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Application of pressure–state–response approach for developing criteria and indicators of ecological health assessment of wetlands: a multi-temporal study in Ichhamati floodplains, India

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Abstract

Background Tropical floodplain wetlands are among the most disturbed and intensively harvested ecosystems. Their sustainable management is often hindered due to the lack of comprehensive, coherent, and standardized assessment frameworks of wetland ecological health (WEH). In this study, a set of appropriate criteria and indicators (C&I) of WEH assessment was developed and tested on seven wetlands of River Ichhamati, eastern India.

Methods Based on the pressure–state–response (PSR) approach, evaluation indicators representing ecological, socio-economic, and institutional sustainability issues of floodplain wetland systems were either selected or formulated through literature survey and stakeholder consensus. Weights of indicators were assigned by the entropy weighting method and then used in the Technique for Order of Preference by Similarity to Ideal Solution model to determine the Euclidean distances of each wetland from the positive ideal solution and negative ideal solution. Subsequently, a comprehensive wetland ecological health index (CWEHI) was constructed from these distances to portray the condition of any PSR system component in a wetland under a fivefold classification scheme, namely 'excellent health' (CWEHI ≥ 0.81), 'good health' (0.61–0.80), 'moderate health' (0.41–0.60), 'weak health' (0.21–0.40), and 'morbid' (≤ 0.20).

Results The developed C&I set contains 8 criteria and 38 indicators under pressure component, 7 criteria and 49 indicators under state component, as well as 4 criteria and 18 indicators under response component. When applied in 2016 and 2022, it was found that the Panchita and Aromdanga wetlands were continuously in weak and morbid health status, while the Madhabpur wetland always showed an excellent or good status for all components. Health of other wetlands oscillated between moderate and morbid health across assessment years and system components.

Conclusions The developed C&I set was found to be a flexible, holistic, and refined framework that could be applied elsewhere in similar assessments with minor indicator-level adjustments. The present assessment inferred that agriculture-dominated wetlands were more affected by amplified environmental pressure than fishing-dominated wetlands. Absence of persistent water flow from main river channel, wide-spread jute-retting, agriculture-induced eutrophication, proliferation of aquatic weeds were identified as the major causes of rapid ecological deterioration.

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Keywords Entropy weighting method, Environmental indicator, Floodplain wetland, TOPSIS, Wetland influence zone, Wetland ecological health

Introduction

The floodplain wetlands of tropical countries are considered as essential landscape units for maintaining regional environmental health as well as human wellbeing with its wide range of provisioning, regulating, cultural and supporting services (MEA 2005; Zhang et al. 2023). These freshwater wetlands boost regional biodiversity with a wide gamut of floral and faunal species such as amphibians, reptiles, birds, fishes and numerous invertebrate micro-fauna (Bansal et al. 2019; Gayen et al. 2020). These wetland ecosystems have served as primary means of livelihood of the people living nearby from time immemorial (Ramsar Convention 2008; Sarkar et al. 2022). In many densely populated floodplain areas of the developing countries, such wetlands and river cut-offs are often poorly managed and overexploited for a number of socio-economic needs resulting in severe degradation and deterioration of wetland ecosystem health (WEH) (Wang et al. 2011; Datta and Ghosh 2015; Gayen et al. 2020). WEH indicates towards an ideal ecosystem which has no distress syndrome such as fish death, algal bloom, water pollution, eutrophication, etc. (Rapport et al. 1998, 2001; Lu et al. 2015; Ayele and Atlabachew 2021). Essentially, WEH could be understood through the current state of hydro-biological vigor, organization of ecosystem components and integration of a wetland into the larger landscape complexity which resulted from mutual interactions between wetlands and humans across space and time (Jørgensen et al. 2005; Horwitz and Finlayson 2011). WEH can be assessed by synthesizing various criteria and indicators (C&Is) consisting of aquatic, edaphic, biotic and socio-economic aspects of wetlands (Ren et al. 2014; Sun et al. 2016). Since the 1990s, several practical frameworks of indicators for assessment of ecosystem health have been developed (Costanza et al. 1992; Cui and Yang 2002; Jørgensen et al. 2005; Horwitz and Finlayson 2011; Bunch et al. 2011). However, holistic framework of criteria and indicators (C&I) yielding quantitative outcomes as well as encompassing ecological, social, economic and cultural criteria are still evidently rare in case of freshwater floodplain wetlands of the tropics (Datta and Ghosh 2015; Gayen et al. 2020).

In India, the floodplain wetlands are disappearing at a rate of 2–3 percent per year chiefly due to conversions into croplands, aquafarms and built-ups thereby increasing its ecological vulnerability (CPR Environmental Education Centre 1989; SAC 2011; Paul and Pal 2020). Within this region, the floodplains of River Ichhamati are characterized by diverse types of tropical wetlands, ranging from swamps to marshy lands, lakes to paleochannels, natural to man-made (Bassi et al. 2014). Proliferation of human habitations along with their unsustainable resource extraction practices have exacerbated degradation processes of these wetlands through land filling; construction of brick kilns, houses and roads; retting of jute; bathing and washing; idol emersion, open defecation, poaching and killing of wild animals, indiscriminate use of fertilizers, insecticides and pesticides, etc. (Mondal and Kaviraj 2007; Hossain et al. 2013). Few activities among these have proved to be fatal and acting as major stressors to the sustenance of the aquatic life in these wetland ecosystems (Gayen et al. 2020). In the long run, it will also have serious negative impact on the subsistence based livelihood of the local populace (Datta and Ghosh 2015). Accordingly, comprehensive assessment of the status of WEH in a periodic manner has become a prerequisite of sustainable management of these floodplain wetlands towards regional socio-economic and ecological prosperity at present. Unfortunately, no such all-inclusive study has been conducted on these wetlands till date, thereby making the hitherto adopted management efforts truly futile.

In this backdrop, the present research aims to identify and construct a realistic, adaptive and comprehensive set of C&I, which would further assist us to develop a comprehensive wetland ecological health index (CWEHI) for the tropical floodplain wetlands in general and Ichhamati floodplains in particular. This research also evaluates the states of WEH of selected wetlands of the Ichhamati floodplains in 2016 and 2022 based on the developed set of C&I. The pressure–state–response (PSR) based modeling approach, proposed by Rapport (1979) and OECD (1993), was used in this context to identify and categorize relevant C&I of WEH assessment. Certainly, results of this assessment would serve as a tool for regular monitoring, early warnings of ecological deterioration and consequently implementation of apt mitigation measures.

Materials and methods

Delineation of study area

The floodplains of River Ichhamati have notable presence within the moribund part of the Ganges–Brahmaputra–Meghna (GBM) delta system (Gayen et al. 2020). A wetland complex had been formed the in these floodplains comprising seven wetlands namely Berkrishnapur, Panchpota, Panchita, Aromdanga, Gopalnagar, Manigram and Madhabpur (Fig. 1). These wetlands have originated as river cut-offs and developed into oxbow lakes due to extreme meandering and channel avulsion processes of the River Ichhamati and are locally known as *baor* (Datta and Ghosh 2015; Gayen et al. 2020). These perennial wetlands get wastewater from nearby agricultural lands, domestic and market sources as surface runoff and influx of effluents through irrigation and sewage canals. The wastewater gets naturally treated with the help of ample sunshine and abundant algae within the watered areas (Ghosh 2005). These seven wetlands are also still connected to the river by a narrow inlet which dries up completely from November to June each year, causing immense hydrological pressure on the wetland ecosystem. In spite of these stresses, this wetland complex plays crucial roles in biodiversity conservation, flood mitigation, groundwater recharge, supply of irrigation water, captive fishing, domestic uses and animal rearing. Since no systematic study has been done on the status of WEH of this wetland complex till now, this was selected as the present study area to test the constructed set of C&I. For this purpose, the general environmental characteristics of the wetlands of this complex have been shortlisted from various primary (Focus Group Discussion (FGD), $n=6$) and secondary sources first and subsequently considered during the health indicator selection phase (Additional file 1: Table S1).

The PSR-based approach of ecological modeling

Rapport (1979) first proposed the concept of PSR approach and the Organisation for Economic Co-operation and Development (OECD) had further refined it (OECD 1993). The approach was initially created to support environmental policy-making. Subsequently, it had been used equally in other studies to assess environmental quality, ecosystem sustainability and ecosystem health, etc. (United Nations Commission on Sustainable Development 1996; OECD 1997; Convention on Biological Diversity 2003; Gabrielsen and Bosch 2003). The effectiveness of this modeling approach lies in the fact that the approach facilitates

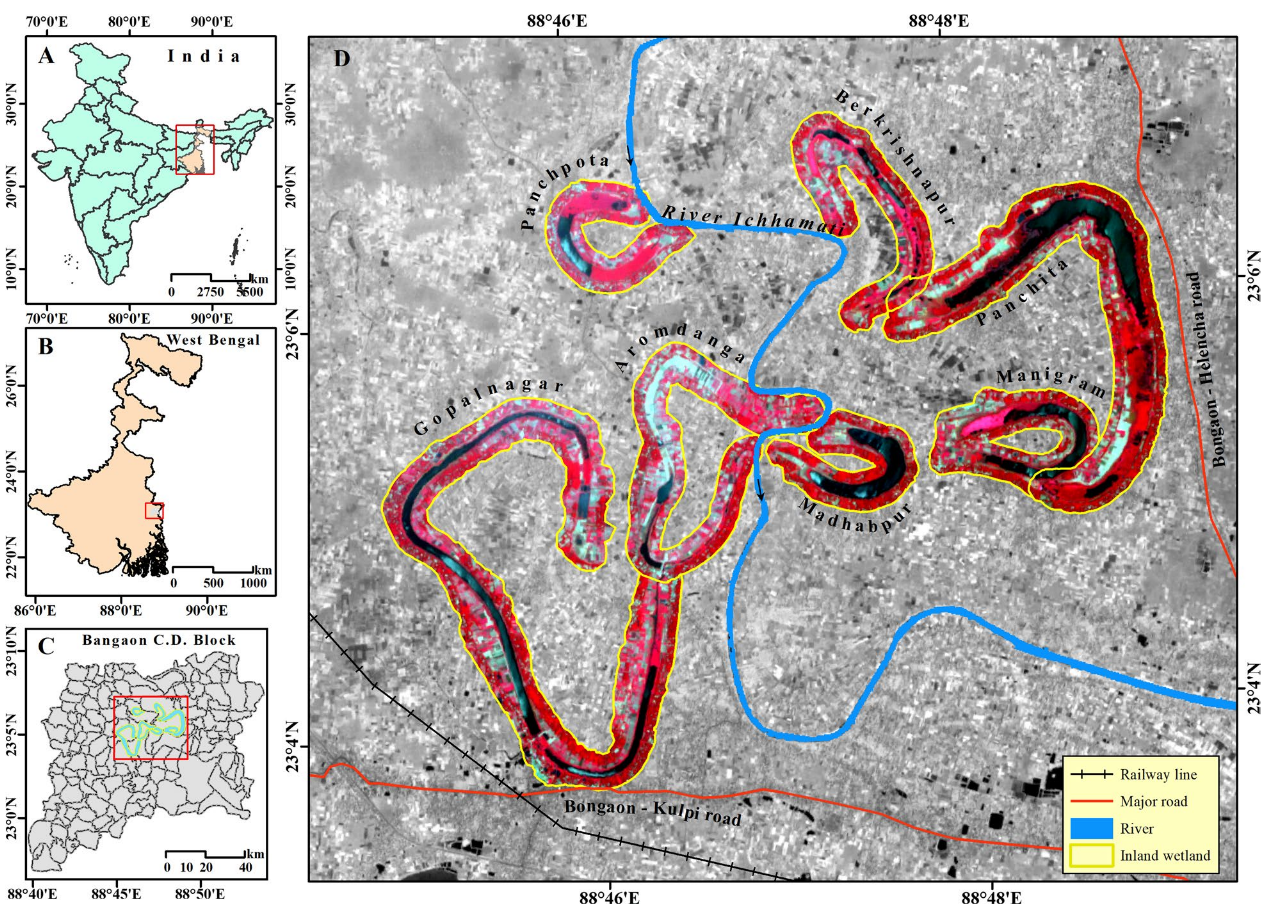

Fig. 1 Location of the studied wetland complex: **A** India showing West Bengal in red colored box; **B** West Bengal showing N 24 Parganas in red colored box; **C** Bangaon C.D. Block showing studied wetland complex in red colored box; **D** selected wetlands under wetland complex

researchers and planners to identify and capture those driver variables that have substantial positive and negative impacts on different natural systems such as wetlands (Mao et al. 2014; Ren et al. 2014; Liu and Hao 2017; Sun et al. 2019). This approach also allows researchers to assess the pressure of anthropogenic activity on the physical condition of wetlands, measure the existing state of ecosystem health, and identify possible responses necessary for the recovery of wetland system (Mao et al. 2014; Ren et al. 2014; Liu and Hao 2017; Sun et al. 2019; Das et al. 2020). It integrates system responses as well as institutional responses to achieve the 'desired state'. In reality, all human activities eventually affect state of the ecological health of wetland systems, either in a positive or a negative manner. Since institutional responses control human activities, the role of the organizations and society in mitigating the negative consequences of both human response as well as institutional response are seemingly decisive (Liu and Hao 2017). This approach thus helps to realize the detrimental effects of human activities and to address the health conditions of the ecosystem from a social and economic point of view. In this study, the assessment of WEH involves various 'pressures' exerted on the wetlands which eventually affect wetland's state and accordingly demand for a response to deal with the situation. Hence, the PSR approach was considered to be highly effective here in assessing the WEH in a comprehensive yet coherent manner.

The PSR framework generally consists of three essential components such as 'pressure', 'state' and 'response' which have synergic interconnection and ultimately influence the WEH (Fig. 2). In this approach, the first level is defining the target object as 'assessment of changing ecosystem health of wetlands' and the second level is the 'system' which indicates 'environmental pressures' (viz. the pressures or stresses from expanding population growth, increasing water demand, uneven resource extraction, water resources consumption, etc.); 'state of wetland ecosystem' (viz. ecological state, environmental state and function state, etc.), and 'response' (viz. ecological response, societal response, institutional response to be employed to restore degraded eco-environmental system, etc.); while the third level indicates the evaluation criterion part that describes specific environmental aspects under each system component (second level) and the fourth level describes the scientifically justifiable and

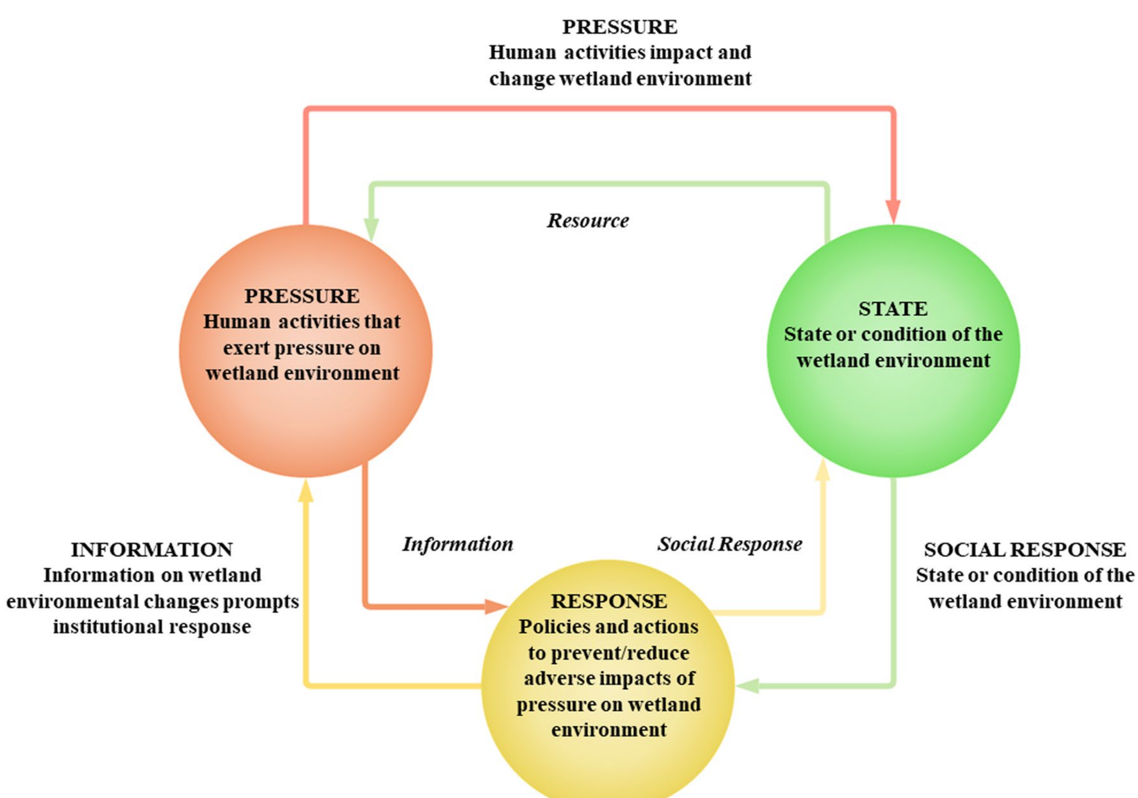

Fig. 2 PSR framework defining interconnections between human pressure, wetland state and institutional and community responses (adapted from OECD 1993)

ecologically robust evaluation indicators of WEH (Jørgensen et al. 2005; Mao et al. 2014).

Identification of C&I for floodplain wetland health assessment

The selection of evaluation indicators entirely depends on the type of wetland ecosystem under investigation, its geographical location, the specific interests, skills, competencies and objectives of the researcher (Cui and Yang 2002; Jia et al. 2015). General environmental indicators with 'one size fits all' status explicitly do not exist, or at least have not yet been found (Jørgensen et al. 2005). To bridge this gap, we have proposed a set of general C&I which is scientifically sound, environmentally strong, and socio-economically relevant and able to meet the long-standing demand of WEH assessment in Ichhamati floodplains in specific and similar areas in general (Fig. 3). Here, a thorough review of published relevant literature was conducted first to identify the best suited indicators that could accurately reflect WEH in the study sites. Thereafter, these indicators were validated and updated according to the opinions of local stakeholders through FGDs ($n=6$). Lastly, the arrangement of different sets of indicators under respective criteria was done by five regional wetland experts using the Delphi Consensus method of three rounds. The C&I framework was constructed in such a way that it could reflect the health status of the wetlands in terms of ecosystem structure, functionality and their socio-economic relevance. In reality, each component of the developed C&I set under the PSR approach would individually bear characteristic information only on a part of the overall health of a wetland ecosystem at a specific space–time context. Since wetland ecosystem exhibits a complex structure with many open and closed systems, both qualitative and quantitative indicator based assessments were, therefore, applied for accruing better results in relation to the overall WEH (Wang et al. 2011; Jia et al. 2015). Here, indicators for each component of the PSR approach were identified

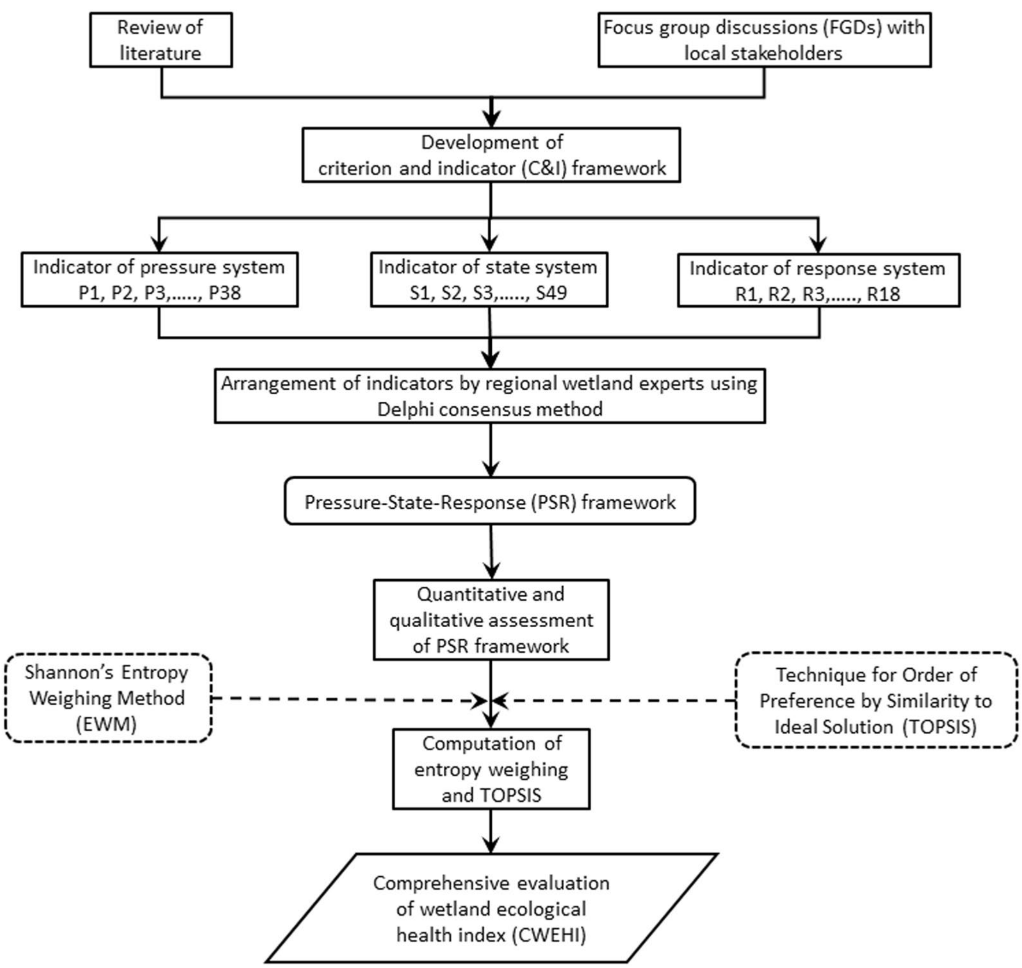

Fig. 3 Methodological outline for development of PSR-based comprehensive wetland ecological health index (CWEHI)

from aquatic, edaphic, floral, faunal and human realms of the wetland environment towards developing a holistic assessment framework.

Methods adopted for indicator-wise assessment

Field and laboratory-based measurement

Altogether, 24 physicochemical parameters of surface water health and 14 physicochemical parameters of soil health were shortlisted in this study (Cui et al. 2012; Baird et al. 2017). Among the surface water health parameters, 12 parameters, viz. water depth, surface temperature, turbidity, pH, dissolved oxygen (DO), electrical conductivity (EC) and eutrophication level were measured in situ using standard instruments and field observations (Table 1). Remaining 12 parameters of water such as biological oxygen demand (BOD), chemical oxygen demand (COD), fecal coliform bacteria, total coliform (TC), amount of phosphate (PO_4^{3-}), amount of ammoniacal nitrogen (NH_3-N), amount of nitrate (NO_3^-), arsenic (As), fluoride (F^-), concentration of cadmium (Cd), mercury (Hg), lead (Pb), chromium (Cr) were subsequently tested in the departmental laboratory following the standard procedures of APHA (2017) (Agboola et al. 2016; Saran et al. 2018; Buwono et al. 2021; Khan et al. 2021; Rakib et al. 2021; Saturday et al. 2021; Henderson et al. 2021). Water samples were collected from wetlands at a depth 0.5 m using grab sampling procedure and stored in purified glass bottles that were initially washed with nitric acid (HNO_3) (Agboola et al. 2016). Sub-surface soil samples were collected from 10 to 20 cm depths in order to avoid fresh organic litter (Power et al. 1981; Gallo et al. 2018). Parameters like soil bulk density, soil pH, total organic carbon (TOC), available nitrogen (N), available phosphorus (P), potassium (K), soil EC, concentration of As, Cd, Hg, Pb and Cr were also tested in the laboratory (Jackson 1967; Blake and Hartge 1986; Tandon 1993; Basak 2000; Rokosch et al. 2009; da Silva et al. 2014). Among edaphic parameters, only the level of soil moisture was measured in the field.

Indicators based on geospatial assessment

Land use/land cover (LULC) of floodplain wetlands of southern West Bengal has changed primarily due to prevalence of intensive farming practices, lackluster implementation of regulations against land conversion, uncontrolled urban sprawl, and rapid growth of aquaculture in the last decade (Roy et al. 2021). In order to trace the LULC dynamics of the studied wetland complex, remote sensing (RS) based geospatial technologies were applied. Both the class level and landscape level spatial metrics were computed to determine the nature and amount of environmental pressure and subsequent changes (state) in the wetland landscape (Mao et al. 2014; Lu et al. 2015; Liu and Hao 2017; Das et al. 2020). For this purpose, Sentinel 2A-MSI level-1C data (tile number: T45QXF) of two post-monsoonal lean periods (2016 and 2022) with moderately fine spatial resolution (10 m) were downloaded from the Copernicus Open Access Hub. Two LULC maps and normalized difference vegetation index (NDVI) maps were prepared for 2016 and 2022, respectively, using the atmospherically corrected and georeferenced data (Nandi et al. 2020). Then, these maps were used to derive values for several spatial metrics and indicators pertaining to the wetland catchment characteristics using the spatial analyst software FRAGSTATS 4.2 (McGarigal and Marks 1995). These indicators include level of human-induced stresses on the LULC of wetland influence zone (WIZ), areal fragmentation of perennial wetland zone (PWZ), patch density (PD), largest patch index (LPI), landscape diversity index (LSDI), landscape contagion index (LCI) of WIZ, existing extent of the WIZ around the wetland acting as buffer, ratio of wetland wetted perimeter to WIZ perimeter, etc. (Datta et al. 2021; Jia et al. 2015) (Table 1).

Questionnaire surveys for perception-based indicators

Several indicators dealt with temporal and societal changes happening in and around the wetland sites, which might not be assessed correctly through direct field measurements or geospatial analyses. The only viable option remaining is a participatory appraisal and subsequent inference of information on the complex biological and socio-cultural systems of the studied wetlands. Twenty indicators related to edaphic, aquatic, biotic and socio-economic realms of the environment and having qualitative dimensions were selected for this purpose and placed in front of the respondents belonging to different stakeholder groups to understand the amount of 'pressures' on wetland ecosystems exerted by anthropogenic activities. Similarly, 13 indicators were used to understand the 'state' of the wetland and sixteen questions were asked to understand the 'response' component. In each wetland site, 10–12 individuals from different stakeholder groups (viz. farmers, fishermen, livestock rearer, domestic users, government officials, etc.) were surveyed for this purpose with a structured questionnaire in a systematic random sampling approach.

Procedure of indicator scoring

Since this study dealt with a wide variety of assessment indicators (i.e., both quantitative and qualitative), it was not possible to follow a single scoring method to evaluate all the identified indicators (Datta and Chatterjee 2012). Altogether, four types of scoring methods were applied following the nature of indicators. Initially, we calculated the arithmetic mean (μ) and standard deviation

Table 1 Field and laboratory-based analyses of physico-chemical parameters of water and soil of the studied wetlands

Evaluation indicator	Instrument/method used	References
Fecal coliform (mpn 100 mL^{-1})	APHA 23rd Edition-2017	Zhang et al. (2019)
Phosphate (PO_4^{3-}) (mg L^{-1})	APHA 23rd Edition-2017	Buwono et al. (2021)
Ammoniacal nitrogen (NH_3-N) (mg L^{-1})	APHA 23rd Edition-2017	Henderson et al. (2021)
Nitrate (NO_3^-) (mg L^{-1})	APHA 23rd Edition-2017	Buwono et al. (2021)
Arsenic (As) (mg L^{-1})	APHA 23rd Edition-2017	Rakib et al. (2021)
Fluoride (F^-) (mg L^{-1})	APHA 23rd Edition-2017	Rakib et al. (2021)
Depth of water (m)	Staff gauge	Magee and Kentula (2005); Henderson et al. (2021)
Turbidity (m)	Sechi disk	Saturday et al. (2021); Henderson et al. (2021)
Surface temperature (°C)	A mercury-in-glass thermometer	Saturday et al. (2021); Henderson et al. (2021)
Biological oxygen demand (BOD) (mg L^{-1})	APHA 23rd Edition-2017	Buwono et al. (2021); Saturday et al. (2021)
Chemical oxygen demand (COD) (mg L^{-1})	APHA 23rd Edition-2017	Buwono et al. (2021)
pH	Hanna Pocket Type pH meter (Model number: HI96107)	Agboola et al. (2016); Saturday et al. (2021)
Cadmium (Cd) (mg L^{-1})	APHA 23rd Edition-2017	Saran et al. (2018)
Mercury (Hg) (mg L^{-1})	APHA 23rd Edition-2017	Khan et al. (2021)
Lead (Pb) (mg L^{-1})	APHA 23rd Edition-2017	Saran et al. (2018)
Chromium (Cr) (mg L^{-1})	APHA 23rd Edition-2017	Saran et al. (2018)
Dissolved oxygen (DO) (mg L^{-1})	Lutron DO meter (Model number: Lutron/PDO-520)	Buwono et al. (2021); Henderson et al. (2021)
Electrical conductivity (EC) (µS cm^{-1})	HM Digital EC meter (Model number: HM_AP2)	Hardie and Doyle (2012); Saturday et al. (2021)
Salinity of wetland water (ppt)	HM Digital EC meter (Model number: HM_AP2)	Hardie and Doyle (2012)
Rate of siltation (mm h^{-1})	Sediment volume was calculated over a period of 1 h of residence and settling of colloidal particles of sediment	Wieland and Hayward (1997)
Availability of soil moisture	Luster Leaf 1827 soil moisture meter (Model: Rapitest Digital Plus)	Hájek et al. (2013)
Soil bulk density (g cm^{-3})	Soil bulk density was calculated as the ratio of the mass of dry solids to the bulk volume of soil	Blake and Hartge (1986); Rokosch et al. (2009)
Available soil nitrogen (N) (kg ha^{-1})	Procedure involves distilling the soil with alkaline potassium permanganate solution and determining the ammonia liberated	Tandon HLS. (1993)
Available soil phosphorus (P) (kg ha^{-1})	Olsen's method was used for neutral–alkaline soils while the Bray and Kurtz method was used for acidic soils	Tandon HLS. (1993)
Status of potassium (K) (kg ha^{-1})	Potassium with flame photometer model (Systronics flame photometer 128)	Jackson (1967)
Soil organic carbon (SOC) (mg ha^{-1})	Wet oxidation method modified from Walkley and Black	Jackson (1967)
Soil EC (µS cm^{-1})	Systronic EC meter (Model number: Systronics µ Conductivity meter 306)	Basak (2000)
Soil pH	Systronic pH meter (Systronics µ pH meter 361)	Jackson (1967)
Arsenic (As) (µg kg^{-1})	USEPA Acid Digestion Method 3050	da Silva et al. (2014)
Cadmium (Cd) (mg kg^{-1})	USEPA Acid Digestion Method 3050	da Silva et al. (2014)
Mercury (Hg) (µg kg^{-1})	USEPA Acid Digestion Method 3050	da Silva et al. (2014)
Lead (Pb) (mg kg^{-1})	USEPA Acid Digestion Method 3050	da Silva et al. (2014)
Chromium (Cr) (mg kg^{-1})	USEPA Acid Digestion Method 3050	da Silva et al. (2014)
Human induced stresses on LULC of wetland influence zone	$\text{Pressure on LULC}_{WIZ} = \frac{(A_{BL}+A_{AL}+A_{AF})}{TA_{WIZ}} \times 100$, where WIZ = wetland influence zone; BL = built-up land, AL = agricultural land, AF = agricultural fallow, TA = total area (m^2) of WIZ	Proposed by the authors; Roy et al. (2020)
Areal fragmentation of perennial wetland zone	$\text{Areal fragmentation}_{WPZ} = \frac{TA_{WPZ}-WV_{WPZ}}{TA_{WPZ}}$, where TA_{WPZ} = area (m^2) of perennial wetland zone (WPZ), WV_{WPZ} = vegetated area (m^2) of WPZ	Proposed by the authors
Patch density (PD)	$PD = \frac{n_i}{A}$, where n_i = number of patches of i^{th} class A = the total landscape area (m^2)	McGarigal and Marks (1995); Jia et al. (2015); Sun et al. (2016); Sun et al. (2017)

Table 1 (continued)

Evaluation indicator	Instrument/method used	References
Largest patch index (LPI)	$LPI = \frac{\max_{j=1}^{n} a_{ij}}{A} \times 100$, where a_{ij}= area (m^2) of patch *j* of i^{th} class and *A* = the total landscape area (m^2)	McGarigal and Marks (1995); Jia et al. (2015)
Shannon's diversity index (SHDI)	$SHDI = -\sum_{i=1}^{m} (p_i ln p_i)$, where p_i= the proportion of the landscape occupied by each patch type *i*	McGarigal and Marks (1995); Jia et al. (2015); Liu and Hao (2017); Sun et al. (2016); Sun et al. (2017)
Landscape contagion index of WIZ	$CONTAG = [1 + \frac{\sum_{i=1}^{m}\sum_{k=1}^{m}[(P_i)(\frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}})] \times [ln(P_i)(\frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}})]}{2\ln(m)}] \times (100)$, where P_i = proportion of landscape occupied by i^{th} patch type, g_{ik} = the number of adjacencies between pixels of patch types *i* and *k*, and *m* = number of patch types present in the landscape	O'Neill et al. (1988); Sun et al. (2017)
Existing extent of WIZ around the wetland acting as buffer	Average width [(major axis width + minor axis width)/2] of WIZ acting as buffer	Proposed by the authors
Ratio of wetland wetted perimeter to WIZ perimeter acting as buffer	Ratio of WP_{WIZ} *to* $WP_{WPZ} = \frac{WP_{WIZ}}{WP_{WPZ}} \times 100$, where WP = wetted perimeter (m)	Proposed by the authors
Normalized difference vegetation index (NDVI)	$NDVI = \frac{(NIR-RED)}{(NIR+RED)}$	Liu and Hao (2017); Sun et al. (2016); Nandi et al. (2020)
Rate of change of vegetated area (VA)	Reduction in VA (%) $= (\frac{VA_{Y1} - VA_{Y2}}{VA_{Y2}}) \times 100$, where VA = Vegetation area (m^2), Y1 = base year, Y2 = final year	Proposed by the authors
Rate of change of open water surface area (OWSA)	Reduction in OWSA (%) $= (\frac{OWSA_{Y1} - OWSA_{Y2}}{OWSA_{Y2}}) \times 100$, where OWSA = open water surface area (m^2), Y1 = base year, Y2 = final year	Proposed by the authors

Instruments for in situ measurement, testing method specifications used in laboratory-based analyses and calculation techniques of few geospatial indicators are mentioned for possible universal adaptation of the developed C&I framework

(σ) values of all the C&I for the base year of the study. Then, either direct or inverse scores were assigned to the indicators following their positive and negative impact on the WEH, respectively. Firstly, indicators having positive impact were classified into five categories indicating different ecological health status, i.e., excellent health [$>(\mu + 1.5\sigma)$], good health [$(\mu + 0.5\sigma)$ to $(\mu + 1.5\sigma)$], moderate health [$(\mu - 0.5\sigma)$ to $(\mu + 0.5\sigma)$], weak health [$(\mu - 1.5\sigma)$ to $(\mu - 0.5\sigma)$] and morbid [$<(\mu - 1.5\sigma)$]. Secondly, indicators having negative impact were also scored with respect to these five categories, but in an inverse manner where $>(\mu + 1.5\sigma)$ values indicate morbid health and vice versa (Datta et al. 2010; Fontalvo-Herazo et al. 2007). Thereafter, a five-point scoring system following the Likert-scaling scheme was introduced to standardize data values containing measurements in different units and dimensions. Here, a score of 'five' indicates excellent health and 'one' represents morbid health, other intermediate scores represent good (4), moderate (3) and weak (2) health status, respectively (Datta et al. 2010). Thirdly, there were few indicators having a central optimal value condition with respect to WEH, meaning excellent health status at the center [$(\mu + 0.5\sigma)$ to $(\mu - 1.5\sigma)$] of value distribution and gradually the health status wanes away as one moves to either side of the data distribution. Thus, both of [$>(\mu + 2\sigma)$] and [$<(\mu - 2\sigma)$] indicate morbid status. Fourthly, there were some indicators that could not be assigned with the five-point scores as the outcome is in binary, e.g., 'yes' or 'no'. In this case, scores of 'five' for the best and 'one' for the worst were set to maintain parity in the overall scheme of scoring.

Assignment of indicator weight

The concept of C&I theoretically comes under the broader domain of the multiple criteria decision-making (MCDM) techniques (Datta et al. 2010; Ding et al. 2017). In these techniques, relative choices are made for evaluation, prioritization and selection of alternatives (*i*) or wetlands which are normally attributed by multiple mutually conflicting criteria/indicators. Each indicator represents some information that has a significant meaning and is certainly different from other indicators. Depending on the varying roles of indicators, not every indicator will carry equal weight. Therefore, one of the main objectives of MCDM is to find the appropriate weight for each indicator (*j*) (Taheriyoun et al. 2009). Among the different subjective and objective weight assignment techniques, the entropy weighting method (EWM) was applied here to assign relative weights to all the evaluation indicators (Dehdasht et al. 2020). Shannon's entropy (1948), an important measure of the likelihood of uncertainty in information theory, measures the relative importance of one indicator based on differences in information (Lotfi and Fallahnejad 2010; Monghasemi et al. 2015). It can equally be used for extracting objective weights for both qualitative and quantitative attributes. The larger the value of entropy related to a particular indicator, smaller will be the weight of that indicator and it will represent relatively lesser discriminatory capacity in the decision-making process and vice versa. For these reasons, the EWM is widely used by researchers to incorporate reliable outputs in decision-making regarding similar problems of natural resource management (Sahin 2021).

In EWM, m alternatives (e.g., wetlands) and n indicators are considered to evaluate the value of x_{ij}. Here, x_{ij} = the standardized score of jth indicator for ith wetland. The obtained decision matrix of these x_{ij} scores is further normalized by Eq. (1) in order to eliminate anomalies in data dimensions and convert different units and scales into common measurable units to facilitate comparisons of different indicators:

$$r_{ij} = \frac{X_{ij}}{\sum_{i=1}^{m} X_{ij}}, \tag{1}$$

where r_{ij} = the normalized score of jth indicator for ith wetland; $i=1, 2, 3, \ldots\ldots\ldots m$; $j=1, 2, 3, \ldots\ldots\ldots n$. Then, entropy ($e_j$) for each indicator was computed as follows:

$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m} r_{ij}\ln r_{ij}, \tag{2}$$

where $\ln r_{ij}$ is defined as 0, if $r_{ij} = 0$. Thereafter, the calculation of degree of variation (d_j) for each criterion was done as:

$$d_j = 1 - e_j, \tag{3}$$

where d_j measures the degree of variation of vital information for the jth indicator. Lastly, calculation of the final entropy weight for each indicator (w_j) was as follows:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}. \tag{4}$$

Construction of CWEHI using TOPSIS method

A comprehensive ecological health index (CWEHI) to infer the overall condition of the wetlands was developed by merging the weighted scores of indicators (fourth level) under each system (second level), i.e., pressure or state or response. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was applied in this regard as the method of aggregation towards constructing this composite index (Hwang and Yoon 1981; Yoon and Hwang 1985; Aslam et al. 2021). TOPSIS relies on the principle that the mostly preferred alternative should have the shortest geometric distance from the positive ideal solution (PIS) and the longest geometric distance from the negative ideal solution (NIS). It allows differentiation among alternatives in terms of weight of each indicator, its normalized score and geometric distance between alternatives in terms of each criterion. Here, ideal alternative is the one which scores the best in each criterion (Dakos et al. 2015). For the construction of CWEHI using TOPSIS, an evaluation matrix (X) was conceived first and may be described as:

$$X = (x_{ij})_{m\times n} = \begin{bmatrix} x_{11}, & x_{12}, & x_{1n} \\ x_{21}, & x_{22}, & x_{2n} \\ x_{m1} & x_{m2} & x_{mn} \end{bmatrix}, \tag{5}$$

where m denotes the total number of wetlands within the complex (P). $P = \{P_i|i = 1, 2, \ldots, m\}$; n denotes total number of evaluation indicators under a criterion (C); $C = \{C_j|j = 1, 2, \ldots, n\}$. The normalization of the evaluation matrix and computation of normalized score (r_{ij}) were done using the following equation:

$$\text{Normalized matrix, } R = (r_{ij})_{m\times n} = \begin{bmatrix} r_{11}, & r_{12}, & r_{1n} \\ r_{21}, & r_{22}, & r_{2n} \\ r_{m1} & r_{m2} & r_{mn} \end{bmatrix},$$

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}. \tag{6}$$

Thereafter, final normalized weighted score ($\mathrm{WS_{ij}}$) of an indicator was computed as:

$$WS_{ij} = r_{ij} \times w_j, \tag{7}$$

where W_j = final entropy weight for each indicator obtained through Shannon's EWM. $W = \{W_j|j = 1, 2, \ldots, n\}$; $W_j > 0\, and\, \sum_{j=1}^{n} W_j = 1$.

The determination of the best alternative (A_b) and the worst alternative (A_w) for each wetland (ith) was then assessed based on the impact of each indicator (positive or negative) interplayed upon the cumulative characteristics of the wetlands. In this case,

$$\begin{aligned} A_b = \{ & \langle \min(r_{ij}|i = 1, 2, 3, \ldots.., m|j \in J_-\rangle, \\ & \langle \max(r_{ij}|i = 1, 2, 3, \ldots, m|j \in J_+\rangle \} \\ \equiv & \{r_{bj}|j = 1, 2, 3, \ldots, n\}, \end{aligned} \tag{8}$$

$$\begin{aligned} A_w = \{ & \langle \max(r_{ij}|i = 1, 2, 3, \ldots.., m|j \in J_-\rangle, \\ & \langle \min(r_{ij}|i = 1, 2, 3, \ldots, m|j \in J_+\rangle \} \\ \equiv & \{r_{wj}|j = 1, 2, 3, \ldots, n\}, \end{aligned} \tag{9}$$

where $J_+ = \{j = 1, 2, 3, \ldots.., n|j\}$ indicates indicator having positive impact, and $J_- = \{j = 1, 2, 3, \ldots.., n|j\}$ having negative impact on overall WEH.

The Euclidean distance ($Ed_b^+ \& Ed_w^-$, respectively) of the ith target alternative from the best and worst alternatives is measured, respectively, as following:

$$Ed_b^+ = \left[\sum_{j=1}^{m}\left(V_{ij} - V_j^+\right)^2\right]^{0.5}, \tag{10}$$

$$Ed_w^- = \left[\sum_{j=1}^{m}\left(V_{ij} - V_j^-\right)^2\right]^{0.5}, \tag{11}$$

where Ed_b^+ and Ed_w^- are two distances from the target alternative i to the PIS and NIS, respectively.

The CWEHI of each wetland under each system component is then computed by Eq. (11):

$$\text{CWEHI}_i = \frac{Ed_w^-}{(Ed_w^- + Ed_b^+)}, \tag{12}$$

where $0 \leq Ed_{iw} \leq 1$; $i = 1, 2, 3, \ldots.., m$; $\text{CWEHI}_\text{i} \leq 1$, in case the alternative has a better condition; and $\text{CWEHI}_\text{i} \geq 0$, when the alternative solution has an inferior condition. All wetlands were then ranked in ascending order based on these CWEHI_i values for each system (Ren et al. 2014; Sun et al. 2019). All wetlands were also classified using the CWEHI scores as 'morbid' (≤0.20), 'weak health' (0.21–0.40), 'moderate health' (0.41–0.60), 'good health' (0.61–0.80) and 'excellent health' (≥0.81) as per standard scientific literature on this aspect (Additional file 1: Table S1) (Sun et al. 2017; You et al. 2019).

Results

Developed C&I for assessment of WEH

A comprehensive set of C&I was constructed to measure the WEH in a floodplain environment based on the PSR approach. The set contains 8 criteria and 38 indicators under the pressure component, 7 criteria and 49 indicators under the state component, as well as 4 criteria and 18 indicators under the response component (Tables 2, 3, and 4). Although this C&I set was initially applied to Ichhamati floodplain wetlands for WEH measurement in this study as test cases, we, however, propose that it may equally be applicable to any similar site worldwide with site-specific minor modifications. Along with the indicators, their relative weights were also specifically assigned for the assessment years, viz. 2016 and 2022, using the EWM. In addition, the type of relationship, i.e., positive or negative, between the individual indicators and WEH under a particular system component was explicitly stated here. Again, these relationships were fixed based on the studied wetlands only and, therefore, might vary in direction elsewhere depending on the local conditions and management priorities.

Changing ecological health of pressure system component

The poorest WEH status (morbid) of pressure system among the studied wetlands was found in Panchpota (0.19), followed by Panchita (0.24), Aromdanga (0.25), and Gopalnagar wetland (0.34) in 2016 (Table 5). In contrast, good health status in pressure system was found in Madhabpur wetland (0.69) in 2016 (Fig. 4). In general, the pressure-related WEH of the wetland complex had not changed noticeably in 2022 since all the wetlands except Panchpota (morbid to weak health) remained under the same health classes as those were in 2016. Among all, the Madhabpur wetland had again scored higher CWEHI in 2022 (0.72 with 4.35% increase as compared to 2016) indicating a decreasing trend of environmental pressure. However, Panchita (0.23 with 4.17% decrease), Aromdanga (0.29 with 16% increase) and Gopalnagar (0.33 with 2.94% decrease) wetlands had been found with morbid and weak health status of pressure system, respectively, in this later assessment (Table 6). Overall, the wetland complex represented very high levels of environmental pressure throughout the assessment period.

Changing ecological health of state system component

Owing to the overwhelming environmental pressure, majority of the wetlands of the studied complex exhibited weak WEH status of the state system in 2016. In this assessment year, the lowest CWEHI score for the state system was found in Berkrishnapur (0.21) followed by the Panchpota (0.24), Panchita (0.33), and Aromdanga (0.36) wetlands. While Gopalnagar (0.50) and Manigram (0.59) wetlands showed moderate WEH status during this time, excellent WEH status had been achieved only by the Madhabpur wetland (0.88). In 2022, the major detrimental changes in the health of state system were observed in the Berkrishnapur (0.19 with 9.52% decrease: from weak to morbid health) and Aromdanga (0.20 with 44.44% decrease; from weak to morbid health) wetlands. Only the Panchita (0.32 with 3.03% decrease) wetland retained its same weak health status of the state component in this year. Two wetlands, namely Gopalnagar (0.46 with 8% decrease) and Manigram (0.59), were in the moderate health category like those of 2016. In addition, Panchpota also joined (0.42 with 75% increase) this category. Again,

Table 2 Set of criteria and indicators (C&I) and indicator weights for assessment of wetland pressure system

Evaluation criterion	Indicator	Relation with WEH	Indicator weight	
			(W_j), 2016	(W_j), 2022
Catchment characteristics of wetlands	Status of human-induced stresses on LULC of WIZ (P_1)	–	0.023	0.028
	Areal fragmentation of perennial wetland zone (P_2)	–	0.023	0.028
	Arable land area per capita (P_3)	+	0.019	0.031
Pressure on hydrology: physical components	Intensity of point sources of pollution (P_4)	–	0.035	0.037
	Rate of change of non-point pollution in the wetland influence zone (P_5)	–	0.023	0.029
	Water resource ownership per capita (P_6)	–	0.017	0.036
	Change in hydraulic perimeter of channel inlet (P_7)	+	0.033	0.033
	Rate of change of water flow in channel inlet (P_8)	+	0.151	0.128
	Change in hydraulic perimeter of channel outlet (P_9)	+	0.033	0.028
	Rate of change of water flow in channel outlet (P_{10})	+	0.151	0.128
Pressure on hydrology: chemical components	Status of saline water intrusion through inlets (P_{11})	–	0.053	0.028
	Status of fecal coliform bacteria (P_{12})	–	0.031	0.026
	Amount of phosphate in wetland water (P_{13})	–	0.026	0.024
	Amount of ammoniacal nitrogen (P_{14})	–	0.040	0.034
	Amount of nitrate in wetland water (P_{15})	–	0.019	0.015
	Amount of arsenic in wetland water (P_{16})	–	0.000	0.019
	Amount of fluoride in wetland water (P_{17})	–	0.039	0.028
Pressure on wetland soils: physical components	Rate of sedimentation (P_{18})	–	0.017	0.015
	Availability of soil moisture (P_{19})	+	0.004	0.004
Pressure on wetland soils: chemical components	Number of chemical pesticides and insecticides used in WIZ (P_{20})	–	0.033	0.033
	Number of chemical fertilizers used in WIZ (P_{21})	–	0.031	0.025
Pressure on biota: floral components	Status of invasive species within WPZ (P_{22})	–	0.033	0.022
	Status of invasive species within WIZ (P_{23})	–	0.023	0.022
	Magnitude of harmfulness of invasive plant species (P_{24})	–	0.006	0.017
Pressure on biota: faunal components	Occurrence of exotic insects (P_{25})	–	0.007	0.011
	Magnitude of harmfulness of insects (P_{26})	–	0.009	0.008
	Level of introduction of exotic fishes (P_{27})	–	0.014	0.018
Pressure from livelihood activities	Household density (P_{28})	–	0.014	0.034
	Road density (P_{29})	–	0.013	0.019
	Number of dependent populaces per unit land (P_{30})	–	0.031	0.026
	Poaching intensity of birds (P_{31})	–	0.002	0.008
	Status of lift irrigation from wetlands and inlets to total water (P_{32})	–	0.011	0.019
	Irrigational water for agricultural purposes from ground water (P_{33})	–	0.005	0.017
	Human disturbance intensity (P_{34})	–	0.014	0.008
	Intensity of using of finer nets for catching fishes (P_{35})	–	0.004	0.007
	Intensity of using WIZ for sanitation and domestic purposes (P_{36})	–	0.005	0.001
	Intensity of using WIZ for animal husbandry (P_{37})	–	0.005	0.003
	Intensity of using WIZ for jute retting (P_{38})	–	0.005	0.003

only the Madhabpur wetland (0.95) achieved an excellent health status in 2022. In fact, this wetland recorded a notable increase of 7.95% in its CWEHI score in 2022, when compared to that of 2016.

Changing ecological health of response system component

Among the three system components of WEH, most prominent changes were observed for the response system. In 2016, the poorest CWEHI scores for the response

Table 3 Set of C&I and indicator weights for assessment of wetland state system

Evaluation criterion	Indicator	Relation with WEH	Indicator weight	
			(W_j), 2016	(W_j), 2022
State of wetland catchment	Patch density (S_1)	+	0.037	0.033
	Largest patch index (S_2)	+	0.043	0.041
	Landscape diversity index (SHDI) (S_3)	+	0.039	0.033
	Landscape contagion index of WIZ (S_4)	+	0.032	0.023
	Existing extent of WIZ around the wetland acting as buffer (S_5)	+	0.024	0.048
	Ratio of wetland wetted perimeter to WIZ perimeter acting as buffer (S_6)	+	0.012	0.036
State of wetland hydrology: physical properties	Depth of water (S_7)	+	0.036	0.035
	Average turbidity condition of wetland water (S_8)	–	0.034	0.023
	Temperature of surface water of wetland (S_9)	–	0.014	0.007
State of wetland hydrology: chemical properties	Status of biological oxygen demand (S_{10})	–	0.036	0.034
	Status of chemical oxygen demand (S_{11})	–	0.036	0.034
	Status of pH (S_{12})	–	0.018	0.015
	Concentration of cadmium (S_{13})			
	Concentration of mercury (S_{14})			
	Concentration of lead (S_{15})			
	Concentration of chromium(S_{16})			
	Status of dissolved oxygen (S_{17})	+	0.011	0.034
	Eutrophication level (S_{18})	–	0.043	0.070
	Status of salinity of wetland water (S_{19})	–	0.016	0.017
State of wetland soils: physico-chemical components (WIZ)	Status of soil bulk density (S_{20})	–	0.014	0.011
	Available nitrogen (S_{21})	+	0.033	0.033
	Available phosphorus (S_{22})	+	0.021	0.034
	Status of potassium (S_{23})	+	0.016	0.029
	Status of organic carbon (S_{24})	+	0.016	0.012
	Soil electrical conductivity (S_{25})	–	0.036	0.035
	Soil pH (S_{26})	–	0.035	0.034
	Concentration of arsenic (S_{27})	–	–	–
	Concentration of cadmium (S_{28})	–	–	–
	Concentration of mercury (S_{29})	–	–	–
	Concentration of lead (S_{30})	–	–	–
	Concentration of chromium (S_{31})	–	–	–
State of wetland biota: floral characteristics	Normalized difference vegetation index (NDVI) (S_{32})	+	0.021	0.015
	Species diversity in WPZ (S_{33})	+	0.024	0.017
	Species diversity in WIZ (S_{34})	+	0.030	0.028
	Tree density in WIZ (S_{35})	+	0.035	0.034
	Number of dominant aquatic species (S_{36})	+	0.027	0.027
	Level of presence of eutrophic species (S_{37})	–	0.021	0.036
State of wetland biota: faunal characteristics	Status of fish diversity (S_{38})	+	0.030	0.036
	Status of avifauna diversity (S_{39})	+	0.000	0.003

Table 3 (continued)

Evaluation criterion	Indicator	Relation with WEH	Indicator weight	
			(W_j), 2016	(W_j), 2022
State of ecosystem products and services derived from the wetland	Status of crop productivity (S_{40})	+	0.026	0.003
	Availability of sellable wetland flora (S_{41})	+	0.043	0.009
	Availability of sellable fishes (S_{42})	+	0.018	0.015
	Availability of another sellable wetland fauna (S_{43})	+	0.008	0.013
	Potential to regulate floodwater (S_{44})	+	0.016	0.034
	Potential to ground water recharging (S_{45})	+	0.012	0.002
	Capacity of the wetland to facilitate transport (S_{46})	+	0.021	0.002
	Potential of the wetland as an ecotourism site (S_{47})	+	0.036	0.019
	Realization of educational and recreational values (S_{48})	+	0.018	0.021
	Presence of traditional, esthetic and ritual values (S_{49})	+	0.012	0.013

Table 4 Set of C&I and indicator weights for assessment of response systems of wetland

Evaluation criterion	Indicator	Relation with WEH	Indicator weight	
			(W_j), 2016	(W_j), 2022
Ecological response	Rate of change of vegetation area (R_1)	–	0.030	0.154
	Rate of change of water cover area (R_2)	–	0.030	0.127
	Rate of change in number of sites functioning as habitat of migratory birds within WIZ (R_3)	–	0.085	0.153
	Intensity of prominent soil erosion (R_4)	–	0.002	0.045
	Frequency of floods (R_5)	–	0.002	0.043
	Incidence of fish species extinction (R_6)	–	0.003	0.024
	Incidence of plant species extinction (R_7)	–	0.008	0.015
Economic and epidemiological responses	Intensity of out migration in fishermen community (R_8)	–	0.010	0.029
	Level of satisfaction of the local community regarding livelihood generating potential of the wetland (R_9)	+	0.019	0.021
	Water borne diseases (R_{10})	–	0.104	0.069
Socio-cultural response	Rate of extinction of wetland related traditional rituals/activities/traits (R_{11})	–	0.060	0.032
	Status of public environmental awareness (R_{12})	+	0.051	0.019
	Status of wetland conservation and sustainable utilization initiatives (R_{13})	+	0.203	0.082
	Status of research activities (R_{14})	+	0.185	0.112
Management response	Incidence of plantation and weed removal programme (R_{15})	+	0.208	0.075
	Waste water treatment index (R_{16})	+	0.000	0.000
	Intensity of soil erosion management initiatives (R_{17})	+	0.000	0.000
	Incidence of organic farming (R_{18})	+	0.000	0.000

system were found in the Aromdanga (0.05) and Berkrishnapur (0.06) wetlands, thereby pointing towards their morbid WEH status. While two wetlands, namely Panchpota (0.27) and Panchita (0.37), received a weak health status, other two wetlands, namely Gopalnagar (0.56) and Manigram (0.60) were found with the moderate health status for this component in 2016. Similar to that of the state system component, only the Madhabpur wetland (0.95) achieved an excellent health status in terms of the response system in 2016 possibly due to the prevailing wise-use practices of both local fishermen and farmers (Additional file 1: Table S2). In the later assessment year of 2022, only the Manigram (0.63 with 5% increase) wetland showed a notable increase from its

Table 5 Status of the comprehensive wetland ecological health index (CWEHI) for 2016 and 2022 for pressure, state, and response system components of the studied wetlands

System health status						
Wetland	**2016**			**2022**		
	Pressure	**State**	**Response**	**Pressure**	**State**	**Response**
Berkrishnapur	0.51	0.21	0.06	0.50	0.19	0.06
Panchpota	0.19	0.24	0.27	0.21	0.42	0.28
Panchita	0.24	0.33	0.37	0.23	0.32	0.16
Aromdanga	0.25	0.36	0.05	0.29	0.20	0.08
Gopalnagar	0.34	0.50	0.56	0.33	0.46	0.37
Manigram	0.49	0.59	0.60	0.48	0.59	0.63
Madhabpur	0.69	0.88	0.95	0.72	0.95	0.97

Index values were obtained using the set of C&I developed in this study

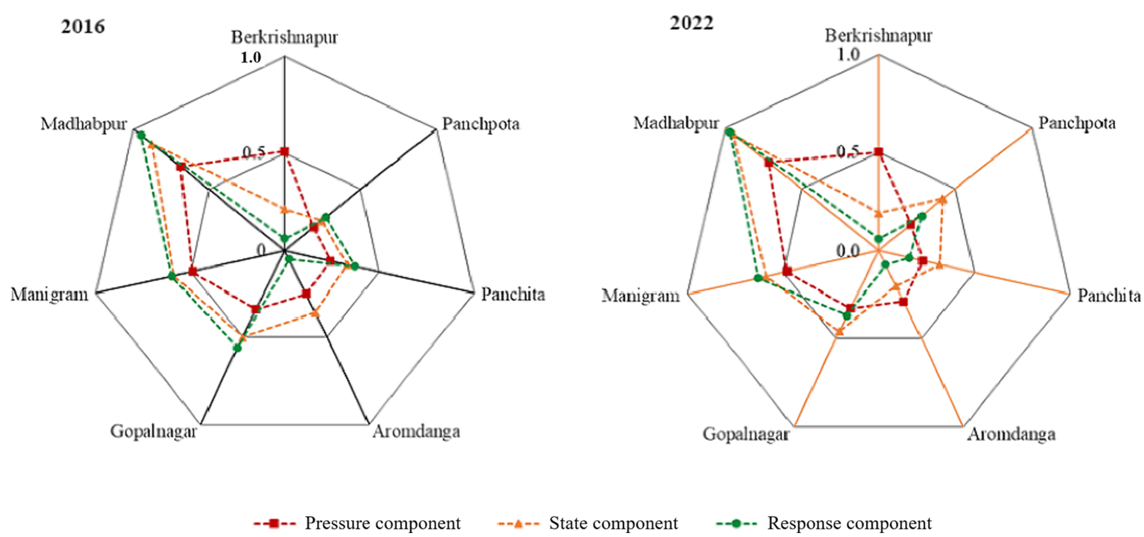

Fig. 4 Changing wetland ecological health status from 2016 to 2022

moderate WEH status to a good health status under the response system. Moreover, Madhabpur wetland also bettered its condition (0.97 with 2.11% increase; excellent health) during this year. This noteworthy performance of the Madhabpur wetland may be attributed to the continuation of pre-existing good practices as well as newly introduced awareness campaigns and workshops by a non-governmental organization with local fishermen and farmers. Conversely, WEH of response system decreased considerably at Panchita (0.16 with 56.76% decrease) and Gopalnagar (0.37 with 33.93% decrease) wetlands in 2022. Other wetlands, namely Aromdanga (0.08), Panchpota (0.28) and Berkrishnapur (0.06) almost maintained a status quo in terms of their response-based WEH status, thereby mostly representing weak to morbid health conditions.

Discussion

Evaluating WEH is often a challenging task chiefly since the CWEHI value depends on the performance score of each indicator, arranged hierarchically within the diverse and dynamic set of C&I, and measured at varied scales and dimensions (Datta and Chatterjee 2012; Mao et al. 2014). In some instances, the CWEHI score might not represent the actual condition of a specific ecological aspect of a wetland, and for that, intensive analysis focussed on specific indicator(s) related to that aspect had to be conducted (Chattopadhyay and Datta 2010). Since the developed set of C&I here comprised a staggering 105 indicators, this kind of indicator(s)-specific analyses become more imperative in unearthing the socio-ecological complexities of these intensely humanized wetland sites (Roy et al. 2020). During assignment

Table 6 A comparative account of the ecological health status of pressure, state and response systems of the studied wetlands in 2016 and 2022, respectively

Year	2016					2022				
CWEHI range	**(≥ 0.81)**	**(0.61–0.80)**	**(0.41–0.60)**	**(0.21–0.40)**	**(≤ 0.20)**	**(≥ 0.81)**	**(0.61–0.80)**	**(0.41–0.60)**	**(0.21–0.40)**	**(≤ 0.20)**
HS	**Excellent health**	**Good health**	**Moderate health**	**Weak health**	**Morbid**	**Excellent health**	**Good health**	**Moderate health**	**Weak health**	**Morbid**
Berkrishnapur			P	S	R			P		SR
Panchpota				SR	P			S	RP	
Panchita				PSR					PS	R
Aromdanga				PS	R				P	SR
Gopalnagar			SR	P				S	RP	
Manigram			PSR				R	PS		
Madhabpur	SR	P				SR	P			

CWEHI comprehensive wetland ecological health index; *HS* ecological health status category of relative weight, few indicators were found to be least important with respect to the existing scenario of the studied wetland complex in an assessment year (2016 and/or 2022) and, therefore, were removed from the respective CWEHI estimation. For example, indicators such as the amount of Cd, Hg, Pb, and Cr in wetland water (in 2016 and 2022) as well as concentration of As, Cd, Hg, Pb, and Cr in wetland soil (in 2016 and 2022) were found with negligible concentration and were, therefore, excluded from the developed C&I set in this case. Besides, few indicators such as the amount of As in wetland water (in 2016), waste water treatment index (in 2016 and 2022), intensity of soil erosion management initiatives (in 2016 and 2022), and incidence of organic farming (in 2016 and 2022) were registered with zero weight in this study and, subsequently, did not have any role in CWEHI estimation. However, these same indicators might become highly relevant elsewhere and accrue larger weights. Since the relative weights were derived only from the empirically measured values (successively transformed into scores) of the indicators in this supervised learning methodology, the application of EWM, as a bias-reducing weight assignment technique, had proven to be immensely beneficial here (Datta et al. 2010; Mao et al. 2014).

Regarding the overall condition of the pressure system component, the same four wetlands (viz. Panchpota, Panchita, Aromdanga, and Gopalnagar) in 2016 as well as 2022 showed either a weak or a morbid WEH status (< 0.40). The indicator-level assessments clearly revealed this was primarily due to the rapid transformation of LULC patterns, intensified settlement densities, accelerated fragmentation of perennial wetland areas, mushrooming of multiple point and non-point pollution sources, excessive use of chemical fertilizers, pesticides and insecticides within the WIZ of most of these wetlands. In the recent past, incessant construction of houses and roads along and across wetlands (Aromdanga and Gopalnagar) as well as expansion and concretization of the major roads and railway lines (e.g., State Highway-14, Bangaon-Helencha road and Bangaon-Ranaghat railway line) have further exacerbated pollution and led to substantial deterioration of WEH in the whole wetland complex (Sun et al. 2019). Moreover, intensive culture of exotic fishing, use of finer fishing nets, rampant extraction of water for irrigation, wide-spread jute-retting, washing and bathing activities also affected wetlands like Berkrishnapur and Manigram, although these are still showing a moderate WEH status for pressure (Mondal and Kaviraj 2007; Ghosh and Biswas 2018). In all wetlands except Madhabpur, illegal trapping and selling of endangered species such as migratory waterbirds, cuchia fish (*Monopterus cuchia*), freshwater turtles and tortoise caused rapid deterioration of the WEH status, posing a major threat to regional biodiversity (Mondal and Kaviraj 2007; Gayen et al. 2020). Only the Madhabpur (0.69) wetland was found with comparatively low environmental pressure in 2016 and even a lesser pressure (0.72) in 2022 that may be attributed to the almost absence of jute-retting activities, lesser amount of arable land within the WIZ, and existing good management practices exercised by fishing cooperative members and farmers. Although the WEH status of the studied wetlands was largely controlled by anthropogenic factors, the role of few biogeochemical parameters such as sedimentation characteristics, weed infestation rate, absence of river inflow and outflow during lean seasons, and climatic changes should also be accounted in this regard in spite of the fact that these later ones mostly exerted regional level impacts (Ansari et al. 2010; Chen and Wong 2016; Gayen et al. 2020; Bhattacharjee et al. 2023).

WEH status of the state system declined in four wetlands from 2016 to 2022, indicating their unsatisfactory performances under the state-based indicators mainly due to incessant environmental pressure on these wetlands (Datta et al. 2022). Among these, three were agriculture-dominated wetlands (Berkrishnapur, Aromdanga, and Gopalnagar) and one was fishing-dominated wetland (Panchpota). Higher patch density of non-water LULCs, decreasing water depth, increased turbidity, low DO and high BOD, high eutrophication level, presence of excess amount of phosphorus and nitrogen in wetland water, low fish and other faunal diversity, etc., were identified as the major reasons of the lower scores of these indicators (Ansari et al. 2010). Subsequently, the availability of various ecosystem services and wetland biota with commercial as well as subsistence value were found to be alarmingly diminished (Chislock et al. 2013; Mazumder et al. 2021). Again, only the fishing-dominated Madhabpur wetland retained its exceptional health status along with the Manigram wetland (moderate WEH status) under the state system, largely due to the good practices performed by the fishing cooperative members and fishermen, thereby sustaining the vital ecological processes.

The societal, ecological, and institutional responses of the studied wetlands in relation to the impending pressure and existing state systems varied, both spatially and temporarily. While most of the wetlands failed to respond adequately to the deteriorating ecological state and, thereby, were found in either weak or morbid status of WEH-based response, only the Madhabpur and Manigram wetlands exhibited relatively better status of the same. Lesser rates of change of watered areas, higher number of avifauna habitat sites, infrequent soil erosion, effective plantation schemes, and, most importantly, enhanced levels of community awareness and participatory management activities in the WIZ were recognized as the key features of better responses of these two wetlands. However, the response conditions, in general, either slightly bettered or remained almost same from 2016 to 2022 in case of five wetlands except Gopalnagar and Panchita. This pointed to the fact that the regional socio-ecological system was gradually trying to cope with the burgeoning pressure component and alleviate the already deteriorated state component, albeit in a very slow manner. Hence, this remains to be seen in the imminent years whether this abysmally slow response rate would be enough to make the wetland complex resilient against augmented environmental transformations, mostly led by climatic changes (Bhattacharjee et al. 2023; Roy et al. 2021). This apprehension gets further validation from the derived format of indicator weights in which the indicators with zero weights were mostly emanating from the response system, thereby becoming ineffective in further assessment of WEH (Table 4).

Conclusions

Sustainable management of WEH is not entirely an ecological matter; rather it is entangled among ecological, socio-economic, and institutional issues that frequently augment the management complexity in reality (Wang et al. 2011). This study provided a comprehensive yet in-depth analysis of the PSR-based C&I development approach with the help of an illustrative example. The set of C&I, developed in this study, encompasses all the relevant sustainability issues of wetland management mentioned above. The application of PSR approach made it convenient to distinctly identify the drivers of WEH dynamics in a causal structure and quantify those accordingly (Cui and Yang 2002). It facilitated the development of a hierarchical analytical framework in which, at one end, every small aspect of WEH could be evaluated with ease and, at the other, the overall appraisal of system components could be done by a unique degree, composite score, or index of WEH (e.g., CWEHI in this study). In this regard, the use of EWM and TOPSIS as weight assigning and aggregation procedure of indicators, respectively, within the broad PSR approach enabled the researchers to successfully address the common problems of sustainability assessments, viz. ambiguity, biased weight, and boundary uncertainties of indicator-wise scoring (Aslam et al. 2021). Of course, the study could have been better if provisions of continuous measurements were there and live-monitoring-based findings could have been readily translated into management outcomes (Sun et al. 2017). However, that sort of sophistication of evaluation methodology and monitoring infrastructure was certainly out of the scope and ambit of the present study, keeping in mind the socio-economic realties and practical logistic-related impediments existing in the intensely humanized rural landscapes of eastern India. Thus, considering all the pros and cons, we firmly advocate the further application of the developed C&I in similar studies of WEH elsewhere as a highly refined and holistic method of evaluation.

This study found that primarily the absence of persistent inflow and outflow from the main river channel and degeneration of River Ichhamati, wide-spread jute-retting activities, indiscriminate use of chemical fertilizers and pesticides, and infestation of water hyacinth along with other aquatic weeds have exacerbated the processes of wetland degradation and eutrophication in the wetland complex. As a result, biodiversity status, ecosystem services, and range of human non-economic uses of these wetlands have been observed to decline alarmingly in this region. Therefore, the results of this study could provide meaningful information on WEH for the stakeholders and environmental planners to take site-specific management strategies. Future in-depth researches may be conducted on the level of wetland degradation-induced weakening of public health, environmental recovery strategies in weed engulfed and eutrophicated wetlands, sustainable management of water hyacinths and other aquatic weeds, and their specific ecological roles in influencing wetland systems on a landscape scale in this region.

Abbreviations

BOD	Biological oxygen demand
C&I	Criteria and indicators
COD	Chemical oxygen demand
CWEHI	Comprehensive wetland ecosystem health index
DO	Dissolved oxygen
EC	Electrical conductivity
EWM	Entropy weighting method
FGD	Focus group discussion
GBM	Ganges–Brahmaputra–Meghna
LCI	Landscape contagion index
LPI	Largest patch index
LSDI	Landscape diversity index
LULC	Land use/land cover
MCDM	Multiple criteria decision-making
NDVI	Normalized difference vegetation index
NIS	Negative ideal solution
OECD	Organisation for Economic Co-Operation and Development
PD	Patch density
PSR	Pressure–state–response
RS	Remote sensing
TC	Total coliform
TOC	Total organic carbon
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
WEH	Wetland ecosystem health
WIZ	Wetland influence zone
WPZ	Wetland perennial zone

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13717-023-00447-8.

Additional file 1: Table S1. Health status, score based classification of CWEHI and ecological characteristics of studied wetland. **Table S2.** Environmental attributes of studied wetlands of the Ichhamati floodplains. The environmental attributes are modified after Gayen et al. (2020). The presence or absence of an environmental characteristic is indicated by yes (+) or no (-), respectively. W1 = Berkrishnapur, W2 = Panchpota, W3 = Panchita, W4 = Aromdanga, W5 = Gopalnagar, W6 = Manigram W7 = Madhabpur (Source: Primary field survey, 2015–2022 and focus group discussions with stakeholder groups in each wetland)

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Author contributions
JG and DD conceptualized and designed the study. JG performed the field surveys and ecological measurements. Organization of C&I was done by both JG and DD. Statistical analyses were conducted by DD and JG. All authors contributed equally to the interpretation and discussion of the results. JG wrote the first draft and DD read, revised, and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests regarding the publication of this paper.

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