TYPOLOGICAL INVENTORIZATION AND RAPID ECOLOGICAL HEALTH ASSESSMENT OF THE WETLANDS OF MEDINIPUR COASTAL PLAIN, INDIA

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Abstract
Coastal wetlands provide a multitude of ecosystem services and diversified livelihood opportunities for millions in India. Due to unsustainable human activities and recent climatic anomalies, many of these wetlands are losing their ecological vitality and even extirpating in extreme cases; as evident in the Medinipur Coastal Plain of Eastern India. However, no comprehensive management plan has been framed till date, towards sustainable utilization of these wetlands. In this context, development of an appropriate regional wetland inventory, based on relevant ecological parameters, was conceived to be the pre-requisite for implementing such management strategies. Accordingly, an attempt had been made here to develop a typological inventory based on the ecological health status of major wetlands (>2.25 ha) of this region. Cumulatively, four varied ecological health scenarios were identified for these wetlands using multi-source geospatial datasets, on-field measurements, focus group discussions, and secondary sources. Specifically, wetlands with lesser human footprints, synergetic agroecosystem practices, and better intertidal connectivity displayed superior ecological health compared to the ones associated with tourism and aquafarming. It was also realized that this study could greatly enhance the decision making capability of the stakeholders, researchers, and policy makers involved in sustainable management of these resources.

Key words
Anthropogenic stress, Aquatic ecosystem, Brackish water farming, Ecological indicator, Sustainable livelihood.

INTRODUCTION

Coastal wetlands occupy the transitional zones between land and sea, consequently merging both marine and terrestrial ecosystems. In general, these ecosystems support a rich biological diversity, which is highly beneficial for generating a wide range of livelihood opportunities for communities living near wetlands, as well as promoting broader regional economic activities (Fretwell et al., 1996;

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Lee et al., 2006; Borchert et al., 2018). The saline environment of shallow marine water, coral reef, estuarine mudflat, salt marsh and lagoon offers favourable conditions for commercial fishing and aquaculture; specifically, in the tropics where different types of euryhaline fishes, crustaceans and halophytic plants are found in abundance (Lee et al., 2006; Secretariat of the Ramsar Convention, 2010; Borchert et al., 2018). In addition, the rain-fed coastal depressions are also utilized here for paddy-cum-brackish water fish cultivation, which has been identified as one of the most effective instances of agroecosystem practices in tropical Asia (Datta et al., 2012; Lescourret et al., 2015; Langerwisch et al., 2017; Kumaran et al., 2020).

Being an abode to both terrestrial and marine organisms, coastal wetlands are favoured by many fishes (*viz. Harpadon nehereus, Hilsa kelee, Penaeus monodon, Pampus argenteus*), reptiles (*viz. Lepidochelys olivacea, Varanus salvator*) and water birds (*viz. Ardea alba, Calidris ferruginea, Pelargopsis capensis*) for breeding and migratory activities (Chakraborty, 2017). In fact, millions of migratory waterbirds feed on the extensive fish population which thrive here (Sievers et al., 2018). However, the habitat conditions of these wetlands have severely degraded due to several perilous natural and anthropogenic forces in recent times (Kennish, 2002; Barbier et al., 2011). Occurrences of eminent eustatic changes, repetitive extreme cyclones, destructive tsunami waves, and striking tidal surges were the naturally occurring factors chiefly responsible for the deteriorating habitat condition of these wetlands. However, the degree of decaying has noticeably accelerated due to the addition of human induced stresses (Cahoon et al., 2006; Datta et al., 2012). Expansion of coastal settlements, growth of beach tourism, construction of protective embankments, commercial aquafarming, extensive crop farming and over exploitation of wetland resources are some factors responsible for the degradation and increasing vulnerability of this fragile coastal ecosystem (Kirwan and Megonigal, 2013; Roy and Datta, 2018).

Along the East Coast of India, the states of West Bengal and Odisha have noticeably high concentration of coastal wetlands (Venkataraman, 2008). Though a major part of the West Bengal coast is bordered by the Sundarbans mangrove swamps, its south-western littoral part is also interspersed with several other types of coastal wetlands (*e.g.* intertidal mudflats, salt marshes, interdunal wetlands), which contributes to the wide range of biodiversity of this region (Chakraborty, 2017). These wetlands are primarily located in adjoining areas of tidal creeks, along the intertidal lowlands and within the interdunal swales. In reality, all of these wetlands and their coupled agricultural systems together create a rich coastal agroecosystem (Bassi et al., 2014). Over the last few decades, many of these wetlands have been converted into commercial fisheries, paddy mono-cropping fields and salt production units (Rani et al., 2015; Jayanthi et al., 2018).

The populace of coastal West Bengal and Odisha are notably dependent on either brackish water aquaculture or the emerging beach tourism activities of this region. The economic prospects offered here, lead this entire coastal tract to be populated gradually (Tripathy, 2012; Dutta et al., 2016). Eventually, this was only possible through reclaiming those coastal wetlands and altering its prevailing natural landscape (Dutta et al., 2016; Roy and Datta, 2018). An extensive review of literature indicates that the environmental conditions of many of these wetland complexes are degrading due to intrusion of polluting agents originating from fish farms and tourism industries (Lee et al., 2006; Chakraborty, 2010; Jayanthi et al., 2018; Ragavan et al., 2020).

In this context, the present study has been designed to develop a typological inventory and infer the current ecological health status of diversified coastal wetlands of the Medinipur coastal plain of West Bengal and Odisha. Several studies had already been conducted focusing on coastal morphodynamics and biological diversity of this region separately (Niyogi, 1975; Chakrabarti, 1995; Chakraborty, 2010; Roy and Mitra, 2019). However, no comprehensive environmental assessment of these wetlands has been done till date, on the integrated approach of inventorying and appraisement of ecological health. In view of this immense research gap, the present study had been primarily initiated to identify the major coastal wetland composites of the study region and thereby develop a typological inventory considering the major wetland composites under each distinct wetland types, already established in several relevant literatures (Secretariat of the Ramsar Convention, 2010; Panigrahy et al., 2011). Later on, a rapid ecological health assessment was also conducted on those major wetland composites.

METHODOLOGY

Delineation of the study region

The south-western part of littoral West Bengal occupies an elongated coastal tract along the margin of Bay of Bengal. This coastal tract, also known as Medinipur Coastal Plain (MCP), is situated along the Purba Medinipur district of West Bengal and extended till the Baleshwar district of Odisha (Chakrabarti, 1995; Chakrabarti and Nag, 2015; Roy and Datta, 2018). Noticeably, this 46 km long mesotidal (2-4 m) coastal plain is variegated in terms of several geomorphic features such as long sandy beaches, successive rows of dunes, interdunal swales, and intertidal mudflats (Niyogi, 1975; Chakrabarti, 1995; Chakrabarti and Nag, 2015). Specifically, these successive rows of dunes, parallel to the beaches from north to south, also known as frontal dunes; are one of the most prominent terrain units of this region. Among these, the Ancient Dune Complex (ADC) in the north and the beach-face dune complex in the south, act as the upper and lower extent of the MCP (Chakrabarti, 1991; Wal and McManus, 1993; Chakrabarti, 1995). Based on physiography, MCP can be divided into four sectors from west to east namely Digha, Chandpur, Dadanpatrabar and Junput. These sectors had been separated by few tidal inlets like Champa creek, Jaldha creek, and Pichaboni creek (Chakrabarti and Nag, 2015).

In the presence of the complex geomorphic setting, coupled with the regional hydrological system, different types of coastal wetlands have formed along this coastal plain among which mangroves, mudflats, saltmarshes and interdunal wetlands are the most prominent and naturally evolving wetland types of this region (Morris et al., 2002). Here, the mangrove patches are usually found along the sheltered coastline fringed with sandy or muddy beaches, adjacent to the clayey sediments supplied by several rivers (*e.g.* Subarnarekha, Rasulpur, and Haldi) and tidal creeks (Nayak and Bahuguna, 2001). Mudflats are also an integral part of these coastal wetlands, mostly developed due to sedimentation of clay rich sediments in the presence of calm depositional environment on either side of the estuaries (Nowacki and Ogston, 2013). Moreover, saltmarshes are usually found along the coastal depressions, located at the supratidal zone of Chandpur and Dadanpatrabar sectors; which were previously inundated by diurnal tides (Allen 2000). Some areas of this coastal plain are also characterized by marshy swales, identified as interdunal wetlands; generally, found along the depressions of both older as well as younger dune complexes of MCP (Running et al., 2002). However, these mudflats, saltmarshes and interdunal wetlands are rapidly being converted into aquacultural farms in places like Kirtaniajalpahi, Kumbhirgari, Sankarpur, Tajpur, Sona Muhi, Dakshin Purushottampur, Junput, and Bankiput during the last two

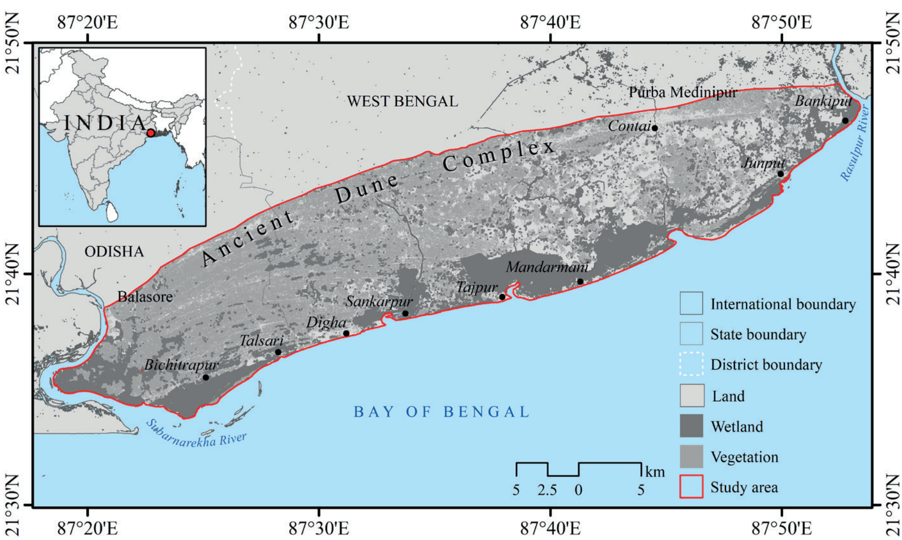

Figure 1
Location of the study region

decades. Consequently, these partially modified or constructed wetlands had also become integral parts of the regional coastal agroecosystem.

The MCP extends from the left bank of Subarnarekha estuary to the right bank of Rasulpur estuary and from the northern elongated arc shaped ADC to the southern continuous shoreline of Bay of Bengal (Fig. 1). The entire region was studied rigorously to develop a detailed inventory of diversified coastal wetlands with special focus on their ecological health status. The latitudinal and longitudinal extension of the study region was from 87°18 ′ 35″E to 87°53″19E and 21°32′56″N to 21°48′39″N occupying an area of nearly 64313.4 ha.

Comprehending coastal wetland typologies

A clear and discrete classification of tropical coastal wetlands has rarely been established by scholars in the related fields of research (Morris et al., 2002). However, Ramsar Convention on Wetlands provides a comprehensive definition of wetlands exhibiting an array of coastal wetland types such as estuaries, deltas, marshes, tidal flats, mangroves, coral reefs and salt pans (Secretariat of the Ramsar Convention, 2010). The information brochure of National Wetland Inventory and Assessment (NWIA) of India prepared under the joint initiative of Ministry of Environment and Forests (MOEF), Government of India (GOI), and Space Applications Centre of ISRO, Ahmedabad; provides copious information on different types of wetlands of India. According to this report, nineteen types of wetlands actually exist in India, among which nine types have been found along the coastal areas of West Bengal and Odisha (Panigrahy et al., 2011).

Based on peer reviewed literature on tropical coastal wetlands and analyzing the study region through on-field reconnaissance surveys, five distinct types of coastal wetlands *viz.* mangroves, mudflats, salt marshes, interdunal wetlands, and constructed wetlands had been identified, which were directly exposed to the numerous anthropogenic stressors. These wetland types were further verified with the wetland classification system of NWIA and Ramsar definition of wetlands. Among the five identified wetland types; mangroves, mudflats and salt marshes are situated at the active coastal zone (Morris et al., 2002). Conversely, Interdunal wetlands are mainly located far away from the present shoreline since it originated due to paleo marine-coastal actions during the transgressive phase of the late Holocene epoch (6000 years B.P.) along this coastal tract (Chakrabarti and Nag, 2015). Furthermore, constructed wetlands are usually found nearer to the coastline to take advantage of intrusive sea water during flood tide for practicing brackish water aquaculture (Dutta et al., 2016; Jayanthi et al., 2018).

Inventorization of coastal wetlands of the study region

The principal aim of any wetland inventory is to provide a detailed account of distribution, categorization and physiographic characteristics of diversified wetlands (Scott and Jones, 1995; Secretariat of the Ramsar Convention, 2010). Hence, identification of the probable types and perceiving their spatial distribution patterns is highly imperative before developing such an inventory. Accordingly, a typological inventory of coastal wetlands had been developed here considering multiple key indicators associated with the general characteristics of coastal wetlands as well as their surrounding environment. Information regarding those indicators had been derived from remote sensing (RS) and geographic information systems (GIS) along with field based observations and secondary data sources (Panigrahy et al., 2011; Chunye and Delu, 2017).

Initially, two multispectral satellite images, acquired by Sentinel 2B with 10 m spatial resolution (Date of acquisition: 15th April, 2018; Tile No.: T45QWE and T45QWD), were used for delineating the area of interest (AOI) of this study using the Erdas Imagine 2014 software (Shalaby and Tateishi, 2007; Datta and Deb, 2012; Roy and Datta, 2018). Thereafter, maximum likelihood algorithm based supervised classification technique had been applied on this AOI to identify the zones with water/ moisture content, as the spectral reflectance of land with high moisture content is completely different from the rest of the land use/ land covers (LULCs) (Lillesand et al., 2008; Li et al., 2018; Roy and Datta, 2018). Furthermore, the widely used Normalized Difference Water Index (NDWI) had been derived for the AOI to demarcate the area under perennial wetlands by detecting the changes in water content within green foliage (Ji et al., 2009; Kuleli et al., 2011; Kaplan and Avdan, 2017; Wu et al., 2018). McFeeters (1996) defined NDWI as the ratio of two possible combinations of Green and Near-Infrared (NIR) channels, which can also be explained using the following equation (i):

$$NDWI = (Green - NIR)/(Green + NIR) \qquad (i)$$

The value of NDWI ranges from -1 to +1, where higher value indicates more amount of water content in vegetation cover and vice versa (Ji et al., 2009). After corresponding the pixels having higher NDWI values with the pre-determined wetland areas obtained from the LULC classification maps; the actual spatial distribution of coastal wetlands had been delineated. Finally, the raster dataset covering all wetland sites of the region was converted into a vector layer (.shp) to make it compatible with ArcGIS platform for further geospatial analyses (McCarthy et al., 2018).

Through this procedure, approximately 78,419 individual wetland polygons had been identified. A shortlisting of major wetlands had further been done by removing small/ minor wetlands having an area of less than 2.25 ha and merging separate polygons under individual wetland composites (Panigrahy et al., 2011;

Tiner et al., 2015). Subsequently, around 203 individual wetland composites had been identified through this procedure. Among these, in terms of their maximum areal Coverage, the five biggest wetland composites were identified from each coastal wetland types and a total of 25 representative wetland composites were shortlisted from the entire study region for in-depth research. Few other indicators related to physical characteristics of wetlands (*i.e.* dominant land surface features, soil types, types of water, primary sources of water) as well as related socio-economic and institutional sustainability issues (*i.e.* presence of management organization, major livelihood option and existing threat to wetland ecosystem etc.) were also used for this purpose (Table 1). Accordingly, these 25 coastal wetlands were intensively studied to develop a typological inventory of the coastal wetlands of MCP. These indicators had been quantified by a mixed method incorporating geo-spatial databases, personal interactions with members of coastal communities, intensive field based observations and secondary data sources.

Table 1 Identified major indicators related with inventorization of coastal wetlands

Indicator	Description	Source
Areal extent (WA)	Wetlands with more than 2.25 ha area	Panigrahy et al., 2011; Tiner et al., 2015
Wetland type (WC)	NWIA, 2011	Panigrahy et al., 2011
Dominant land surface features (LF)	Dominated geomorphic features in the wetland area	Field observation
Soil type (ST)	USDA World Soil Information acquired from International Soil Reference and Information Centre (ISRIC)	FAO, 2014
Water type (WT)	Based on total dissolved solids (TDS) characteristics of water	Field measurement
Primary source of water (WS)	Information obtained from primary field based survey	Field survey
Presence of management organization (MO)	Profit and non-profit organization are engaged in environmental management	Focus group discussion
Major livelihood option (LO)	Wetland resource based rural livelihood pathways	Focus group discussion
Existing threat for wetland ecosystem (ET)	Adverse environmental impacts as offshoots of natural calamities and maladaptive economic engagements of inhabitants	Field observation and focus group discussion

Ecological health assessment of different types of coastal wetlands

Ecological health is a comprehensive concept, which represents a synthesis of the quality of different ecological indicators in a particular environmental state (Jørgensen et al., 2005; Datta and Deb, 2017). In this study, the status of ecological health was assessed for the selected 25 representative wetlands of the study region. Several indicators related to physical, chemical, and biotic characteristics of wetlands, human encroachment, and provisions of agroecosystem services (AES) were identified after reviewing relevant literature on ecological health indicators of coastal wetlands as well as from field based experiences (Table 2) (Jørgensen et al., 2005; Jiang et al., 2014; Datta and Deb, 2017). Some of the indicators (*e.g.* water pH and faecal coliform) were measured by testing wetland water samples under laboratory conditions (Alexakis et al., 2016; Sinaga et al., 2016). Conversely, some other indicators such as turbidity, dissolved oxygen, eutrophication status, and tree density were assessed or measured in-situ (Alexakis et al., 2016; Bachmann et al., 2017; Jakobsson and Lindborg, 2017). Information regarding dominant LULC patterns from around 500 m of the wetlands were collected through field observations of the investigators and validated by the open-source thematic database (https://bhuvan-app1.nrsc.gov.in/thematic/thematic/index.php) of national level LULC map (Scale 1:250,000) derived from the Advanced Wide-Field Sensor (AWiFS) data of Resourcesat-1 and 2 (NRSA, 2007). Information related to rest of the indicators (*e.g.* flooding frequency, seasonality or duration of water, status of weed infestation, presence of native rare or endangered floral and faunal species, spread status of invasive or exotic species, instances of mass death of animals as well as human-wildlife conflicts, and provision of agroecosystem services) were collected through focus group discussions (FGDs) with local community members in groups of 5-8 persons using a semi-structured questionnaire (Supplementary Table 1). Among these indicators, a detailed directory of native rare or endangered as well as invasive or exotic floral and faunal species were already prepared before surveying the coastal populace, using the open source data archive of the International Union for Conservation of Nature (IUCN), repository of the Botanical Survey of India and a priori knowledge of the investigators regarding the study region (MOEF, 2011; ENVIS Center on Floral diversity, 2016; IUCN, 2020). During these interactive sessions, care was taken for gathering as much local knowledge as possible on the wetland characteristics and their utilization scenarios (Krueger, 2014; Bartlett et al., 2017). Since, all of these selected indicators are equally liable to determine a healthy ecological condition of coastal wetlands, the multi-scaled original datasets of health indicators were standardized by assigning scores from 1 to 5, considering their impacts in maintaining an optimal environmental quality in a wetland (Datta and Ghosh, 2015). Here, the score of 1 represented very low and 5 represented very high status of ecological health. Through in-depth literature review, it had

Table 2 Identified ecological health indicators of coastal wetlands of the study region

Group	Indicator	Data source/ method of measurement	Reference
Physical	Flooding frequency (FF)	FGD	Tran and James, 2017
	Seasonality or duration of water cover (DW)	FGD	Tran and James, 2017
	Dominant land use in the immediate surroundings of wetland (DL)	In-situ field survey and open-source LULC of Bhuvan-AWiFS database	NRSA, 2007
	Presence of agroecosystem services (AES)	FGD	Lescourret et al., 2015
Biochemical	Water pH in logarithmic scale (pH)	Bench top pH meter (HANNA HI2221)	Datta and Deb, 2017
	Dissolved oxygen in mg l^{-1} (DO)	Portable EI Products' Digital DO Meter (Model 831 E)	Said et al., 2004; Jørgensen et al., 2005
	Turbidity in NTU (T)	Turbidity meter (HACH LXV322.99.00002)	Said et al., 2004
	Eutrophication status (EU)	In-situ field survey on algal bloom and Secchi depth transparency	Smith, 2003
	Faecal coliform in CFU ml^{-1} (FC)	Laboratory analysis by membrane filter technique	Said et al., 2004
Biotic	Tree density in number of trees ha^{-1} (TD)	In-situ field survey	Datta and Deb, 2017
	Status of weed infestation (WI)	FGD and in-situ field survey	Tomita et al., 2003
	Presence of native rare/ endangered plants in number of species ha^{-1} (EP)	FGD and in-situ field survey	Laba et al., 2008; ENVIS Center on Floral diversity, 2016; IUCN, 2020
	Status of invasive/ exotic plant species in number of species ha^{-1} (IP)	FGD and in-situ field survey	Laba et al., 2008; ENVIS Center on Floral diversity, 2016; IUCN, 2020
	Presence of native rare/ endangered animals in number of species ha^{-1} (EA)	FGD and in-situ field survey	Serafy et al., 2007; MOEF, 2011; IUCN, 2020
	Status of invasive/ exotic animal species ha^{-1} (IA)	FGD and in-situ field survey	Serafy et al., 2007; MOEF, 2011; IUCN, 2020
	Instance of mass-death of animals in last 5 years (AD)	FGD	Distefano, 2005
	Intensity of man-animal conflict (C)	FGD and in-situ field survey	Distefano, 2005

been observed that if the higher value of any indicator tended to be detrimental to the environmental sustainability of a wetland, then the score was given in an inverse order with 1 being the score of higher values and vice versa (Datta and Ghosh, 2015; Majumdar et al., 2019).

For the physical indicator of dominant LULC, the weightage given was dependent on the presence and nature of vegetal cover within a particular LULC class. For instance, other vegetation covers have been assigned higher score than Casuarina plantation and agricultural lands. In contrast, the rest of the physical indicators have been scored in a manner so that higher values of indicators correspond to higher scores (Supplementary Table 2).

A wide variety of chemical indicators had been used in this study to assess the wetland health in an inclusive manner. One of the most important chemical indicator is water pH, which was scored in a quite different manner. Since, the extreme conditions of pH, *viz.* highly acidic (<3) and highly alkaline (>11), were both not suitable for maintaining healthy wetland condition, minimum score was accordingly assigned to the corresponding extreme values. In this way, the maximum score had been specified to the optimum range of pH, from 6 to 8. For other chemical indicators such as status of eutrophication (EU), turbidity (T), and faecal coliform (FC), higher values were identified to be detrimental to wetland vitality. Hence, minimum scores were given with respect to higher values and vice versa.

Several biotic indicators associated with the floral and faunal diversity were also incorporated in this study to comprehend the relative ecological sensitivity of coastal wetlands. Among these, tree density (TD) (Supplementary Table 3), presence of endangered plant species (EP) (Supplementary Table 4), and endangered animal species (EA) (Supplementary Table 6) had a direct scoring system as higher values were found to have positive effects on wetland health thereby obtaining higher scores. Conversely, other biotic indicators like status of weed infestation (WI), status of invasive plant species (IP) (Supplementary Table 5), status of invasive animal species (IA) (Supplementary Table 7), mass-death of animals in last 5 years (AD) (Supplementary Table 8), and presence of man-animal conflict (C) were given an inverse scoring system where lesser scores corresponded to higher values, as these were recognized to be unfavourable for maintaining healthy wetland conditions.

Classifying wetlands based on health status

Classification of wetlands based on their health status is very important, particularly since it provides crucial information about wetland condition to key stakeholders. For this purpose, two exercises had been conducted. Firstly, the individual indicator based scores were aggregated by summation to obtain a composite score of wetland health condition (Datta and Ghosh, 2015). Here, the composite scores were supposed to be the best representative numerical that could depict the real ground situation of the studied wetlands individually. These obtained scores had been further classified into three broad categories based on their mean (μ) and standard deviation (σ) values (μ ± σ) to make a relative assessment among the studied wetlands.

Secondly, ordination of indicator scores were performed to analyze their patterns of association over mathematical space. Principal Component Analysis (PCA) is one such widely accepted statistical technique that can be applied on predefined wetland health indicators to recognize the independent uncorrelated factors or principal components as these hold the majority of information of the original data sets (Bro and Smilde, 2014; Datta and Deb, 2017). Here, the obtained major principal components (PC1 and PC2) derived from the PCA with Eigen value >1 were plotted in a bi-axial graph to explore the pattern of orientation of individual wetlands on the mathematical hyperspace depending on their association and characteristics (Datta and Deb, 2017). For applying PCA, the standardized data of five-point scoring system mentioned above had been used in this study. Here, all statistical analyses were performed by Microsoft Excel 2016 and its add-on XLSTAT (version 2016.4) (DasGupta and Shaw, 2015; Rani et al., 2015).

RESULTS

The fieldwork and data collection part of this study was conducted between June, 2017 and May, 2019. Additionally, information collected from secondary databases proved very useful for the selection of indicators related to the ecological health of wetlands.

Typological inventory of coastal wetlands of the study area

Focusing on the 25 selected coastal wetlands, the typological inventory was developed, which enumerated the overall wetland characteristics of the MCP region (Table 3). Initially, the wetlands with a spatial coverage of at least 2.25 ha were taken into consideration for this study, since wetlands with less than 2.25 ha area were observed exerting comparatively negligible impact on the regional environment and appeared as point features during digital mapping (Panigrahy et al., 2011; Tiner et al., 2015).

This typological inventory gave a clear understanding of the dominant geomorphic features present in each individual wetland composite. Usually, interdunal wetlands were situated at the dune swales; mudflats and mangroves were developed along the tidal creeks and tidal flats; and the salt marshes and constructed wetlands were found to be associated with the tidal channels and coastal depressions of this region. Regarding the soil characteristics of wetland composites, it was found that the soil type of interdunal wetlands was Aquents in nature. Whereas,

Table 3 Typological inventory of representative coastal wetlands of the study region; inventorization has been formulated based on Areal extent of wetland (WA), Wetland type (WC), Dominant land surface features (LF), Soil type (ST), Water type (WT), Primary source of water (WS), Presence of management organization (MO), Major livelihood option (LO), Existing threat to wetland ecosystem (ET); prevailing major livelihood options are agriculture (AGR), brackish water aquaculture (BWA), fishing (FSH), NWP collection (NCL), tourism (TRM); existing threats to wetland ecosystems are categorized as coastal erosion (COE), deforestation (DFN), eutrophication (EUT), excessive NWP collection (ENC), land use conversion (LUC), overgrazing (OGR), salinization (SLN), sewage disposal (SWD).

Wetland ID	WA (ha)	WC	LF	ST	WT	WS	MO	LO	ET
ID1–	157.68	Interdunal	Dune swale	Aquents	Fresh water	Rain water	Absent	AGR	LUC
ID2	65.39	Interdunal	Dune swale	Aquents	Brackish water	Rain water	Absent	AGR, FSH	EUT, LUC
ID3	64.58	Interdunal	Dune swale	Aquents	Fresh water	Rain water	Absent	AGR, FSH	EUT, LUC
ID4	13.44	Interdunal	Dune swale	Aquents	Fresh water	Rain water	Absent	NCL	LUC, SWD
ID5	8.30	Interdunal	Dune swale	Aquents	Fresh water	Rain water	Absent	NCL	LUC, SWD
MF1	241.55	Mudflat	Tidal creek	Albolls	Brackish water	Tidal inlet	Present	FSH, NCL	LUC, OGR
MF2	99.18	Mudflat	Tidal flat	Aquepts	Brackish water	Tidal inlet	Absent	FSH	LUC
MF3	87.47	Mudflat	Tidal flat	Aquepts	Brackish water	Tidal inlet	Absent	FSH	OGR
MF4	83.54	Mudflat	Tidal flat	Aquepts	Brackish water	Tidal inlet	Absent	FSH	LUC
MF5	45.73	Mudflat	Tidal creek	Albolls	Brackish water	Tidal inlet	Absent	FSH	LUC
MG1	893.30	Mangrove	Tidal creek	Aquepts	Brackish water	Tidal inlet	Present	FSH, NCL, TRM	COE, DFN, LUC
MG2	24.66	Mangrove	Tidal flat	Albolls	Saline water	Tidal inlet	Present	NCL	DFN, ENC
MG3	15.15	Mangrove	Tidal creek	Aqualfs	Brackish water	Tidal inlet	Present	FSH	LUC
MG4	13.20	Mangrove	Tidal flat	Aquepts	Saline water	Tidal inlet	Present	FSH	OGR
MG5	12.12	Mangrove	Tidal flat	Aqualfs	Saline water	Tidal inlet	Present	FSH	OGR
CW1	2050.05	Constructed	Coastal depression	Albolls	Brackish water	Tidal canal	Present	BWA	SLN
CW2	1165.07	Constructed	Tidal creek	Aquepts	Brackish water	Tidal canal	Present	BWA	SLN
CW3	613.08	Constructed	Coastal depression	Albolls	Brackish water	Tidal canal	Present	BWA	SLN
CW4	267.09	Constructed	Tidal creek	Albolls	Brackish water	Tidal inlet	Present	BWA	SLN
CW5	198.20	Constructed	Coastal plain	Aquepts	Brackish water	Tidal inlet	Present	BWA	SLN
SM1	523.38	Salt marsh	Coastal depression	Aquepts	Brackish water	Tidal inlet	Present	BWA, FSH	SLN
SM2	65.38	Salt marsh	Coastal depression	Aquepts	Brackish water	Tidal inlet	Absent	BWA, FSH	LUC
SM3	49.04	Salt marsh	Coastal depression	Aquepts	Brackish water	Tidal inlet	Absent	FSH	ENC
SM4	25.89	Salt marsh	Tidal creek	Aquepts	Brackish water	Tidal inlet	Absent	FSH	LUC
SM5	2.94	Salt marsh	Coastal depression	Aquepts	Brackish water	Tidal inlet	Absent	FSH	LUC

Albolls and Aquepts types of soils were usually found in mudflats and constructed wetlands. Furthermore, Aquepts, Albolls as well as Aqualfs soils predominantly appeared in mangrove wetlands and only Aquepts soils were observed in salt marshes. Genetically, Aquents, a subgroup of Entisols, are much younger in age and consist of wet sand deposits. Whereas, Albolls, a subgroup of Mollisols, are developed under the conditions of oscillating ground water flow; and are characterized by albic horizon. In contrast to these, both Aquepts and Aqualfs are poorly drained soils and recorded as the subgroups of wet Inceptisols and Alfisols respectively (FAO, 2014).

There were wide variations in aquatic characteristics from one wetland composite to the other. Interdunal wetlands were primarily found to be containing fresh water (TDS <500 mg l^{-1}). However, some of them were also covered with brackish water (TDS 1,000-10,000 mg l^{-1}). Mudflats, salt marshes and constructed wetlands were mainly occupied by brackish water. Whereas, mangroves had developed in the concurrent exposure of saline (TDS >10,000 mg l^{-1}) and brackish water. In general, this inventory also displayed the prime sources of water in these wetlands. Noticeably, interdunal wetlands were mostly found to be flooded during the monsoon and remained such until the early xeric months of November and December. However, the other four types of wetlands except this one were chiefly dependent on saline water supplied by tidal inlets.

Related socio-economic and institutional sustainability issues also added an extra dimension to this wetland inventory. Sometimes, profit and non-profit institutions such as cooperatives, civil society organizations (CSOs), and independent agencies also take on the responsibility of the sustenance of wetland dependent livelihoods and its overall ecological health. However, the involvement of such management organizations were prominent only in mangroves, constructed wetlands, and salt marshes of the study region. Whereas, interdunal wetlands and mudflats were found to be completely deprived of any of such monitoring by management organizations. These coastal wetlands also play a crucial role in livelihood generation for the local populace. Interdunal wetlands were mainly used for non-wood products (NWP) collection as well as subsistence based agriculture and fishing. Conversely, mudflats and mangroves were utilized for both the subsistence fishing and NWP collection. The mangrove wetland of Bichitrapur (MG1), however, had ecotourism as an additional prospect. Due to the advantage of saline aquatic condition, both the constructed wetlands and salt marshes were used for monospecific brackish water aquaculture. In spite of that, salt marshes had an extra provision of subsistence fishing as well. As an effect of emerging natural calamities and disgraceful economic engagements of inhabitants, coastal wetlands faced various alarming threats. Interdunal wetlands were intimidated by eutrophication, land use conversion, and sewage disposal. Whereas, Mudflats were mainly suffering from overgrazing of livestock and land use conversion. Notably, mangroves of this region experienced numerous hazardous factors, which were: existing coastal erosion, deforestation, land use conversion, excessive NWP collection and over-grazing of livestock. Constructed wetlands were facing specific challenges from increasing alkalinity in soil, as a consequence of periodic stagnation of brackish water in the soil. Apart from that, the excessive NWP collection, rapid land use conversion and emerging soil salinity had also become the most severely injurious factors for salt marshes, situated within the study region.

Status of ecological health of studied wetlands

The composite scores representing overall wetland health conditions had been computed for the 25 selected wetlands (Table 4). Here, the higher composite scores (> μ + σ: >60.62) were found for the MF1, MF5 and MG1 wetlands as a con-

Table 4 Standardized scores of the ecological indicators

Wetland ID	Scores of ecological health indicators																	Composite score
	Physical indicators				Biochemical indicators					Biotic indicators								
	FF	DW	DL	AS	pH	DO	T	EU	FC	TD	WI	EP	IP	EA	IA	AD	C	
ID1	3	4	1	4	5	2	4	4	4	4	1	2	2	3	4	2	3	52
ID2	3	4	4	5	5	2	5	3	4	4	2	2	3	4	4	3	2	59
ID3	3	4	5	5	5	3	4	3	4	4	2	3	2	3	4	3	2	59
ID4	3	4	1	3	5	3	4	2	3	3	2	2	4	2	3	2	1	47
ID5	3	4	3	3	3	2	3	1	1	3	1	2	3	2	3	2	1	40
MF1	5	5	4	5	4	2	1	5	5	3	3	2	4	4	4	3	4	63
MF2	5	5	2	4	4	4	1	5	5	2	3	1	5	2	4	2	2	56
MF3	5	5	1	3	4	4	1	5	5	1	3	1	5	2	4	2	4	55
MF4	5	5	2	3	4	4	2	5	5	1	3	1	5	2	4	3	4	58
MF5	5	5	3	4	4	4	2	5	5	2	3	1	5	1	5	4	3	61
MG1	5	5	4	5	4	2	1	5	5	3	5	3	4	5	2	5	4	67
MG2	5	5	2	3	3	2	1	5	5	2	4	2	4	3	4	5	3	58
MG3	5	5	2	4	4	2	1	5	5	2	5	2	5	2	3	5	2	59
MG4	5	5	2	3	3	2	1	5	5	2	4	2	5	2	5	5	2	58
MG5	5	5	4	3	3	2	1	5	5	1	4	2	5	1	4	5	3	58
CW1	3	4	3	3	4	3	3	3	2	1	3	1	2	2	2	1	2	42
CW2	3	4	3	3	4	3	3	5	3	1	3	1	2	2	3	2	2	47
CW3	3	4	2	3	4	4	3	3	3	1	3	1	3	1	4	3	2	47
CW4	3	4	3	3	3	3	3	3	2	1	4	1	3	1	5	3	3	48
CW5	3	4	3	3	4	3	3	3	2	1	4	1	3	1	5	3	2	48
SM1	3	4	2	5	3	3	3	4	5	1	4	3	4	2	4	4	2	56
SM2	4	2	3	4	3	3	2	4	4	1	3	2	3	2	3	4	3	50
SM3	4	2	4	4	4	3	3	3	5	1	4	2	5	1	4	5	2	56
SM4	4	2	4	4	4	3	3	3	5	1	4	2	4	1	5	4	3	56
SM5	4	2	2	3	4	2	2	3	3	1	4	1	3	1	4	4	2	45

sequence of gaining higher scores for the majority of the physical (*i.e.* FF, DW, DL, and AS), biochemical (*i.e.* pH, DO, EU, and FC) and biotic (*i.e.* IP, EA, IA, and C) indicators. Apart from these, the moderate range (μ - σ to $\mu + \sigma$) of composite scores (46.98 – 60.61) were accrued by the ID1 to ID4, MF2 to MF4, MG2 to MG5, CW2 to CW5, and SM1 to SM4 wetlands. These wetlands generally performed better with respect to some of the physical (*i.e.* FF, DW, and AS), biochemical (*i.e.* pH, DO, T, EU, and FC) and biotic (*i.e.* TD, WI, IP, IA, and AD) indicators. On the contrary, lower range of composite scores ($< \mu - \sigma$: <46.97) were found for the ID5, CW1 and SM5 wetlands due to their overall lesser scores achieved against majority of the ecological indicators considered in this study.

Ecological health based ordination of studied wetlands

Application of PCA for the different indicators used to assess the 25 selected wetlands revealed that the first two principal components, *viz.* PC1 and PC2, together explained 56.48% of the total variability of the dataset. Hence, these two components had been chosen as the ideal representatives of original datasets to be used. These two principal components with Eigen value >1.00 (Eigen value: PC1 = 6.44, PC2 = 3.31) were further plotted in a bi-axial graph, where PC1 and PC2 had been ordinated in X and Y axes respectively. Based on the field observations and a priori knowledge of the investigators, it can be presumed that the degree of terrestrial remoteness and the status of ecosystem composure act as the latent variables in *x* and *y* axis respectively. This bi-axial plot thus helped to decipher few groups in respect of pattern formation for the studied wetlands on the mathematical space.

Four isolated clusters strewed into the PCA plot, which could depict four different conditions of wetland ecological health, *viz.* better, moderate, poor and alarmingly poor (Figure 2). The distinctly isolated cluster (Cluster I) formed at the first quadrant, containing MF1 and MG1, is identified as wetlands experiencing better health condition ecologically. While, another cluster (Cluster IV) situated at the fourth quadrant, containing ID1, ID2 and ID3, represented wetlands with moderate ecological health. A large cluster (Cluster II) situated at the second quadrant containing several wetlands (SM1-SM4, MG2-MG5, and MF2-MF5) had been identified as of poor ecological health. The rest of the wetlands, such as ID4, ID5; CW1-CW5; and SM5 create one separate cluster (Cluster III) in the third quadrant, and belonged to the alarmingly poor health condition. Since, PCA categorized different types of coastal wetlands in accordance to their ecological health conditions, it actually helped to comprehend the overall scenario of coastal wetland landscape of the MCP.

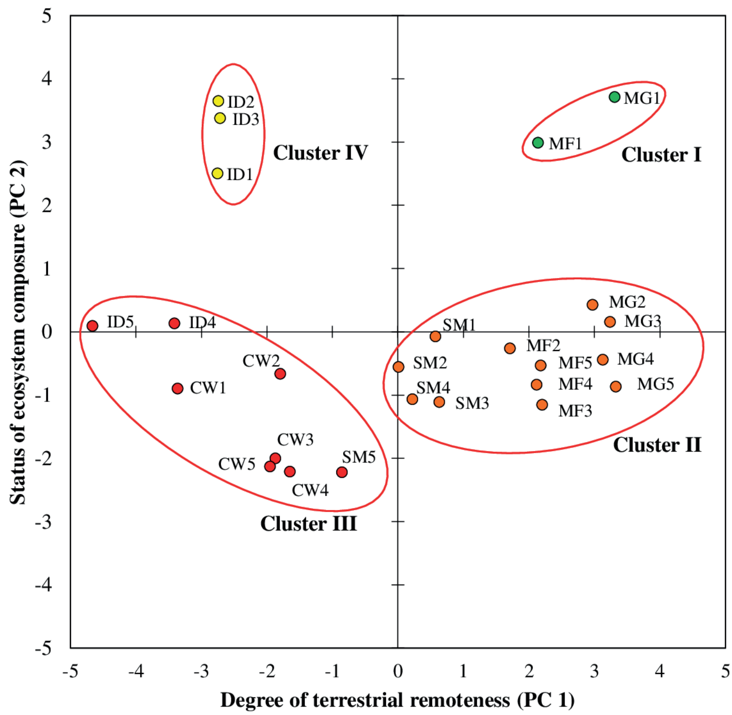

Figure 2

Ordination of studied coastal wetlands through statistical clusters in PCA bi-plot

DISCUSSION

The ecological health status of a wetland is intricately tied to several natural and anthropogenic factors associated with the coastal landscapes. Primarily, the genesis, pattern of spatial distribution, source of water and the evolutionary stage of wetlands are the prime aspects in determining the health condition of wetlands (Meng et al., 2017; Roy and Datta, 2018). Besides these, some anthropogenic agents also play vital roles in it. Dependency of local inhabitants on wetlands, specifically for their livelihood generation and related strategies to utilize the wetland resources, are such anthropogenic factors that act as the prime stressors on the wetland ecological health (Datta and Deb, 2017; Roy and Datta, 2018).

In this study, four different clusters had been identified from 25 studied wetlands with the help of PCA, denoting four different status of wetland ecological health. Among these, only two were of relatively better health condition; namely, the mudflat (MF1) near Junput and the mangrove wetland (MG1) of Bichitrapur (Figure 3). These two wetlands were also notable in terms of their areal coverages, as these two were the largest among all other naturally developed wetlands of this region and occupied approximately 241.55 ha and 893.30 ha area respectively. In addition, due to their positional remoteness, these two wetlands were relatively undisturbed by any human induced stress, thus offering a pristine environment for its native as well as diversified wetland biota. Accordingly, minimal occurrences of man-animal conflicts and better potentiality in generation of agroecosystem (AE) services were also observed here. All these favourable conditions had eventually made these two wetlands the most ecologically resilient coastal wetlands of the MCP.

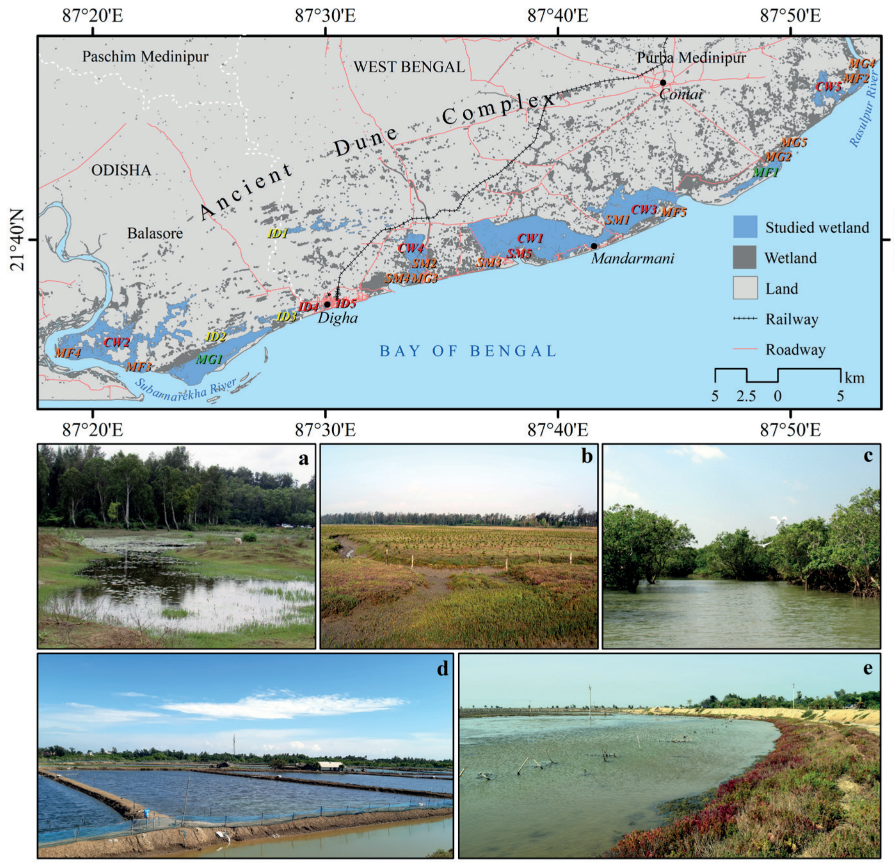

Figure 3

Spatially-explicit distribution of 25 selected coastal wetlands in terms of their ecological health through individual colour codes; shades of green, yellow, orange and red denote better, moderate, poor, and alarmingly poor ecological health condition of wetlands, respectively; bio-physically distinguishable five existing types of coastal wetlands are, *(a)* Interdunal, *(b)* Mudflat, *(c)* Mangrove, *(d)* Constructed, and *(e)* Salt marsh.

Similarly, three major interdunal wetlands (ID1, ID2, and ID3) of the study region had also succeeded in maintaining relatively better ecological health. Although these wetlands were found to be intensively harvested by local marginal farmers on a subsistence basis, a rich gamut of biota as an indirect outcome of traditional AE practices were still persisting there.

Conversely, certain wetlands were grouped together due to their alarmingly poor ecological health. Primarily, these were ID4 and ID5 interdunal wetlands; SM5 salt marsh; and CW1 to CW4 constructed wetlands. Among these, ID4 and ID5 wetlands, situated within the jurisdiction of the Digha-Sankarpur Development Authority (DSDA), frequently experienced severe contamination due to uncontrolled dumping of solid wastes and sewage disposal generated from the expanding tourism sector. Consequently, high levels of eutrophication and faecal coliform concentration had been detected in these wetlands. In contrast, the salt marsh (SM5) was suffering from DO deficiency (5.40 mg l^{-1}) and high turbidity level (86.4 NTU) in the water. Furthermore, less availability of native plants as well as animal species; unwanted existence of exotic plants species and escalating man-animal conflicts brought about by the overuse of wetland resources for aquacultural purposes by local piscators; played pivotal roles in the deteriorating health status of that salt marsh of Sankarpur. Noticeably, four selected constructed wetlands (CW1 to CW4) out of five were found suffering from poor ecological health, as the construction of these wetlands was only possible after destroying the natural habitat of numerous wetland organisms and subsequent transformation into commercial aquacultural farms. In addition, substantial amounts of arboreal vegetation at the wetland peripheral areas, increasing infestation of weeds within wetlands, and the absence of native animal species; also act as the influencing factors behind the poor ecological health of these wetlands. During the field investigation, some exotic plant species such as *Calotropis gigantean*, *Opuntia stricta*, *Pistia stratiotes* and *Portulaca oleracea* were spotted in various sites in and around these wetlands. These exotic plant or animal species may prove to be detrimental to the associated native species, if they destroy and occupy the natural habitat of the native species in the imminent years.

The remaining 12 coastal wetlands such as SM1 to SM4, MF2 to MF5 and MG2 to MG5 belonged to the group displaying moderate ecological health status. Salt marshes and mudflats generally had lower biological diversity in spite of lesser human intervention. Similarly, the mangrove wetlands of the entire MCP, except Bichitrapur, were observed to be in a very early stage of ecological succession and, therefore, were also incapable of supporting a rich biodiversity. Hence, other than Bichitrapur, all other mangrove wetlands belong to moderate ecological health status. Notably, some endangered native plant species like *Pandanus tectorius*, *Salicornia europaea*, *Cyperus arenarius* and *Cyperus stoloniferus* were still spotted in these moderately healthy wetland composites during the field surveys.

After evaluating all the applied physical, chemical and biotic health indicators of wetlands together, it was observed that the degree of human induced stresses and the existing wetland biological diversity were the most explicit determinants of wetland ecological health in the study region.

CONCLUSIONS

The present study tried to demonstrate the variety of coastal wetlands present in the study region emphasizing on their physical characteristics as well as the existing ecological health status. Established international wetland inventorization system, widely accepted national level wetland inventory, primary field based survey data, and secondary records on physical environment were merged together to attain the objectives of this study.

No such regional wetland inventory for the MCP, with special reference to their ecological health condition, had been prepared till date. Consequently, this study on regional level wetland inventorization will certainly offer better solutions to the decision making problems of many stakeholders, researchers, and policy makers towards forwarding any sustainable management plan for these wetlands. However, the relative ecological health status of the studied wetlands derived here was only pertinent for the MCP. This might differ for other coastal areas since the physicochemical characteristics and the corresponding biotic characteristics would substantially change based on geographic variance (Roy and Datta, 2018).

In accordance to the ecological indicator based clustering, it can be concluded that intertidal wetlands such as mangroves and mudflats with remote locational advantages hold the most optimum ecological health status within the MCP. Moreover, some of the interdunal wetlands had also succeeded in maintaining a healthy ecological condition through generation of AE potentiality brought about by traditional subsistence farming practices. Evidently, most of the wetlands, which had been used indiscriminately and even neglected by the local authorities, often failed to retain their ecological composure. Noticeably, few of the interdunal wetlands, most of the constructed wetlands, and certain stretches of salt marshes were found to be severely suffering from deteriorated ecological conditions and subsequently needed intensive restoration measures from active as well as passive users in an immediate basis. This can only be achieved through a synergic endeavour between human and nature that can uphold the diversified ecological functions as well as make provisions of wetland resources for the rural masses.

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