining and pit sections than sandbar sections (Fig. 6b). Poor flow condition is not satisfied for ecological demand, and consequently, low water flow creates a hindrance to health potentiality (Sadat et al. 2020). The value of B2 gradually downed from Lalgah (1.7 m/s) to Kapastikri segment (0.82 m/s). Average value of B2 (1.13 m/s) provides the significant health level in the entire river while monsoonal peak flow from July to October and low base flow from December to April hampered the velocity requirement for ecological flow satisfaction (Bhattacharya et al. 2021). In terms of water quality, B3 demonstrated that good water quality is observed in sandbar Sections (41) than in mining (50) and pit Sections (63) of all segments except Dherua segment where overall water quality is quite good (27.20). In case of pollution level, B4 is highly concentrated in mining Sections (1.20) for significant pollution level and lowly concentrated in sandbar Sections (1.04) for moderate pollution level (Fig. 6b). Moreover, average value of pollution index (1.15) revealed that significant pollution level dominated throughout the river. Over growing mining activities have negative impacts on water quality and also expanded the negative consequences on the ecosystem in Kangsabati River; hence, habitat suitability gradually degraded (Bhattacharya et al. 2020c).

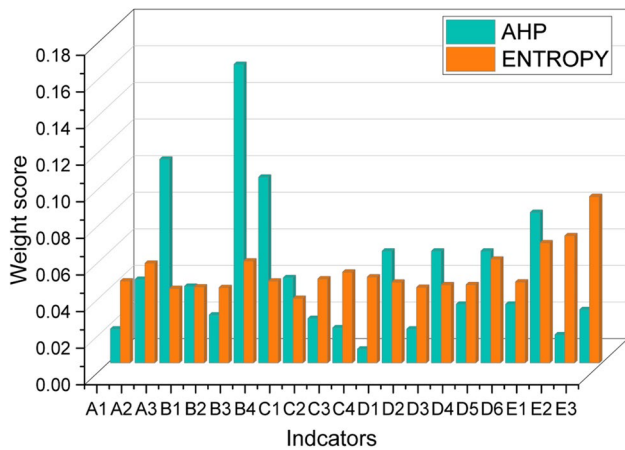


Fig. 5 Weight assigning to every river health indicator using AHP and Entropy methods

Score of substrate composition and hydromorphic health indicators (C)

Substrate composition (C1) in Lalgarh segment (0.30 mm) signified the well healthy level, but this composition gradually reduces the health level in the Dherua (0.18 mm) and Kapastikri (0.08 mm) segment (Fig. 6c). In terms of composition intensity, dense substrate generally forms in sandbar sections than in mining and pit sections of river. Average width (C2) increased the health resilience in Dherua (314 m) than Kapastikri (258 m) and Lalgarh (257 m) segments, while maximum width is recorded in mining Sections (387 m) and minimum section recorded in sandbar Sections (191 m). Similarly, average depth (C3) revealed that depth increases in mining and pit Sections (1.32 m) but decreases in sandbar Sections (0.97 m). Both results demonstrated that instream mining enhanced the spatial extant of river habitat perimeters, but huge sedimentation in sandbar sections is narrowing the habitat realms. In respect to planform change, average value of meandering degree (C4) gradually increases from Lalgarh (1.54) to Kapastikri segment (1.6),

whereas instream mining reduces meandering degree in the entire river through the increasing of average width and depth. Overall results of substrate composition, hydraulic geometry, and planform denoted that excessive human service demands like sand mining interrupted the geomorphic health status.

Score of ecological health indicators (D)

With the application of biodiversity indices on 154 species as collected from three segments of Kangsabati River during 2016–2017, Simpson index of diversity (D1) and Simpson reciprocal index (D2) are highly concentrated in pit sections (D1 0.86, D2 7.70) and sandbar sections (D1 0.84, D2 6.62), but both indices are reaches at the critical state to poor level in mining sections (D1 0.79, D2 5.20). The Shannon–Wiener index (D3) in all sections is situated at the poor level (< 1.60) except Dherua sandbar Sections (1.66). Species richness index (D4) is very poor than that of sustainable health level in mining Sections (3.06), whereas richness increases the potentiality at the health level in pit (3.54) and sandbar Sections (3.31). Overall level of richness index is not good and also propagated towards the critical state over the segments. The value of habitat complexity (D5) is much lower than critical state of health level in pit Sections (0.45), while complexity is slightly lower than poor health level in mining (0.33) and much lower than poor level in sandbar Sections (0.23). In terms of species evenness (D6), very poor health level found in pit section of Lalgarh (1.21) and Dherua (1.20) causes high species evenness and well health level observed in sandbar section of Kapastikri (0.82) for low species evenness (Fig. 6d). Moreover, average value of D5 and D6 indicates that health level reaches at the critical to poor class over the segments. Thus, it points that all biodiversity indices including habitat complexity are suffered as critical to poor health level that means ecological indicators are crossed the resilience state throughout the course.

Table 3 Estimation of weight assignment of the river health indicators using entropy method

Indicators	<i>eij</i>	<i>dij</i>	<i>wij</i>	Indicators	<i>eij</i>	<i>dij</i>	<i>wij</i>
A1	0.668	0.332	0.045	C4	0.652	0.348	0.047
A2	0.597	0.403	0.055	D1	0.673	0.327	0.044
A3	0.698	0.302	0.041	D2	0.694	0.306	0.041
B1	0.692	0.308	0.042	D3	0.684	0.316	0.043
B2	0.695	0.305	0.041	D4	0.683	0.317	0.043
B3	0.587	0.413	0.056	D5	0.58	0.42	0.057
B4	0.668	0.332	0.045	D6	0.672	0.328	0.044
C1	0.739	0.261	0.035	E1	0.514	0.486	0.066
C2	0.66	0.34	0.046	E2	0.485	0.515	0.07
C3	0.632	0.368	0.05	E3	0.326	0.674	0.091

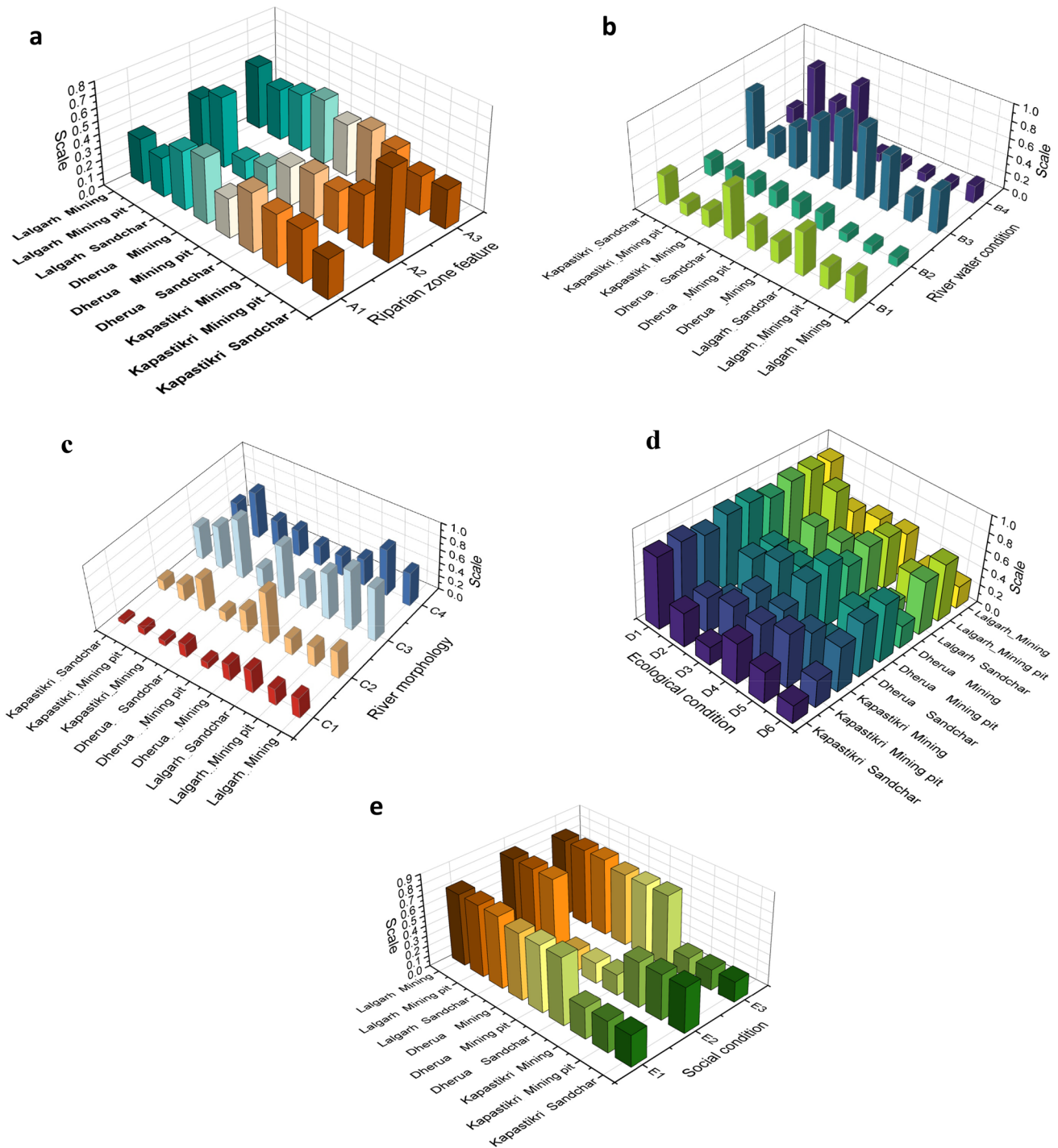


Fig. 6 Normalized value of health indicators: **a** riparian zone feature, **b** river water condition, **c** river morphology and its planform, **d** riverine ecology, and **e** social status

Score of social health indicators (E)

In the response to social structure, land use density (E1) is much higher in Kapastikri segment than Lalgarh and Dherua segments. This result demonstrated

that overgrowing construction activities along with dense population rapidly degraded the standard health level along the lower segment (Kapastikri), while low construction rate with sparse population helps to maintain the threshold state of the health resilience along

the upper segment (Lalgarh) (Mura and Gope 2020). Recently, intensive mining, ongoing urban population, and industrial activities are creating moderate pressure on river health along the middle segment (Dherua). Groundwater depletion level (E2) is not enough for well health state in particular Dherua (2.2 m) and Kapastikri segments (1.01 m) (Fig. 6e). Overall depletion level revealed that intensive sand mining deteriorated the groundwater potentiality in middle and lower segments. In addition, developmental density (E3) is progressively grown up in Kapastikri segment than Lalgarh and Dherua segments as a result very poor health status dominated in the entire lower segment. Therefore, average values of land use density, groundwater depletion level, and development density are reaches at the critical state to poor healthy level in the lower and middle segments than upper segment.

Relationship between pollution index and PPs

In respect of physicochemical parameters at segment scale, BOD, salinity, TDS, turbidity, conductivity, DO, and Mg^{2+} are highly fluctuated from 25 to 75% (range within 1.51 quartile from median) in middle and lower segments except pH which is maximum fluctuated in the upper segment (Fig. 7a, b, c, d, e, f, g, h). On the other hand, value of conductivity, turbidity, salinity, and Mg^{2+} are increasing in mining and pit sections, but these are decreasing in sandbar sections. Similarly, BOD, DO, and pH decreased in mining and pit sections, but these are increased in sandbar sections (Bhattacharya et al. 2019c). Pearson correlation matrix denoted that pollution index is positively correlated with turbidity ($r=0.98$), conductivity ($r=0.69$), and Mg^{2+} ($r=0.4$), and negatively correlated with salinity ($r=-0.13$), pH ($r=-0.14$), and BOD ($r=-0.08$) (Fig. 8). It can be said that intensive sand mining-induced PP changes effectively deteriorated the water quality

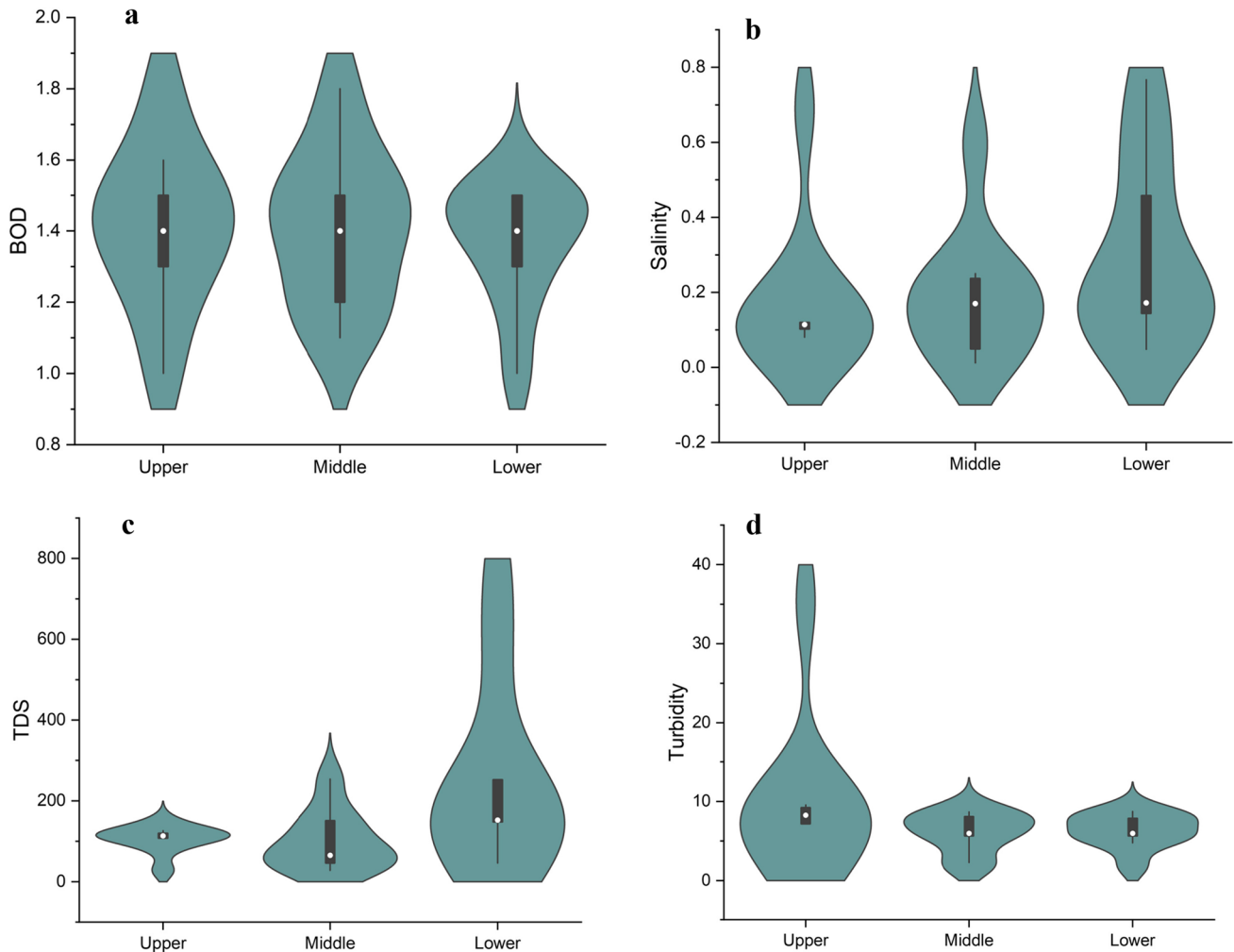


Fig. 7 Variation of water quality parameters along the upper (Lalgarh), middle (Dherua), and lower (Kapastikri) segments of Kangsabati River. **a** BOD (mg/l), **b** salinity (PPT), **c** turbidity (NTU), **d** TDS (mg/l), **e** conductivity ($\mu\text{s}/\text{cm}$), **f** pH, **g** DO (mg/l), and **h** Mg^{2+} (mg/l)

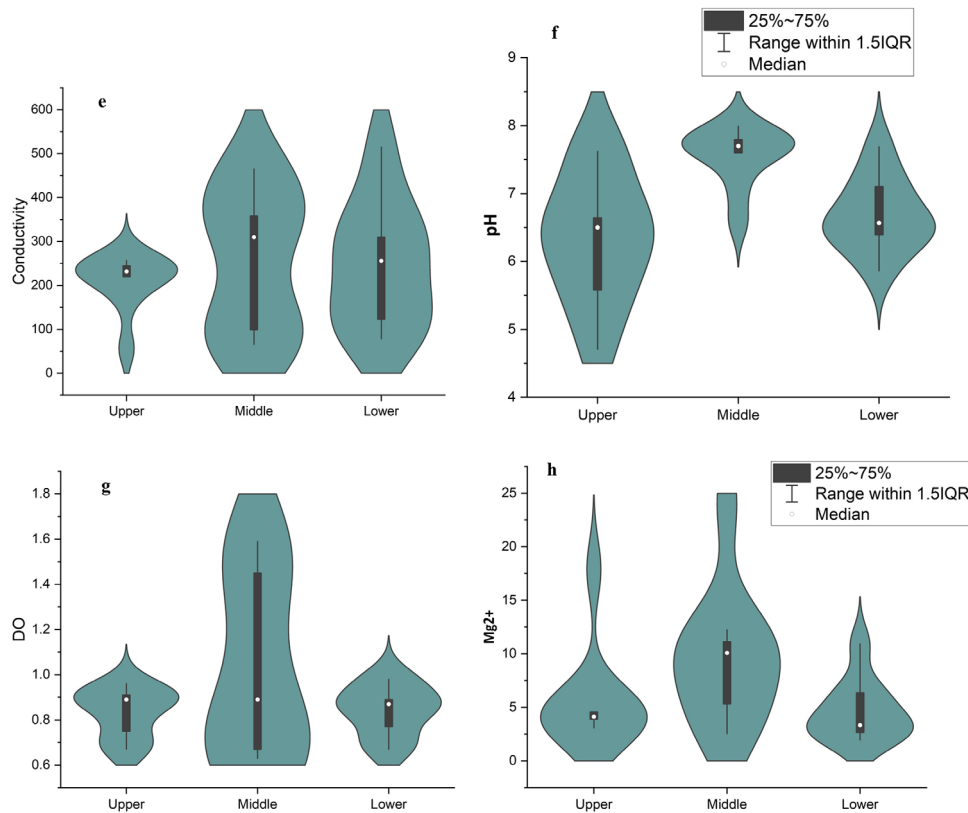


Fig. 7 (continued)

and increased the pollution level in mining and pit sections than in sandbar sections.

Relationship between hydraulic geometry and geomorphic indicators

Based on hydraulic geometry; relationships amongst the flow velocity (v), flow discharge (Q), water depth (d), and channel width (w) in different sections were obtained following equation as follows (Yang et al. 2018):

$$v = kQ^m, d = cQ^f, w = aQ^b \tag{32}$$

According to flow equation of $Q = vwd$, coefficient value of hydraulic geometry in Kangsabati River was estimated as follows:

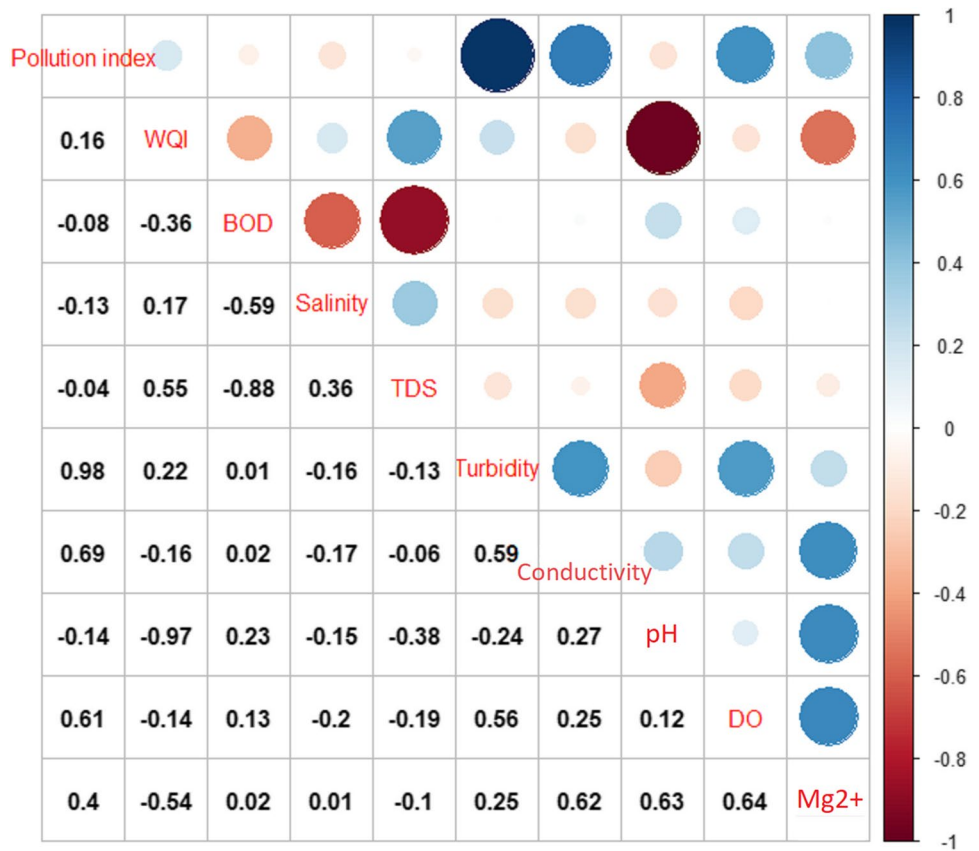
$$b + f + m = 1, a \times c \times k = 1 \tag{33}$$

where $b, f,$ and m are three exponent parameters of reach hydraulic geometry and $a, b,$ and c are three coefficient parameters of reach hydraulic geometry.

In accordance with the hydraulic geometric relationship, b/f ratio denotes how channel morphology changes from upper course to lower course, while m/f ratio demonstrated the relationship between the water

depth and flow velocity as well as change tendency throughout the channel (Navratil and Albert 2010). In present study, all highest values of b/f concentrated in mining (162.52) and pit Sections (242.42) than in sandbar Sections (118.3) that means wide-deep channel forms in mining pit sites and narrow-shallow channel forms in sandbar sites (Fig. 9a). Another coefficient of m/f was used to determine the relationship amongst the flow velocity, channel modification trend, and water depth in comparison between mining and sedimentation at segment level. In this study, all highest values of m/f in each segment are observed in sandbar Sections (2.95), while the least values are recorded in mining (0.78) and pit Sections (1.31) (Fig. 9b). In terms of channel modification, most of the hydraulic changes occurred from mining sites to pit sites than segment to segment change (upper to lower) (Fig. 9c). Thus, flow discharge and water depth are drastically increased in mining and pit sections with the generating of critical flow velocity due to occurring of wide-deep channel, while discharge, depth, and velocity are gradually decreasing in sandbar sites caused by huge sedimentation (Bhattacharya et al. 2019b).

Fig. 8 Pearson correlation matrix of water quality parameters with pollution index



Assessment of health indicators threshold using Fuzzy AHP and fuzzy TOPSIS

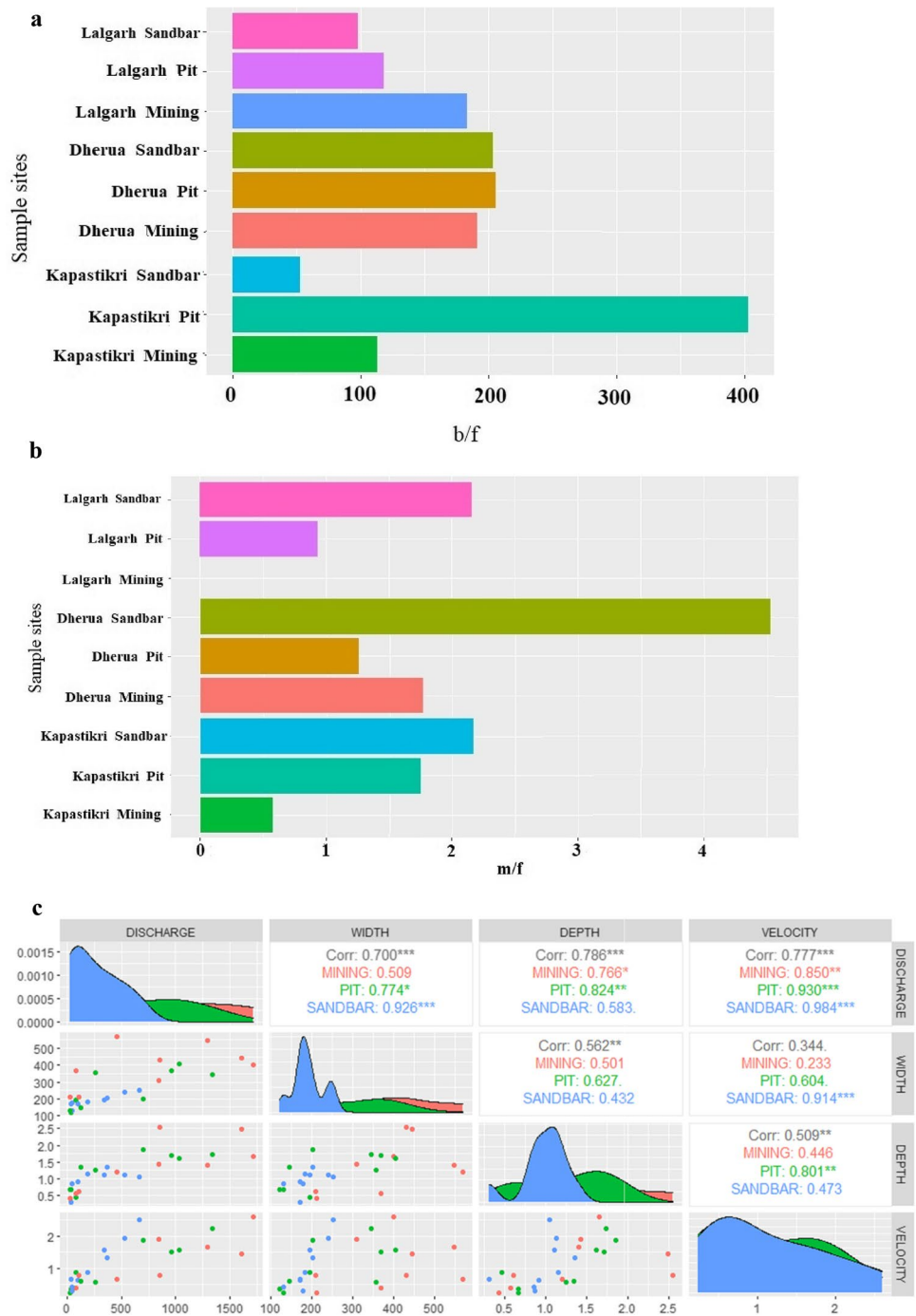
Computation results of fuzzy AHP and fuzzy TOPSIS revealed that both have almost same consistent rank order of the health status in each section (Table 5). In fuzzy method, highest score is assigned as higher priority in terms of weight and health index in each indicator and lowest score is given as lower priority. In case of fuzzy AHP, maximum compound score of Dherua pit (0.1270), Lalgah sandbar (0.1195), and Dherua sandbar (0.1189) sections are given highest rank as 1 to 3 for their well health level, whereas minimum compound scores of Kapastikri sandbar (0.09), Kapastikri mining (0.1046), and Lalgah pit (0.107) sections are given lowest rank as 9 to 7 for unhealthy level (Figs. 10 and 11a). Based on positive relation between final score and health resilience, assessment results of fuzzy TOPSIS demonstrated that maximum compound scores of Dherua pit (1.417), Lalgah sandbar (0.567), and Dherua sandbar (0.540) sections are assigned highest rank as 1 to 3. While minimum scores of Kapastikri sandbar (0.380), Dherua mining (0.421), and Lalgah pit (0.428) are assigned lowest rank as 9 to 7, respectively (Fig. 11b). It points that fuzzy-based rank assignment is same rank order in all sections except mining and pit section of Kapastikri and mining section of

Dherua; however, all except sections fall under unhealthy level as predicted by fuzzy AHP and fuzzy TOPSIS.

Assessment of health indicators threshold using AHP-based MCDM methods

The results of rank prioritization of the river health status and its potentiality at section level of Kangsabati River using AHP weight-based VIKOR, SAW, COPRAS, WASPAS, and TOPSIS methods are presented in Fig. 11b, c, d, e, f. In VIKOR model, based on negative relation between compound score and health level amongst the twenty indicators (Table 6), least compound scores of Dherua sandbar (0), Dherua pit (0.21), and Lalgah sandbar (0.25) sections are given highest rank as 1 to 3 for their potential health level, while more compound scores of Kapastikri pit (0.809), Lalgah pit (0.727), and Kapastikri mining (0.665) sections are assigned lowest rank as 9 to 7 for their unhealthy level (Table 5). Based on positive relation between final score value and health level, AHP weight-based COPRAS, SAW, WASPASS, and TOPSIS denoted that highest final score of Dherua sandbar, Dherua pit, Lalgah sandbar, and Dherua mining sections are evaluated to best rank around 1 to 4 for their high habitat potential level, but least final score of mining, pit, and sandbar sections of Kapastikri and pit section of Lalgah sections are assigned around 9 to 6,

Fig. 9 Hydraulic geometry in mining, pit, and sandbar sites of Lalgarh, Dherua, and Kapastikri segments. **a** b/f, **b** m/f, and **c** hydraulic relationship amongst the flow discharge, width, depth, and velocity



respectively. In addition, SAW and WASPAS models have same assigned rank order in nine sections except pit and sandbar sections of Kapastikri while CORPAS and TOPSIS models have slight changes in rank order. Finally, all AHP weight-based MCDM models give the well health level to Dherua sandbar, Dherua pit, and Lalgarh sandbar sections. On contrary, lowest rank or unhealthy levels are assigned to mining, pit, and sandbar sections of Kapastikri out of nine sections. Therefore, it can be said that sandbar sections of Dherua and Lalgarh segment are sustained their potential

health level, but mining and pit sections of Kapastikri are not sustained their health level. In spite of pit section in Dherua, health potentiality is well for huge natural sand and nutrient replenishment than sediment removal over the segment.

Assessment of health indicators threshold using entropy-based MCDM methods

With the application of entropy weighting in MCDM models, based on negative relation between final score and river

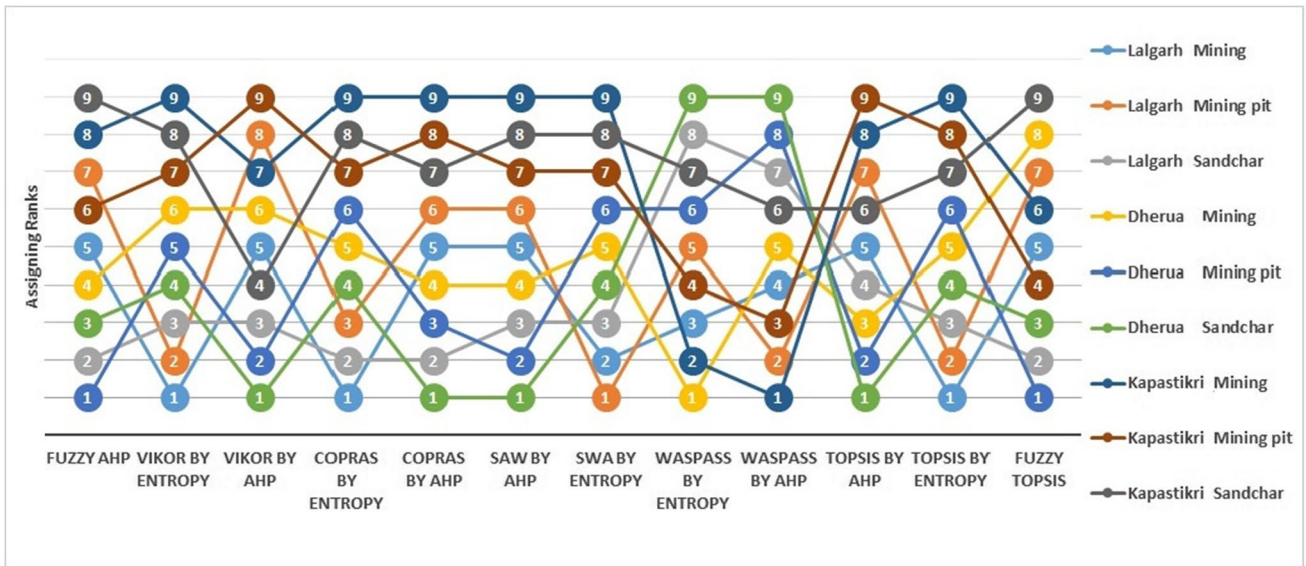


Fig. 10 Rank prioritization of recommending MCDM methods on river health assessment amongst the nine sites of Kangsabati River

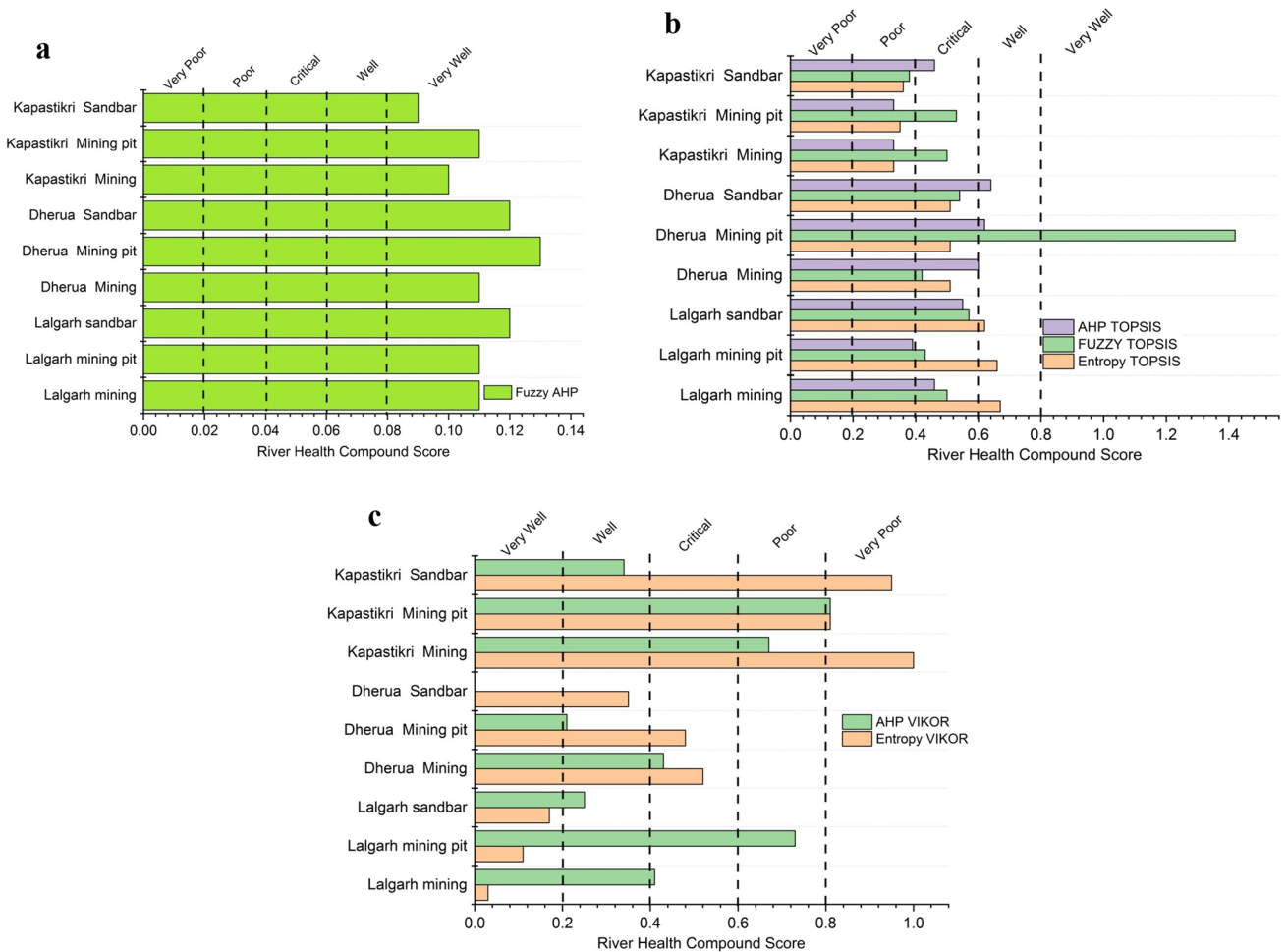


Fig. 11 Compound score of river health in nine sections: a fuzzy AHP; b entropy, AHP, and fuzzy TOPSIS; c AHP and entropy VIKOR; d AHP and entropy SAW; e AHP and entropy COPRAS; and f AHP and entropy WASPASS

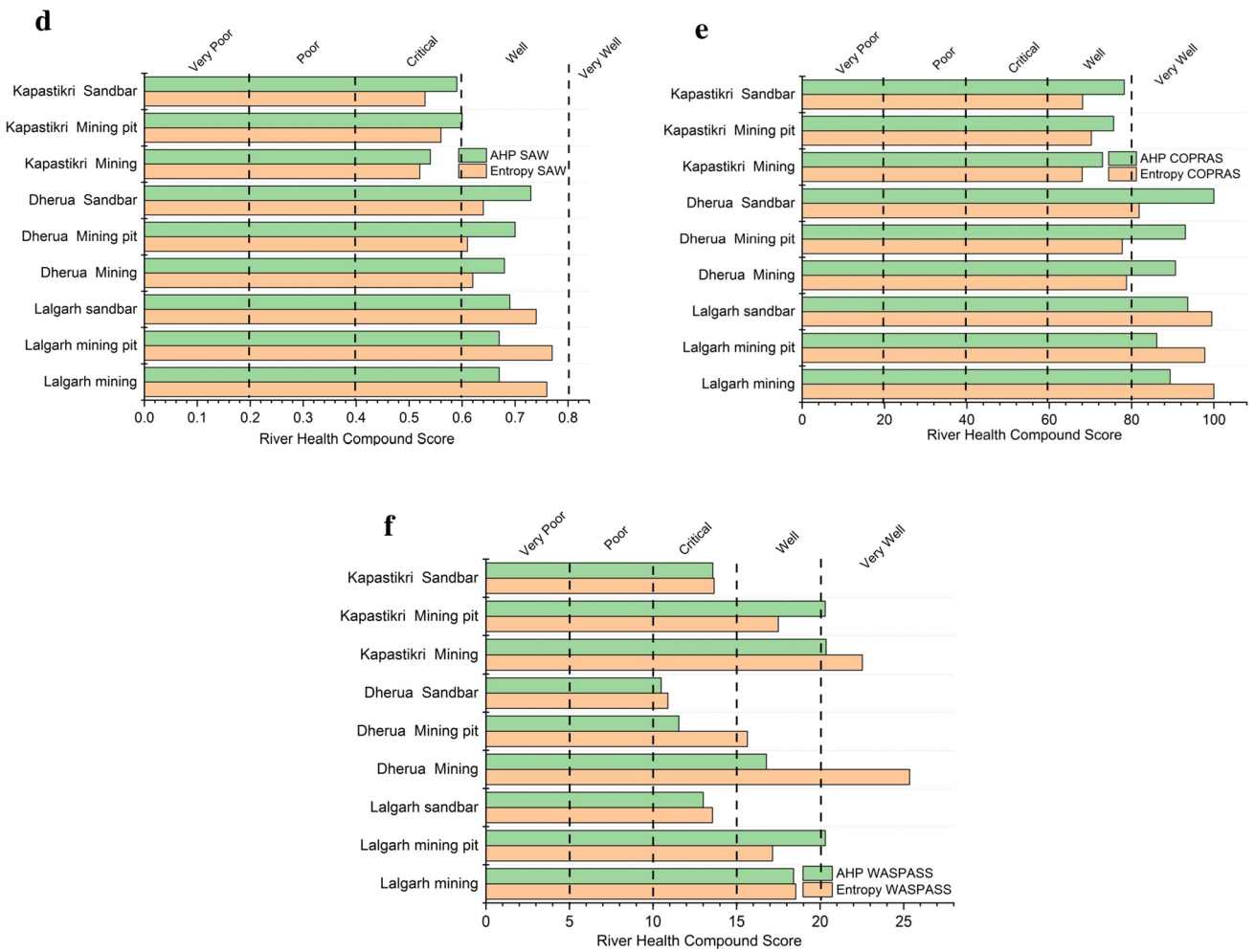


Fig. 11 (continued)

Table 4 Ranking of recommended MCDM methods in different sites using Borda test

Sample sites	Score	Average	Priority	Sample sites	Score	Average	Priority
Lalgarh Mining	73	6.083	4	Dherua Sandbar	62	5.167	5
Lalgarh Mining pit	82	6.833	2	Kapastikri Mining	40	3.333	7
Lalgarh Sandbar	76	6.333	3	Kapastikri Mining pit	31	2.583	8
Dherua Mining	54	4.500	6	Kapastikri Sandbar	30	2.500	9
Dherua Mining pit	92	7.667	1				

Table 5 Computation of total root mean square for proposing MCDM methods to river health assessment

MCDM methods	Symbol	RMSE	MCDM methods	Symbol	RMSE
Fuzzy AHP	A	2.108	Entropy SWA	G	2.055
Entropy VIKOR	B	1.886	Entropy WASPASS	H	2.055
AHP VIKOR	C	2.981	AHP WASPASS	I	2.261
Entropy COPRAS	D	2.211	AHP TOPSIS	J	2.667
AHP COPRAS	E	2.357	Entropy TOPSIS	K	2.211
AHP SAW	F	2.211	Fuzzy TOPSIS	L	2.404

Table 6 The percentage of the changes in the twelve MCDM methods compared to each others

	A	B	C	D	E	F	G	H	I	J	K	L	Average
A	100.00	100.00	88.89	88.89	66.67	77.78	100.00	100.00	77.78	66.67	100.00	33.33	88.89
B	100.00	100.00	77.78	44.44	88.89	55.56	44.44	44.44	77.78	100.00	44.44	100.00	73.15
C	88.89	77.78	100.00	100.00	77.78	55.56	88.89	88.89	55.56	55.56	88.89	88.89	80.56
D	88.89	44.44	100.00	100.00	77.78	66.67	33.33	33.33	88.89	100.00	44.44	88.89	72.22
E	66.67	88.89	77.78	77.78	100.00	44.44	88.89	88.89	22.22	77.78	66.67	77.78	73.15
F	77.78	55.56	55.56	66.67	44.44	100.00	55.56	55.56	22.22	66.67	77.78	88.89	63.89
G	100.00	44.44	88.89	33.33	88.89	55.56	100.00	0.00	77.78	100.00	44.44	100.00	69.44
H	100.00	44.44	88.89	33.33	88.89	55.56	0.00	100.00	77.78	100.00	44.44	100.00	69.44
I	77.78	77.78	55.56	88.89	22.22	22.22	77.78	77.78	100.00	66.67	55.56	88.89	67.59
J	66.67	100.00	55.56	100.00	77.78	66.67	100.00	100.00	66.67	100.00	100.00	77.78	84.26
K	100.00	44.44	88.89	44.44	66.67	77.78	44.44	44.44	55.56	100.00	100.00	100.00	72.22
L	33.33	100.00	88.89	88.89	77.78	88.89	100.00	100.00	88.89	77.78	100.00	100.00	87.04

health in VIKOR model, least final scores of mining, pit, and sandbar sections of Lalgargh are given highest rank as 1 to 3 for significant well health potentiality (Figs. 10 and 11b, c, d, e, f). Contrastingly, maximum final scores of mining, pit, and sandbar sections of Kapastikri are assigned lowest rank as 9 to 7 for staying of poor health level. Based on negative relationship between compound score and health resilience in COPRAS, SAW, WASPASS, and TOPSIS models, maximum final scores of all sections of Lalgargh and sandbar sections of Dherua are evaluated highest rank order around 1 to 4 for good health condition, but all sections of Kapastikri are given lowest rank as 9 to 7 due to poor health scenario (Table 5).

Validation of MCDM model performance

With the following of integrating order of proposed techniques results, pit section of Dherua, pit, and sandbar sections of Lalgargh are considered as highest priority rank order (1–3) for potential health level, while all sections of Kapastikri are regarded as lowest priority rank order (9–7)

for poor health status (Table 4). The result clearly stated that sand mining and other anthropogenic activities are not intensively affected to health potentiality in pit sections of Lalgargh and sandbar sections of Dherua but anthropogenic hindrances including mining extreme consequences in all sections of Kapastikri. On the other hand, RMSE results revealed that entropy VIKOR and entropy SAW models have lowest values of 2 and 2.01 in terms of maximum accuracy and efficiency against the fuzzy and other MCDM models (Table 5). Therefore, both entropy models predicted rank prioritization are more acceptable than other MCDMs on the basis of river health potentiality.

On the other hand, percentage change of every method is compared to each other presented in Table 6. Low percentage change is obtained in AHP SAW (63.88%) than AHP WASPASS (67.59%), entropy SAW (69.44%), entropy WASPASS (69.44%), entropy COPRAS (72.22%), entropy TOPSIS (72.22%), entropy VIKOR (73.14%), AHP COPRAS (73.15%), AHP VIKOR (80.55%), AHP TOPSIS (84.26%), fuzzy TOPSIS (87.03%), and fuzzy AHP (88.88%), respectively. Amongst the twelve methods,

Table 7 The intensity of the changes in the twelve MCDM methods compared to each others

	A	B	C	D	E	F	G	H	I	J	K	L	SUM
A	1.00	1.52	1.20	1.44	1.16	1.13	1.64	1.62	1.98	1.17	1.53	1.04	16.42
B	1.44	1.00	1.45	1.02	1.36	1.39	1.06	1.75	1.85	1.44	1.01	1.47	16.24
C	1.14	1.58	1.00	1.50	1.05	1.04	1.76	1.82	1.99	1.05	1.58	1.18	16.70
D	1.49	1.02	1.46	1.00	1.33	1.40	1.13	1.67	1.88	1.45	1.02	1.53	16.37
E	1.16	1.47	1.06	1.40	1.00	1.02	1.53	1.69	2.07	1.04	1.47	1.22	16.12
F	1.10	1.48	1.05	1.43	1.02	1.00	1.54	1.68	2.06	1.02	1.49	1.15	16.01
G	1.53	1.06	1.49	1.09	1.37	1.42	1.00	1.68	1.81	1.47	1.06	1.57	16.55
H	1.81	1.49	2.06	1.53	2.05	2.00	1.59	1.00	1.20	1.95	1.48	1.84	20.00
I	2.01	1.48	2.13	1.56	2.10	2.11	1.36	1.34	1.00	2.11	1.47	1.98	20.65
J	1.14	1.55	1.04	1.49	1.05	1.02	1.66	1.57	2.03	1.00	1.54	1.22	16.31
K	1.53	1.01	1.47	1.02	1.36	1.42	1.06	1.67	1.86	1.45	1.00	1.58	16.44
L	1.05	1.53	1.21	1.47	1.22	1.19	1.67	1.90	1.77	1.26	1.57	1.00	16.84

AHP SAW with the least value of percentage change is considered a more efficient and accurate method for giving the rank priority at section level on the basis of health potentiality and its connotations (Badri 2003; Ameri et al. 2018).

The pair-wise comparison method has been used to determine the intensity change in each method presented in Table 7. Maximum rate of changed is observed in AHP WASPASS (20.65) followed by entropy WASPASS (20), fuzzy TOPSIS (16.84), AHP VIKOR (16.70), entropy SAW (16.55), entropy TOPSIS (16.43), entropy COPRAS (16.37), AHP TOPSIS (16.30), entropy VIKOR (16.23), AHP COPRAS (16.11), and AHP SAW (16.01), respectively. Therefore, AHP WASPASS with highest intensity change is regarded as a much more efficient and accurate method than others. According to percentage and intensity changes for fuzzy logic, AHP, and entropy MCDM validation test, it is true that AHP SAW and AHP WASPASS methods are more accurate than others due to present their best efficiency and accuracy values. Moreover, both methods have same priority rank order amongst the nine sections.

Discussion

The results of fuzzy techniques and MCDM models revealed that rank order of the river health condition in each section of Kangsabati River is not same level (Table 5); however, these models help to detect the resilience capacity of river health indicators (Deng et al. 2015; Sadat et al., 2020). Moreover, rank order of entropy weight-based MCDM models is not always the same assigned as given by AHP weight-based MCDM models. With the harmonic relationship between the river and its ecosystem, entropy-based MCDM approaches are employed to synthesize the evaluation of indicators (Sadat et al., 2020; Xue et al. 2020). On contrary, comprehensive processes of AHP-based MCDM models are used to assess the actual RHR for considering of HSDs (Luo et al. 2018). In respect of MCDM validation performance, entropy-based MCDM models are given as high priority to Lalgah segment than Dherua segments for healthy physical setup, while AHP-based MCDM models are assigned as maximum priority to Dherua segment than Lalgah segment for optimum HSDs; however, both weight methods stated to low priority rank order for Kapastikri segment due to over HSDs, respectively. Rank assignment in all entropy-based MCDM models demonstrated that the entire upper segment (Lalgah) and sandbar section of the middle segment (Dherua) have high health potentiality including enough healthy resilience, whereas entire lower segment (Kapastikri) has low health potentiality including fragmented connotations.

Huge sediment deposition increases the resilience level of damaged indicators with the increasing substrate composition, water quality, species diversity, and richness as well as less encroachment activity near riparian sites in sandbar section of Lalgah segment (Bhattacharya et al. 2020a; Bhattacharya and Das Chatterjee, 2021). Widen vegetation buffer zone, wide and deep channel, meandering channel, rich biodiversity indices, numerous species, and high habitat complexity are sustained potential habitat level in pit section of Lalgah segment. Nevertheless, lack of sediment in pit sites leads to massive bank erosion, thin substrate composition, polluted water quality, and species evenness as a result; health potentiality gradually decreases over time. Furthermore, low species diversity indices, moderate riparian vegetation buffer zone, wide and meandering channel, low species evenness, meagre land use density, and low development density including low groundwater deterioration level are provided as medium standard habitat level in Lalgah mining section. With the following overall model results, upper segment fall in medium health level but indicators in this segment are relative changes from sandbar to mining and pit sections. Therefore, it points that overall river health status in upper segment reaches the standard level in Kangsabati River.

In sandbar section of Dherua segment, entropy-based MCDM models have clarified the moderate bank erosion, poor water quality, narrow with shallow channel, and low vegetation complexity for hindrance to health standards (Bhattacharya et al. 2021), while AHP-based MCDM models signified the less encroachment activity near riparian zone, widen riparian vegetation buffer, long water flow condition, moderate water velocity, slightest pollution level, thick substrate composition, meandering channel, rich biodiversity indices, moderate species evenness, and meagre development density for enhancing the health resilience (Liu et al. 2019; Yang et al. 2018). Despite the wide and deep channel and restricted bank erosion in mining section of Dherua, maximum encroachment activity near riparian, narrow riparian vegetation buffer, low water flow, variable flow velocity, high pollution level (more fluctuated physicochemical parameters), straight channel pattern, least biodiversity indices, and species richness damage the health potentiality (Yang et al. 2018; Zeng et al. 2020; Bhattacharya and Das Chatterjee, 2021; Gupta and Gupta 2021). In addition, sediment deficiency causes intense bank erosion, high pollution level, thin substrate composition, and massive encroachment activity near riparian sites. On contrary, wide riparian vegetation buffer, good water quality, wide and deep channel, rich biodiversity, high species richness, and vegetation complex are maintained to suitable health level in pit sites of Dherua segment (Bhattacharya et al. 2019c). Contrastingly, regardless of widened riparian vegetation buffer and meandering channel pattern, massive bank erosion, least

water flow condition, and water velocity, poor water quality, meagre thickness of substrate composition, low biodiversity and species richness, slight habitat complexity, maximum groundwater deterioration level, and dense land use density including over growing development density helped to cross the resilience capacity of health potentiality in the entire lower segment (Bhattacharya et al. 2019a, b; Bhattacharya et al., 2021). Finally, it can be said that enough replenishment of sediment over the sand mining maintained the health status in upper and middle segments but massive sand mining than replenishment degraded the health resilience in mining and pit even sandbar sites of lower segment (Bhattacharya et al. 2019c).

On the other hand, some major limitations are observed in this study, i.e. certain degree of subjectivity and uncertainty in indicators assessment, none uniformly dealing, and less cross-section selection; hence, indicator system cannot provide the details information about the river health in the Kangsabati River. In addition, assessment methods are incapable of actual estimating the indicator's role in decision process. However, findings in this research also help to identify the sick health sites where most of the indicators crossed their resilience capacity. Moreover, applied MCDM models provided the threshold status of indicator for policy makers to take proper management for ecological restoration.

Conclusion

The present research has evaluated the multifunctional resilience of river health to HSDs with the consideration of twenty pressure-state-response (PSR) indicators of the riparian structure, water flow condition, channel geomorphic structure and its planform, ecological connotation, and social structure along the upper, middle, and lower segments of Kangsabati River. Indicator assessment results demonstrated that HSDs crossed the tolerated level of natural integrity of river hydraulics, morphology, ecology, and social services in Kangsabati River especially lower course. However, uncertainty and unevenly dealing with indicator assessment results along with fewer cross-sections along the upper, middle, and lower segments have made such limitations in this research. With the following of river health prioritization at section level, entropy-based MCDM models comprehensively assess the state of natural integrity indicators to acquire the harmonic relationship, while fuzzy set theory and AHP-based MCDM models accurately determined the anthropogenic pressure and its response indicators to find out the unhealthy level in lower segment and healthy level in upper and middle segments of Kangsabati River. Based on validation results through RMSE, percentage and intensity change of every entropy, fuzzy, and AHP MCDM methods in comparison to each other, entropy

SAW, AHP SAW, entropy VIKOR, and AHP WASPASS have more reliability and least error in assessing the river health resilience for over growing HSDs. On contrary, the rest of entropy and AHP MCDM including fuzzy logic have less reliability and maximum error with the integrating results of health resilience in response to HSDs at segment scale. Therefore, development of an assessment index system of the multi-functional reliability and resilience of river system integrity for HSDs including proposing validated models in this research enriched the literature on river health assessment and also helps to take effective ecological restoration management policy at unhealthy sites over the world.

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Author contribution Raj Kumar Bhattacharya: conceptualization, methodology, software, data curation, writing — original draft. Nilanjana Das Chatterjee: supervision, writing — review and editing. Kousik Das: software, visualization, investigation.

Data availability All data generated or analyzed during this study are included in this published article (and its supplementary information files).

Declarations

Ethics approval Not applicable.

Consent for publication Not applicable for that specific section.

Consent to participate All authors are approved and confirmed for submission to this journal.

Competing interests The authors declare no competing interests.

References

- Aazami J, Esmaili-Sari A, Abdoli A, Sohrabi H, Van den Brink PJ (2015) Monitoring and assessment of water health quality in the Tajan River, Iran using physicochemical, fish and macroinvertebrates indices. *J Environ Health SCI* 13(1):1–12
- Alemu T, Bahrndorff S, Pertoldi C, Hundera K, Alemayehu E, Ambelu A (2018) Development of a plant based riparian index of biotic integrity (RIBI) for assessing the ecological condition of highland streams in East Africa. *Ecol Indic* 87:77–85
- Ameri AA, Pourghasemi HR, Cerda A (2018) Erodibility prioritization of subwatersheds using morphometric parameters analysis and its mapping: a comparison among TOPSIS, VIKOR, SAW, and CF multi-criteria decision making models. *Sci Total*

- Environ 613:1385–1400. <https://doi.org/10.1016/j.scitotenv.2017.09.210>
- Badri SA (2003) Models of rural planning. Pamphlets Practical Lesson in Geography Rural Planning. Payame Noor University, p. 126
- Bhattacharya R, Dolui G, Chatterjee ND (2019a) Effect of instream sand mining on hydraulic variables of bedload transport and channel planform: an alluvial stream in South Bengal basin. *India Environ Earth Sci* 78(10):1–24
- Bhattacharya RK, Chatterjee ND, Das K (2019b) Geomorphic response to riverine land cover dynamics in a quarried alluvial river Kangsabati, South Bengal India. *Environ Earth Sci* 78(22):1–18
- Bhattacharya RK, Chatterjee ND, Dolui G (2019c) Consequences of sand mining on water quality and instream biota in alluvial stream: a case-specific study in South Bengal River India. *Sustain Water Resour Manag* 5(4):1815–1832
- Bhattacharya RK, Chatterjee ND, Das K (2020a) Impact of instream sand mining on habitat destruction or transformation using coupling models of HSI and MLR. *Spat Inf Res* 28(1):67–85
- Bhattacharya RK, Chatterjee ND, Das K (2020b) Sub-basin prioritization for assessment of soil erosion susceptibility in Kangsabati, a plateau basin: a comparison between MCDM and SWAT models. *Sci Total Environ* 734:139474
- Bhattacharya RK, Chatterjee ND, Das K (2020c) An integrated GIS approach to analyze the impact of land use change and land cover alteration on ground water potential level: a study in Kangsabati Basin India. *Groundw Sustain Dev* 11:100399
- Bhattacharya RK, Das Chatterjee N (2021) Sand mining consequences on habitat ecology, water quality and species diversity: implementing of HSI, MLR, WQI and ANN methods. In *River sand mining modelling and sustainable practice* (pp. 251–311). Springer, Cham. https://doi.org/10.1007/978-3-030-72296-8_7
- Bhattacharya RK, Chatterjee ND, Das K (2021) Assessment of habitat quality in quarried reach of alluvial river B. C. Patra et al. (eds.), *River Health and Ecology in South Asia*. https://doi.org/10.1007/978-3-030-83553-8_11
- Birk S, Bonne W, Borja A, Brucet S, Courrat A, Poikane S, Solimini A, Van De Bund W, Zampoukas N, Hering D (2012) Three hundred ways to assess Europe's surface waters: an almost complete overview of biological methods to implement the Water Framework Directive. *Ecol Indic* 18:31–41
- Boulton AJ (1993) Stream ecology and surface-hyporheic hydrologic exchange: implications, techniques and limitations. *Mar Freshw Res* 44(4):553–564
- Boulton AJ (2000) River ecosystem health down under: assessing ecological condition in riverine groundwater zones in Australia. *Ecosyst Health* 6(2):108–118
- Cheng X, Chen LD, Sun RH, Kong PR (2018) Land use changes and socio-economic development strongly deteriorate river ecosystem health in one of the largest basins in China. *Sci Total Environ* S616–617:376–385. <https://doi.org/10.1016/j.scitotenv.2017.10.316>
- Deng X, Xu Y, Han L, Yu Z, Yang M (2015) Assessment of river health based on an improved entropy-based fuzzy matter-element model in the Taihu Plain. *China Ecol Indic* 57:85–95. <https://doi.org/10.1016/j.ecolind.2015.04.020>
- Deveci M, Camtez F, Gökaşar I (2018) WASPAS and TOPSIS based interval type-2 fuzzy MCDM method for a selection of a car sharing station. *Sustain Cities Soc* 41:777–791
- Ding Y, Shan B, Zhao Y (2015) Assessment of river habitat quality in the hai river basin, northern China. *Int J Environ Res* 12(9):11699–11717
- Dutta V, Sharma U, Kumar R (2017) Assessment of river ecosystems and environmental flows: Role of flow regimes and physical habitat variables. *Clim Chang Environ Sustain* 5(1):20–34
- Feng B, Zhang M, Chen J, Xu J, Xiao B, Zhou M, Zhang M (2021) Reduction in the phytoplankton index of biotic integrity in riverine ecosystems driven by industrial activities, dam construction and mining: a case study in the Ganjiang River. *China Ecol Indic* 120:106907
- Folk RL, Ward WC (1957) Brazos River bar: a study in the significance of grain size parameters. *J Sediment Petrol* 27(1):3–26. <https://doi.org/10.1306/74D70646-2B21-11D7-8648000102C1865D>
- Friend PF, Sinha R (1993) Braiding and meandering parameters. *Geol Soc Lond Spec Publ* 75(1):105–111
- Gain AK, Giupponi C (2015) A dynamic assessment of water scarcity risk in the Lower Brahmaputra River Basin: an integrated approach. *Ecol Indic* 48:120–131. <https://doi.org/10.1016/j.ecoli.2014.07.034>
- Ghaleno MRD, Meshram SG, Alvandi E (2020) Pragmatic approach for prioritization of flood and sedimentation hazard potential of watersheds. *Soft Comput* 24:15701–15714
- Gupta S, Gupta SK (2021) Development and evaluation of an innovative Enhanced River Pollution Index model for holistic monitoring and management of river water quality. *Environ Sci Pollut Res* 28(21):27033–27046
- Hezer S, Gelmez E, Özceylan E (2021) Comparative analysis of TOPSIS, VIKOR and COPRAS methods for the COVID-19 Regional Safety Assessment. *Infect Public Health* 14(6):775–786
- Julien IY (2002) *River mechanics*. Cambridge University Press, Cambridge. <https://doi.org/10.1017/CBO9781139164016>
- Kadam AK, Wagh VM, Muley AA, Umrikar BN, Sankhua RN (2019) Prediction of water quality index using artificial neural network and multiple linear regression modelling approach in Shivganga River basin India. *Model Earth Syst Environ* 5(3):951–962
- Kaganski S, Majak J, Karjust K (2018) Fuzzy AHP as a tool for prioritization of key performance indicators. In *Procedia CIRP*. <https://doi.org/10.1016/j.procir.2018.03.097>
- Karr JR (1999) Defining and measuring river health. *Freshw Biol* 41:221–234
- Karr JR (1981) Assessment of biotic integrity using fish communities. *Fisheries* 6(6):21–27
- Kristensen EA, Baattrup-Pedersen A, Thodsen H (2011) An evaluation of restoration practises in lowland streams: Has the physical integrity been re-created? *Ecol Eng* 37(11):1654–1660
- Kuo Y, Yang T, Huang GW (2008) The use of grey relational analysis in solving multiple attribute decision-making problems. *Comput Ind Eng* 55:80–93. <https://doi.org/10.1016/j.cie.2007.12.002>
- Liu W, Xu M, Zhao N, Zhou X, Pan B, Tian S, Lei F (2019) River health assessment of the Yellow River source region, Qinghai-Tibetan Plateau, China, based on tolerance values of macroinvertebrates. *Environ Sci Pollut Res* 26(10):10251–10262
- Luo Z, Zuo Q, Shao Q (2018) A new framework for assessing river ecosystem health with consideration of human service demand. *Sci Total Environ* 640:442–453
- Ma D, Luo W, Yang G, Lu J, Fan Y (2019) A study on a river health assessment method based on ecological flow. *Ecol Modell* 401:144–154
- Maddock I (1999) The importance of physical habitat assessment for evaluating river health. *Freshw Biol* 41(2):373–391
- Margalef RAMON (1958) *Temporal succession and spatial heterogeneity in Phytoplankton In; Perspective in marine biology*. University of California press. USA. <https://doi.org/10.1525/9780520350281-024>
- Mittal N, Mishra A, Singh R, Bhawe AG, van der Valk M (2014) Flow regime alteration due to anthropogenic and climatic changes in the Kangsabati River, India. *Ecohydrol Hydrobiol* 14(3):182–191
- Mupenzi C, Li L, Al LNE (2017) Spatial pattern assessment of lake kivu basin rivers water quality using national sanitation foundation water quality and rivers pollution indices. *Desalin Water Treat* 95:128–143
- Mura SNS, Gope A (2020) Anthropogenic impact on forms and processes of the Kangsabati River Basin. In *Anthropogeomorphology*

- of Bhagirathi-Hooghly River System in India (253–296). CRC Press. <https://doi.org/10.1201/9781003032373>
- Nädäban S, Dzitac S, Dzitac I (2016) Fuzzy TOPSIS: a general view. *Procedia Comput Sci* 91:823–831
- Navratil O, Albert MB (2010) Non-linearity of reach hydraulic geometry relations. *J Hydrol* 388:280–290
- Opricovic S, Tzeng GH (2004) Compromise solution by MCDM methods: a comparative analysis of VIKOR and TOPSIS. *Eur J Oper Res* 156(2):445–455. [https://doi.org/10.1016/S0377-2217\(03\)00020-1](https://doi.org/10.1016/S0377-2217(03)00020-1)
- Pettesse ML, Siqueira-Souza FK, de Carvalho FCE, Petrere M (2016) Selection of reference lakes and adaptation of a fish multimetric index of biotic integrity to six amazon floodplain lakes. *Ecol Eng* 97:535–544
- Pielou EC (1966) The measurement of diversity in different types of biological collections. *J Theor Biol* 13:131–144
- Poikane S, Kelly M, Cantonati M (2016) Benthic algal assessment of ecological status in European lakes and rivers: Challenges and opportunities. *Sci Total Environ* 568:603–613
- Qiu Y (2011) Management decision entropy and its application. China Electric Power Press, Beijing (in Chinese)
- Restrepo JD, Escobar R, Tosic M (2018) Fluvial fluxes from the Magdalena River into Cartagena Bay, Caribbean Colombia: trends, future scenarios, and connections with upstream human impacts. *Geomorphology* 302:92–105. <https://doi.org/10.1016/j.geomorph.2016.11.007>
- Reynolds CS (2003) Planktic community assembly in flowing water and the ecosystem health of rivers. *Ecol Modell* 160(3):191–203
- Sadat MA, Guan Y, Zhang D, Shao G, Cheng X, Yang Y (2020) The associations between river health and water resources management lead to the assessment of river state. *Ecol Indic* 109:105814
- Sargaonkar A, Deshpande V (2003) Development of an overall index of pollution for surface water based on a general classification scheme in Indian context. *Environ Monit Assess* 89(1):43–67
- Sargaonkar AP, Rathi B, Baile A (2011) Identifying potential sites for artificial groundwater recharge in sub-watershed of river Kanhan. *India Environ Earth Sci* 62(5):1099–1108. <https://doi.org/10.1007/s12665-010-0598-z>
- Saaty TL (1977) A scaling method for priorities in hierarchical structures. *J Math Psychol* 15:234–281
- Shan C, Dong Z, Lu D, Xu C, Wang H, Ling Z, Liu Q (2021) Study on river health assessment based on a fuzzy matter-element extension model. *Ecol Indic* 127:107742
- Shannon CE (1949) The mathematical theory of communication. CE Shannon and Warren Weaver, Urbana. https://pure.mpg.de/rest/items/item_2383164/component/file_2383163/content
- Sharma P, Meher PK, Kumar A, Gautam YP, Mishra KP (2014) Changes in water quality index of Ganges river at different locations in Allahabad. *Sustain Water Qual Ecol* 3:67–76
- Shi X, Liu J, You X, Bao K, Meng B, Chen B (2017) Evaluation of river habitat integrity based on benthic macroinvertebrate-based multi-metric model. *Ecol Model* 353:63–76
- Shukla RK, Garg D, Agarwal A (2014) An integrated approach of Fuzzy AHP and Fuzzy TOPSIS in modeling supply chain coordination. *Prod Manuf Res* 2(1):415–437. <https://doi.org/10.1080/21693277.2014.919886>
- Si T, Wang C, Liu R, Guo Y, Yue S, Ren Y (2020) Multi-criteria comprehensive energy efficiency assessment based on fuzzy-AHP method: a case study of post-treatment technologies for coal-fired units. *Energy* 200:117533. <https://doi.org/10.1016/j.energy.2020.117533>
- Singh PK, Saxena S (2018) Towards developing a river health index. *Ecol Indic* 85:999–1011. <https://doi.org/10.1016/j.ecolind.2017.11.059>
- Solangi YA, Shah SAA, Zameer H, Ikram M, Saracoglu BO (2019) Assessing the solar PV power project site selection in Pakistan: based on AHP-fuzzy VIKOR approach. *Environ Sci Pollut Res* 26(29):30286–30302
- Smith MJ, Kay WR, Edward DHD, Papas PJ, Richardson KSJ, Simpson JC, Pinder AM, Cale DJ, Horwitz PH, Davis JA, Yung FH (1999) AusRivAS: using macroinvertebrates to assess ecological condition of rivers in Western Australia. *Freshw Biol* 41(2):269–282
- Stewardson M (2005) Hydraulic geometry of stream reaches. *J Hydrol* 36:97–111
- Su Y, Li W, Liu L, Hu W, Li J, Sun X, Li Y (2021) Health assessment of small-to-medium sized rivers: Comparison between comprehensive indicator method and biological monitoring method. *Ecol Indic* 126:107686
- Ustaoğlu F, Tepe Y, Taş B (2020) Assessment of stream quality and health risk in a subtropical Turkey river system: A combined approach using statistical analysis and water quality index. *Ecol Indic* 113:105815
- Von Schiller D, Acuña V, Aristi I, Arroita M, Basaguren A, Bellin A, Boyero L, Butturini A, Ginebreda A, Kalogianni E, Larrañaga A (2017) River ecosystem processes: A synthesis of approaches, criteria of use and sensitivity to environmental stressors. *Sci Total Environ* 596:465–480
- Wang Y, Xu L, Solangi YA (2020) Strategic renewable energy resources selection for Pakistan: Based on SWOT-Fuzzy AHP approach. *Sustain Cities Soc* 52:101861
- Wu C, Chen W (2020) Indicator system construction and health assessment of wetland ecosystem—taking Hongze Lake Wetland China as an Example. *Ecol Indic* 112:106164
- Xue C, Shao C, Chen S (2020) SDGs-based river health assessment for small-and medium-sized watersheds. *Sustainability* 12(5):1846
- Yang T, Liu JL, Chen QY (2013) Assessment of plain river ecosystem function based on improved gray system model and analytic hierarchy process for the Fuyang River, Haihe River Basin. *Ecol Model* 268:37–47
- Yang T, Liu J, Li X, Zhao X (2017) Plain river habitat assessment of Haihe River basin. *Environ Sci Technol (china)* 40(3):190–197
- Yang W, You Q, Fang N, Xu L, Zhou Y, Wu N, Ni CY, Liu Y, Liu GH, Yang T, Wang Y (2018) Assessment of wetland health status of Poyang Lake using vegetation-based indices of biotic integrity. *Ecol Indic* 90:79–89
- Zavadskas EK, Kaklauskas A, Vilutiene T (2009) Multicriteria evaluation of apartment blocks maintenance contractors: Lithuanian case study. *Int J Strateg Prop Manag* 13(4):319–338. <https://doi.org/10.3846/1648-715X.2009.13.319-338>
- Zavadskas EK, Turskis Z, Antucheviciene J, Zakarevicius A (2012) Optimization of weighted aggregated sum product assessment. *Electron Electr Eng* 6(122):3–6
- Zheng BH, Zhang Y, Li YB (2007) Study on indicators and methods for river habitat assessment of Liao River Basin. *J Environ Sci* 27:928–936 (in Chinese)
- Zeng P, Sun F, Liu Y, Che Y (2020) Future river basin health assessment through reliability-resilience-vulnerability: thresholds of multiple dryness conditions. *Sci Total Environ* 741:140395. <https://doi.org/10.1016/j.scitotenv.2020.140395>
- Zhao YW, Zhou LQ, Dong BQ, Dai C (2019) Health assessment for urban rivers based on the pressure, state and response framework—a case study of the Shiwuli River. *Ecol Indic* 99:324–331
- Zhu W, Liu Y, Wang S et al (2019) Development of microbial community-based index of biotic integrity to evaluate the wetland ecosystem health in Suzhou China. *Environ Monit Assess* 191:377. <https://doi.org/10.1007/s10661-019-7512-2>
- Zhu Y, Tian D, Yan F (2020) Effectiveness of entropy weight method in decision-making. *Math Probl Eng*. <https://doi.org/10.1155/2020/3564835>
- Zou Z, Yun Y, Sun J (2006) Entropy method for determination of weight of evaluating indicators in fuzzy synthetic evaluation for

water quality assessment. *J Environ Sci (China)* 18:1020–1023.
[https://doi.org/10.1016/S1001-0742\(06\)60032-6](https://doi.org/10.1016/S1001-0742(06)60032-6)

Zuo QT, Luo ZL, Ding XY (2016) Harmonious development between socio-economy and river-lake water system in Xiangyang City. *China Water* 8(11):1–19

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