J. Indian Soc. Coastal Agric. Res. 42(2):1-22(2024) https://doi.org/10.54894/JISCAR.42.2.2024.159555

Mapping Ecosystem Services in India's Largest Estuary: A Systematic Review of the Hooghly Matlah Estuarine System Using CICES

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Received: 05.11.2024 Accepted: 09.12.2024

The Hooghly Matlah Estuarine System (HMES), renowned as India's largest and most productive estuary, provides various ecosystem services essential for human well-being. While some research has concentrated on the Sundarbans region, there have been limited efforts to thoroughly identify all the services offered by the HMES using an internationally recognized classification. This study aims to document and summarize the ecosystem services provided by the HMES in India. To achieve this, a systematic literature review focused on the Common International Classification of Ecosystem Services (CICES, version 5.2) to catalog the relevant services associated with the estuary. We utilized the Google Scholar database and the Google search engine to gather scientifically supported data drawn from both peer-reviewed articles and grey literature. Our findings revealed 59 ecosystem services out of the 99 listed in CICES, constituting approximately 59.60 % of the total. This includes 38 biophysical services provided by the living systems (61.29% of the 62 biophysical class) and 21 geophysical services derived from non-living components of ecosystems (56.76% of the 37 geophysical class). The HMES demonstrates a remarkable level of multifunctionality, with its services almost evenly distributed across provisioning (21), regulating (18), and cultural (20) categories. This broad range of services highlights the essential role of the HMES in sustaining several types of ecological processes essential to both human life and the health of ecosystems. The study suggests prioritizing thoughtful policies and sustainable management approaches to safeguard the estuary's rich biodiversity, keep its ecosystems healthy, and ensure the well-being of the communities that depend on it.

(**Key words:** *Ecosystem Services, CICES, Systematic Review, Hooghly Matlah Estuarine System*)

Estuaries are the tidal mouth of a great river, where the tide meets the current. It is a semi-enclosed coastal body of water which has a free connection with the open sea and within which seawater is measurably diluted with freshwater derived from land drainage (Acharya *et al.,* 2019). They are highly complex but very productive ecosystems with significant economic, social, and environmental importance. They provide ample biological and ecological services to society (Sarkar *et al.,* 2017). Ecosystem services (ES) by estuaries help maintain livelihoods, and people value the quality of estuaries for their well-being (Martin *et al.,* 2020). These ES range from provisioning services (e.g., fish for food) through regulating services (e.g., coastal protection) to cultural services (e.g., sites of symbolic and religious significance) (Defeo *et al.,* 2009; Barbier *et al.,* 2011; Fegley and Michel, 2021; Harris and Defeo, 2022). Estuaries offer ES that promotes human survival and economic progress (Booi *et al.,* 2022). Most people, especially in rural households, rely on provisioning ecosystem services for their livelihoods, with the availability and accessibility of estuarine services being fundamental to their economic existence (Mandal *et al.,* 2021). Additionally, estuaries are ideal sites for human settlement and industrial units (Lal *et al.,* 2021).

Many of the world's great estuaries are in tropical regions, where many taxa form interconnected communities (Blaber, 2002). The Hooghly-Matlah estuarine system (HMES) on the tropical Indian coast of the Bay of Bengal is one of the country's largest and most productive estuaries (Jhingran and Ghosh, 1978). The HMES and the Sundarbans mangroves form one of the world's most diverse and vulnerable ecosystems

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(Ghosh *et al.,* 2019). It was declared a World Heritage Site by UNESCO in 1985, and in 1989, it became a Biosphere Reserve in India, providing various ecosystem services (Roshith *et al.,* 2018; Mukherjee *et al.,* 2019). The system constitutes a crisscross network formed by the main channel and its distributaries, which form an extensive deltaic system leading to the sea (Mandal *et al.,* 2012b; Dutta *et al.,* 2016). Known for its high faunistic richness, it forms the mainstay of the capture fisheries of West Bengal, India. It supports a significant multi-species commercial fishery, serving as a vital source of livelihood for hundreds of thousands of fishermen and sustaining a thriving trade (Mitra *et al.,* 1997).

To date, no attempts have been made to comprehensively identify all of the ES provided by HMES based on an internationally accepted classification. Existing research is mainly lacking and is generally limited to only the most apparent services provided by the Sundarbans of HMES. Some of the scattered studies have limited their focus on some aspects of ES in the Indian Sundarbans part of HMES, like flow-dependent ecosystems and their services (Bhadra *et al.,* 2022); ES of Sundarbans Transnational Site between Bangladesh and India (Islam, 2014); ES valuation (Ekka *et al.,* 2020); conservation priority zones using spatially explicit valued ES (Sannigrahi *et al.,* 2020). Thus, this study attempts to document and summarize the ecosystem services provided by the entire HMES of India.

MATERIALS AND METHODS

Study area

Located between 21°-24° N latitude and 88°-89° E longitude, HMES (Fig 1) is the largest among the estuaries of the Indian coast. It extends 300 km from North to South and 150 km from East to West (Acharya *et al.,* 2019). The entire estuarine system is estimated to

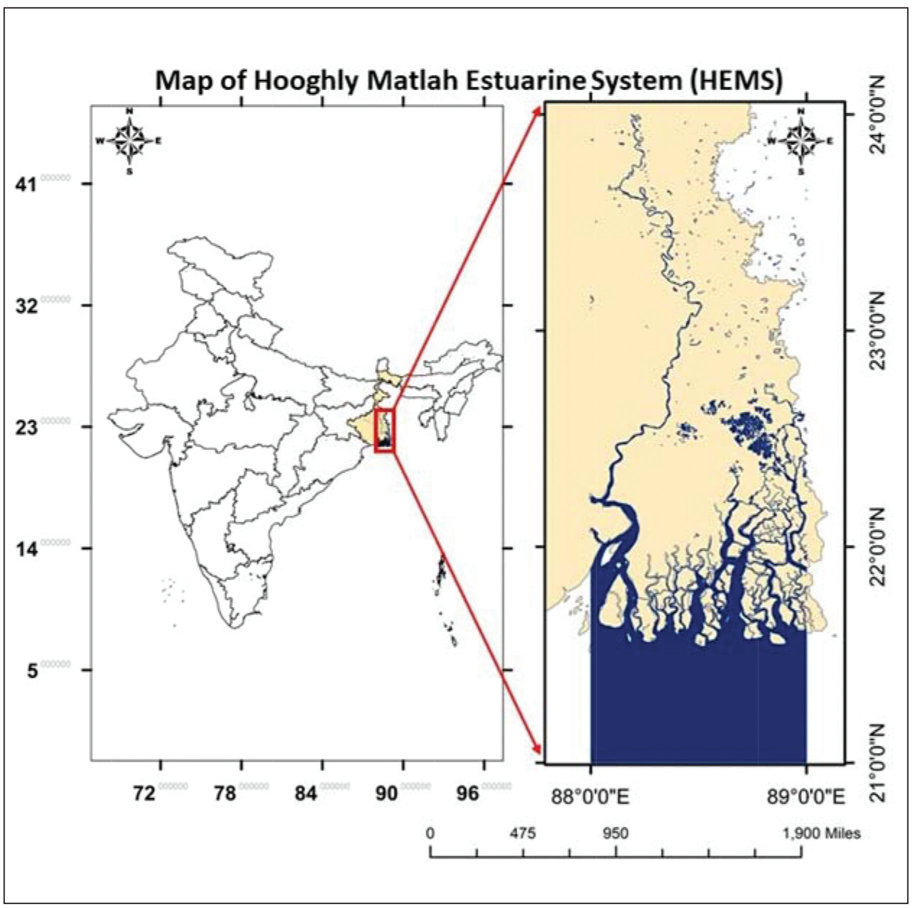

Fig. 1. *Map of study area (HMES), created using ArcGIS (Pro 2.x)*

be about 8,029 sq. km, and the total area of Sundarbans estuarine water is about 2,340 sq. km in India (Sinha, 2004). HMES is a complex network of interconnecting channels, canals and creeks that are associated with seven principal estuaries, *viz.*, Hooghly, Saptamukhi, Thakuran, Matla, Harinbhanga, Raimangal and Bidya. Of these, the Hooghly and Raimangal estuaries form the western and eastern boundaries of the Indian Sundarbans, respectively (Roshith *et al.,* 2018).

Classification of ecosystem services

Since the 2005 Millennium Ecosystem Assessment (MEA), various ecosystem services (ES) classification schemes have been developed, including those by Costanza *et al.* (1997), Daily (1997), and TEEB (2010). Costanza (2008) argued that no single classification should dominate due to ecosystem complexity and diverse decision-making contexts. As ES assessments expanded, a common framework for comparison became essential (Haines-Young and Potschin, 2009), though it must balance specificity with broad applicability (Nahlik *et al.,* 2012).

One such framework, the 'Common International Classification for Ecosystem Services' (CICES), was developed by the European Environment Agency and coordinated by the University of Nottingham (Haines-Young and Potschin, 2013). CICES offers a flexible, hierarchical structure that allows new services to be integrated without disrupting the system, organizing ecosystem services into three main themes - provisioning, regulating and maintenance, and cultural services. This framework focuses on final ecosystem outputs, excluding supporting services, to avoid double-counting in monetary valuations (Fisher and Turner, 2008). It classifies ecosystem services, not the benefits derived from them, focusing on the direct contributions of ecosystems to human well-being (Haines-Young and Potschin, 2013).

This study employed the CICES Version 5.2 framework to categorize and document the ecosystem services ofthe Hooghly Matlah Estuarine System (HMES). CICES's tiered structure, which categorizes services at multiple levels, enabled flexibility in addressing the specific study context while incorporating both biophysical and geophysical outputs (previously classified as biotic and abiotic in earlier CICES versions) (Kubalíková, 2020; Von Thenen *et al.,* 2020; Garcia-Onetti *et al.,* 2021). The CICES framework also facilitated systematic review methodologies and the development of custom analytical frameworks, as demonstrated by Zieritz *et al.* (2022) and Merida *et al.* (2022), making it particularly useful for this study.

Following studies by Ruiz-Agudelo *et al.* (2022) and Sheehy *et al.* (2022), CICES was used to code and classify the ecosystem services identified in the HMES. Other reviewed ecosystem services covered a range of ecological contexts, consistent with similar applications of CICES in marine ecosystems by Kuhn *et al.* (2021) and coastal and aquatic systems by Vander Wilde and Newell (2021) and Miah *et al.* (2021). Other relevant examples include studies on sand dunes (Harris and Defeo, 2022), forest ecosystems (Tiemann *et al.,* 2022), and urban water bodies (Jakubiak and Chmielowski, 2020). This comprehensive application of CICES ensures thorough documentation and consistent comparison of ecosystem services across various ecosystems.

Data source

This study conducted a systematic literature review to understand the ecosystem services (ES) of the Hooghly Matlah Estuarine System (HMES) and its associated benefits. The review followed the methods provided by Collins *et al.* (2015) and Ashley *et al.* (2023), emphasising both peer-reviewed and grey literature.

Literature was gathered from an online database, primarily focusing on Google Scholar (https://scholar.google.com/) because of its vast collection of peer-reviewed research articles. In addition, grey literature - such as books, book chapters, news articles, and websites—was sourced through the Google search engine. This study tried to collect a comprehensive set of scientifically supported data for the documentation.

Although Google Scholar can be labor-intensive and sometimes lacks the precision needed for systematic literature reviews (Boeker *et al.,* 2013), its ability to access a diverse range of sources, including grey literature and articles that may not be indexed in traditional databases, makes it a valuable tool (Giustini & Boulos, 2013).

Search strategy

The search strategy centered on terms in English and utilized a combination of primary and secondary search terms. The primary search term was "Hooghly Matlah Estuary," while secondary search terms related to specific ecosystem services, as defined by the Common International Classification of Ecosystem Services (CICES) framework (Haines-Young and Potschin, 2010; Haines-Young and Potschin, 2018; Ashley *et al.,* 2023), were employed.

For example, to find literature on the ecosystem service "bioremediation" (CICES V5.2 code 2.1.1.1), the search terms "Hooghly Matlah Estuary" and "bioremediation" were used in Google Scholar.

Data extraction

The first ten relevant records obtained from Google Scholar were selected for each combination of search terms, focusing on their availability and relevance to the topic. No other selection criteria were applied. This approach captured as many valid ecosystem services as possible that the HMES provided. Additionally, any extra available information was sourced from the Google search engine.

Description of literature referred

We initially found 970 records on Google Scholar and 17 from the Google search engine. After eliminating duplicates, we were left with 550 unique entries. We then screened these records by examining their titles and abstracts to see how they related to the Hooghly Matlah Estuarine System (HMES), which narrowed our selection to 203 articles. Of these, 101 specifically discussed the ecosystem services provided by HMES, which were included in our study for classification using the CICES.

RESULTS AND DISCUSSION

The CICES V5.2 classification includes 62 biophysical (biotic) and 37 geophysical (abiotic) ES classes (Haines-Young, 2023). However, the ES provided by HMES does not represent all classes, as the review identified 38 biophysical and 21geophysical ES classes. This is more compared to the 36 ES provided by Bangladesh's Meghna River estuarine system (Miah *et al.,* 2021). The identified Provisioning, Regulation and Maintenance, and Cultural ES provided by HMES represents 59.60 per cent of the total number of services mentioned in CICES V5.2. The HMES displays numerous final services (Fig 2), with its ecosystem services spread almost evenly across provisioning (21), regulating (18), and cultural (20) services. This near-balanced service emphasises the estuary's critical role in supporting numerous ecological functions that are essential not just for the survival of local inhabitants but also for the general health of the environment. The HMES balances resource use, environmental regulation, and the cultural and social significance it provides to surrounding communities. However, the

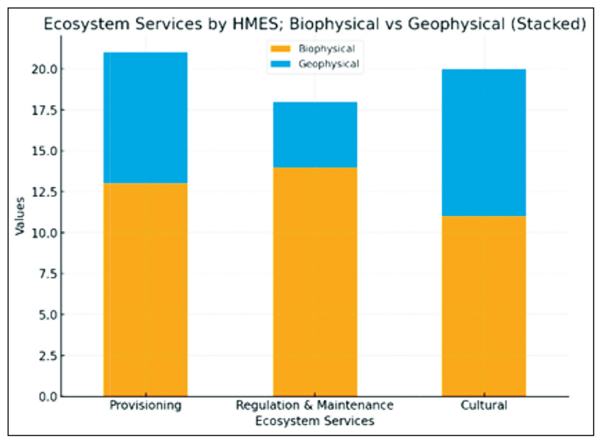

Fig. 2. *Ecosystem services by HMES; Biophysical vs geo physical*

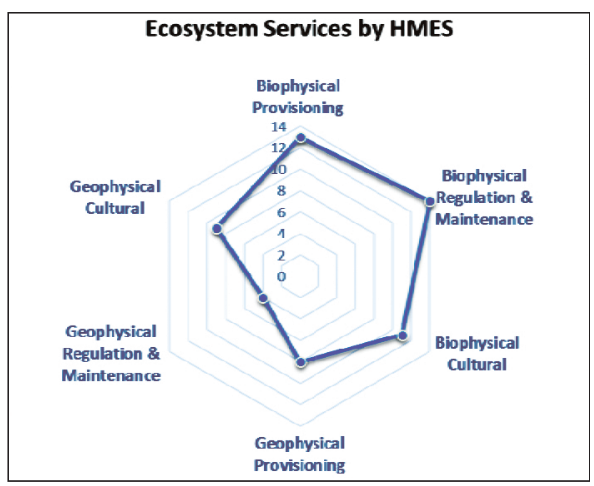

Fig. 3. *Ecosystem services by HMES*

available literature did not represent the remaining 40.4% of ES. This could be due to under reporting, especially for lesser-studied services, or these services may not exist in the HMES due to its unique ecological conditions. Further research is needed to explore these gaps and provide a more complete understanding of the ecosystem services in the region.

Following Haines-Young (2023), ES provided by the HMES has been categorized into six sections, as shown in Figure 3. Among these, biophysical regulation and maintenance services make the highest contribution, accounting for 13 out of the 59 services identified. In contrast, geophysical regulation and maintenance services contribute the least, with only 4 out of the 59 services. A detailed breakdown and explanation of each category are provided in the following paragraphs.

Biophysical provisioning services

The Hooghly-Matlah Estuarine System (HMES) offers significant biophysical provisioning services (Table 1), supplying critical resources for agriculture, aquaculture, and other human needs. These services include cultivating and extracting biomass from both cultured and wild sources alongside the genetic material provided by the region's rich biodiversity.

Historically, the fertile lands on both sides of the Hooghly River have supported agriculture, industry, and domestic consumption, benefiting from the river's perennial water supply (Ivermee, 2017). Agricultural activities have expanded over time, with agricultural land coverage growing from 56.7% (11,324 km²) in 1988 to 67% (13,360.1 km²) in 2022 (Goswami *et al.,* 2023). One of the significant crops cultivated in this region is jute, especially species like *Corchorus capsularis* (white jute) and *Corchorus olitorius* (tossa jute), which are vital to the local economy, earning the moniker "golden fibre" for their economic value and use in textiles, biodegradable materials, and packaging (Chapke, 2009; Ghosh and Shirodkar, 2023). In addition to agriculture, the HMES supports aquaculture, including the farming of tiger shrimp (*Penaeus monodon*) and Pacific white shrimp (*Litopenaeus vannamei*), which has seen rapid growth since 2009 (Subrato, 2019). Other aquaculture activities include the cultivation of species like seabass, mullets, milkfish, and pearlspot, with local finfishes such as *Mystus gulio*, *Terapon jarbua*, and *Lates calcarifer* contributing to the system's diverse aquatic production (Lama *et al.,* 2021). Mud crab fattening and cultured honey production from *Apis indica* are additional examples of biomass provisioning (Saha and Dash, 2021; Singh *et al.,* 2010).

The HMES provides wild biomass, including edible plants and medicinal species. For instance, the nipa palm produces sap for alcohol and vinegar, while seeds and fruits from plants like the mangrove date palm and screwpine are consumed (Mahmood, 2015). Mangrove species like *Ceriops* produce tannin-rich bark (30 - 42% tannin), and the system supplies fuelwood, natural honey from *Apis dorsata*, and fish meal derived from estuarine fish catches (Singh *et al.,* 2010; Ghosh *et al.,* 2022). Fish as food is a vital contribution of the HMES, with key species such as *Tenualosa ilisha* (Hilsa), *Harpadon nehereus* (Bombay duck), and *Otolithoides pama* (Bhola) making up the bulk of the catch. Where expensive Hilsa, in particular, stands out by contributing 51% of the total catch, emphasizing the fishery's importance to the region's livelihood and economy (Ayappan, 2011).

The genetic resources provided by the HMES are vital for various conservation and aquaculture programs. Seeds and saplings of mangroves from the Indian Sundarbans are used in plantation efforts (Banerjee *et al.,* 2023). Wild-caught Hilsa juveniles from the estuary are ranched into upstream waters (Chattopadhyay *et al.,* 2024). This estuary is a significant source of prawn seed for aquaculture because of the Black Tiger Prawn (*P. monodon*) harvested from it (Gopal and Chauhan, 2018). The successful breeding and rearing of declining Hilsa (Saha and Sarkar, 2022) and the conservation efforts for endangered species like the Northern River Terrapin and Estuarine Crocodile under the Sundarbans Tiger Reserve (Kumar *et al.,* 2022) further emphasize the genetic importance of the estuary.

Biophysical regulation and maintenance services

As seen in Table 2, the HMES's regulatory and maintenance services are essential to maintaining the estuary's biological health and long-term environmental balance. The conversion of physical and biochemical components within the environment is one of the essential

Table 1. *Provisioning services (Biotic/biophysical) provided by HMES*

Code	Class	Services by HMES	Source
1.1.1.1	Cultivated terrestrial plants grown for nutritional purposes	67% area under Agriculture	Goswamiet al. (2023)
1.1.1.2	Fibres and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials)	Jute used in textiles, packaging, and biodegradable materials	Ghosh and Shirodkar (2023); Chapke (2009)
1.1.1.3	Cultivated plants grown as a source of energy	Oil seeds: oil from seeds is used for lubrication	Aktar (2016); Mahmood (2015)
1.1.3.1	Animals reared for nutritional purposes	Cultured (apiary) honey; livestock and poultry	Singh *et al.* (2010); Raja *et al.* (2012)
1.1.4.1	Animals reared by in-situ aquaculture for nutritional purposes	Mud Crab fattening; Farming of shrimp; Brackish water culture of fin fishes and shellfish	Saha and Dash (2021); Subrato (2019); Ghoshal *et al.* (2019); Lama *et al.* (2021)
1.1.5.1	Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition	Different edible parts of plants like flowers, seeds, stems, and leaves	Mahmood (2015)
1.1.5.2	Fibres and other materials from wild plants for direct use or processing (excluding genetic materials)	Tannin and roofing	Singh *et al.* (2010)
1.1.5.3	Wild plants (terrestrial and aquatic, including fungi, algae) used as a source of energy	Fuelwood: Biomass gasification-based power plant	Singh *et al.* (2010); Mukhopadhyay (2004)
1.1.6.1	Wild animals (terrestrial and aquatic) used for nutritional purposes	Natural honey; capture fishery	Singh *et al.* (2010); Ayappan (2011)
1.1.6.2	Fibres and other materials from wild animals for direct use or processing (excluding genetic materials)	Fish Meals for fish and animal feeds	Ghosh *et al.* (2022)
1.2.1.1	Seeds, spores and other plant materials collected for maintaining or establishing a population	Indian Sundarbans Plantation program	Banerjee *et al.* (2023)
1.2.2.1	Animal material collected for the purposes of maintaining or establishing a population	Hilsa ranching, Collection of seeds of Black Tiger Prawn and Penaeus monodon; wild seed capture and fattening	Chattopadhyay *et al.* (2024); Gopal and Chauhan (2018); Saha and Dash (2021)
1.2.2.2	Wild animals (whole organisms) used to breed new strains or varieties	Successful artificial breeding of hilsa, northern river terrapin and estuarine crocodile	Kumar *et al.* (2022); Sahoo *et al.* (2018); Gopal and Chauhan (2006); Saha and Sarkar (2022)

services. Significant phytoremediation properties are possessed by mangrove species like *Avicennia officinalis*, *Sonneratia apetala*, and *Excoecaria agallocha*, which aid in the removal of harmful metals from the water and enhance its general quality (Chakraborty, 2024).

Further, the region's halophytes significantly contribute to eco-restoration by acting as natural phytoremediation agents, especially for conservative pollutants (Mukherjee *et al.,* 2021). Natural scavengers like hermit crabs and monitor lizards (Varanus spp.) provide further assistance to the estuary by removing decaying organic matter, reducing odours, and improving soil quality (Chatterjee and Bhattacharyya, 2015; Mukhopadhyay *et al.,* 2022).

The HMES is essential for controlling water flows and protecting against severe weather conditions. As natural bio-shields, mangrove forests protect coastal areas from erosion, storm surges, and tidal waves. These ecosystems can lessen the effects of cyclones, preserving property and lives by stabilising embankments and slowing water currents (Paul *et al.,* 2017; Chowdhury *et al.,* 2021). The estuary's natural barriers have been further reinforced by *Avicennia marina's* notable resilience to flooding and high salinity (Naz and Chowdhury, 2022). This flora is a vital resource for coastal protection since it also lessens the effects of storm surges and wind damage (Marois and Mitsch, 2015).

In addition, the HMES plays a critical role in regulating physical, chemical, and biological conditions. In the *Khalsi* forest of the Sundarbans, wild bees, including *Nomia sp.* and *Apis dorsata*, pollinate key mangrove species like *Acanthus ilicifolius*, supporting biodiversity in the ecosystem (Das, 2020; Pal *et al.,* 2022). The mangrove forests serve as breeding grounds and nurseries for various marine and pelagic species, including commercially valuable fish and shellfish (Ray and Straskraba, 2001; Bera *et al.,* 2022). The estuarine waters receive a substantial influx of nutrients from the adjacent mangrove forests, which contribute to the growth of phytoplankton and zooplankton, supporting a complex and productive food web (Mandal *et al.,* 2009). In addition to being a significant source of food for migratory birds, the estuary is an essential feeding and fattening area for fish species (Lama *et al.,* 2021). This demonstrates how crucial this estuarine system is for sustaining biodiversity and ecological equilibrium (Mallick, 2023).

Also, the estuarine system is essential for regulating climate and sequestering carbon. Its intact mangrove forests contribute to combating climate change by acting as significant carbon sinks, absorbing CO_2 and other greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4) (Das *et al.,* 2023). Thus, underscoring its essential role in regulating the world climate (Bhadra *et al.,* 2022; Bhattacharyya *et al.,* 2023).

Biophysical cultural services

A multitude of cultural services provided by the biophysical components of HMES demonstrate the close relationship between humans and the natural world (Table 3). It provides outdoor activities like a unique experience of watching wildlife through canopy walks at Dobanki and ground fauna consisting of snails, varieties of crabs and molluscs through mud walks at Burir Dabri, which provide unique chances to interact with the estuarine environment (Das, 2015). Ecotourism places like Neti Dhopani in the Sundarbans Tiger Reserve allow visitors to see tigers and birds (Ghosh and Mandal, 2020; Das, 2023). These activities highlight the estuary's ability to facilitate healthy human-nature interactions.

The HMES acts as a bridge between conservation efforts and scientific research. Organisations such as ICAR-CIFRI (Central Inland Fisheries Research Institute), ICAR-CIBA (Central Institute of Brackishwater Aquaculture), and ICAR-CSSRI (Central Soil Salinity Research Institute) conduct a variety of studies on subjects such as fisheries, aquaculture, biodiversity conservation, and soil salinity (Das, 2023). In addition, the area is renowned for its mangrove conservation initiatives, backed by neighbourhood-based initiatives run by the West Bengal State Forest Department and other Non-Governmental Organisations (Bardhan, 2021).

The cultural significance of the estuary is reflected in local folklore, such as the Bonbibi narrative, which symbolises the enduring relationship between the local people and the forest (Karmakar, 2018). Additionally, the Hilsa fish of the estuary holds great cultural value for the

Table 2. *Regulation and maintenance services (Biotic/biophysical) provided by HMES*

Code	Class	Services by	Source
2.1.1.1	Bio-remediation by micro-organisms, algae, plants, and animals	High toxic metal phytoremediation ability of mangroves; halophytes for eco-restoration in the context of conservative pollutants	Chakraborty (2024); Mukherjee *et al.* (2021)
2.1.2.1	Smell reduction	Scavenger animals like monitor lizards, Wryneck woodpeckers, Hermit crabs	Chatterjee and Bhattacharyya (2015); Madhav and Victo (2011); Mukhopadhyay *et al.* (2022)
2.2.1.1	Control of water erosion rates	Erosion control by vegetative cover; soil conservation	Hossain *et al.* (2016); Chanda and Akhand (2023)
2.2.1.2	Control of wind erosion rates	Mangroves, a bio-shield against tidal waves and coastal erosion; break the waves during a storm surge caused by a cyclone	Paul *et al.* (2017); Sen (2020)
2.2.2.2	Regulation of peak flows	Mangrove reduces flooding through earthen embankment stabilization and manages wind speed and direction.	Chowdhury *et al.* (2021)
2.2.3.2	Flood and storm surge mitigation	Wave attenuating mangroves; mitigate cyclone storm surges and small tsunamis	Naz and Chowdhury (2022); Marois and Mitsch (2015)
2.2.3.3	Wind protection	Natural barrier against high winds and storm surges; reduce wind-related damage	Akber *et al.* (2018); Mitra (2020)
2.3.2.1	Pollination (or 'gamete' dispersal in a marine context)	Wild bees cause pollination	Das (2020); Pal, *et al.* (2022)
2.3.2.3	Maintaining or regulating nursery populations and habitats or breeding grounds (Includes gene pool protection)	Hatching, breeding, spawning and nursing grounds for many edible fishes, shellfishes, and turtles	Neogiet al. (2016); Bera *et al.* (2022); Ray and Straskraba (2001); Mukherjee *et al.* (2019); Roshith *et al.* (2013)
2.3.2.4	Maintaining or regulating refuge habitats	Route and refuge areas for a variety of migratory fish species	Roy *et al.* (2016)
2.3.2.5	Maintaining or regulating feeding grounds	Feeding and fattening grounds for resident and migratory fish and birds	Lama *et al.* (2021); Mallick (2023)
2.3.4.2	Decomposition and fixing processes and their effect on soil quality	Nutrients through degradation of leaf litter and breakdown of detritus	Mandala *et al.* (2009)
2.3.4.3	Maintenance of soil structure by biological agents and ecological processes	Annelids contribute to nutrient cycling, soil aeration, and decomposition of organic matter; fiddler crabs contribute by 'bioturbation'.	Saha and Sarkar (2022); Chatterjee *et al.* (2014)
2.3.6.1	Regulation of chemical composition of atmosphere and oceans, including maintaining rainfall patterns through evapotranspiration at the sub-continental scale	Carbon sequestration; acts as a better sink for greenhouse gases; and influences climate	Das *et al.* (2023); Bhattacharyya *et al.* (2023); Bhadra *et al.* (2022)

Bengali people, especially during religious ceremonies, festivals, and weddings (Chakraborty *et al.,* 2024). Also, the estuary has impacted artistic achievements such as Pata Chitra paintings featuring tigers and Bonbibi, films such as Roar, and literary works such as Jungle Nama, all of which emphasise the ecological and cultural relevance of the Sundarbans (Titumir, 2022).

The HMES has a special place in people's hearts on

Table 3. *Cultural services (Biotic/biophysical) provided by HMES*

Code	Class	Services by HMES	Source
3.1.1.1	Elements of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions	Recreational fishing; Canopy walk and mud walk	Jha et al. (2008); Das (2015)
3.1.1.2	Elements of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions	Sighting tigers; bird watching; rarest animals and bird watching	Das (2015); Das (2007); Das (2023)
3.2.1.1	Elements of living systems that enable scientific investigation or the creation of traditional ecological knowledge	A focal area of research: CIFRI, ICAR-CSSRI, Kakdwip Research Centre: CIBA, etc	Das *et al.* (2023)
3.2.1.2	Elements of living systems that enable education and training	Different conservation approaches through sanctuaries and a biosphere reserve	Bardhan (2021)
3.2.1.3	Elements of living systems that are resonant in terms of culture or heritage	Sundarbans, world Heritage site; historical dependence on the forest; 'we-feeling' as forest-dwellers; Cultural dependence in Hilsa	Karmakar (2018); Chakraborty *et al.* (2024)
3.2.1.4	Elements of living systems that enable aesthetic experiences	Poems and paintings; Patachitra; nature's symbol of beauty; tranquillity and a biodiversity hotspot; an inspiration for artist	Titumir (2022); Agencies (2023); Mitra (2023); Das (2014)
3.3.1.1	Elements of living systems used for entertainment or representation outside the setting concerned	Roar movie; Drifting in the Waters of Sundarbans; Jungle Nama: A Story of the Sundarban	Sadanah (2014); Patra (2023); Ghosh (2021)
3.4.1.1	Elements of living systems that have symbolic meaning, capture the distinctiveness of settings or their sense of place	The national animal of India, the Royal Bengal Tiger and the State fish of West Bengal, Hilsa	Khoshoo (1997)
3.4.1.2	Elements of living systems that have spiritual or religious meaning	Sacred groves and sacred trees	Chakraborti *et al.* (2016)
3.4.2.1	Elements or features of living systems whose contemporary existence or conservation is important to people	Five MPAs located in the Sundarbans Biosphere Reserve	Vyas *et al.* (2013)
3.4.2.2	Elements or features of living systems whose inter-generational existence or conservation is important to people.	Endangered Species in IUCN	Khan (2013)

a spiritual and symbolic level. It is home to the Royal Bengal Tiger, India's national animal, and the well-known Hilsa fish, West Bengal's state fish (Khoshoo, 1997). The trees and sacred groves along the banks of the Hooghly River add to the area's spiritual significance (Chakraborti *et al.,* 2016). As part of the Sundarbans Biosphere Reserve, which includes protected areas like the Sundarbans National Park and Sajnakhali Wildlife Sanctuary, the estuary is home to several endangered species, including the critically endangered river terrapin (*Batagurbaska*) and the Ganges and Irawaddy dolphins, which the International Union lists for Conservation of Nature (IUCN) (Khan, 2013;Vyas *et al.,* 2013).

Geophysical provisioning services

HMES provides essential geophysical provisioning services (Table 4), vital in supplying natural resources such as water, sediment, sunlight, wind, and solar energy, supporting human activities and industrial operations in the region.

The Hooghly River is a primary source of potable water for Kolkata, with the Indira Gandhi Water Treatment Plant (formerly Palta Water Works) supplying the city's drinking water (Hati *et al.,* 2020). The river also sustains several industrial activities, including the Budge Budge power station, which uses about 40,000 cubic meters of water daily (Powerline, 2017). The HMES provides a consistent water supply to the plains of West Bengal, facilitating shipping, agriculture, aquaculture, and household water consumption (Mitra *et al.,* 2018). The system's influence on groundwater is further demonstrated by the Hooghly River's contribution to groundwater recharge in the Bengal Basin, which is crucial for the area's sustainable water supply (Jammel *et al.,* 2023). With over 65 brick kilns on the left bank and 50 on the right, the river's bed silt supports a flourishing brick-making industry along its banks, boosting the local economy by excavating riverine sediment (Kanga *et al.,* 2020). This geophysical output emphasises how the river supplies raw resources for building projects.

The region also benefits from sunlight, an abundant natural resource that promotes outdoor work and prevents vitamin D deficiency among outdoor labourers (Goswami *et al.,* 2022). Solar energy is also an essential resource in the estuarine system. Sagar Island, located at the mouth of the estuary, serves as a model for solar-powered electrification efforts in remote and impoverished areas. On the island, households use solar panels to generate electricity and obtain clean drinking water through tube wells installed by the government and non-governmental organisations (Das and Hazra, 2020). This initiative shows the region's ability to produce renewable energy and manage its resources sustainably (Haldar and Bhattacharya, 2020). Wind energy has advanced significantly in the HMES region. The West Bengal Renewable Energy Development Agency operates a wind farm in Freserganj, South 24 Parganas, with wind electric generators contributing to renewable energy production since 2001(Department of Power, 2024). Five wind-power units operate in the region, emphasizing the estuary's role in facilitating clean energy development (Sharma *et al.,* 2012).

Geophysicalregulation and maintenance services

As shown in Table 5, HMES provides essential geophysical regulation and maintenance services crucial for sustaining ecosystems and human well-beingby transforming biochemical or physical inputs. It aids in the dilution of wastewater, naturally reducing pollution levels. (Bhadra *et al.,* 2022).

As natural defences, the coastal dunes of the estuary shield inland regions from coastal erosion and storm surges (Bhattacharya and Jana, 1993). Additionally, HMES replenishes coastal ecosystems by transporting 65.19 x 106 tonnes of sediment to the Bay of Bengal each year (Mukhopadhyay *et al.,* 2006). Coastal temperatures are moderated by the land and sea breeze, which lowers heat and humidity in certain seasons. Ecosystems and societies benefit from this natural wind cycle, improving local climate stability. (Subramanian *et al.,* 2023; Ganguly *et al.,* 2014).

Geophysicalcultural services

Opportunities for physical, intellectual, spiritual, and symbolic encounters with its diversified biophysical environment are among the many geophysical cultural services the HMES offers (Table 6). Recreational activities like kayaking, speed boating, and water sports are just a few of its many chances for experiential and physical engagement with the natural world. Boat excursions and picnics are popular pastimes in tourist

Table 4. *Provisioning Services (Abiotic/geophysical) provided by HMES*

Code	Class	Services by	Source
4.1.1.1	Surface water for drinking	The main source of potable surface water for the city of Kolkata	Hati *et al.* (2020)
4.1.1.2	Surface water used as a material (non-drinking purposes)	Water for power plant; multipurpose activities	Powerline (2017); Mitra *et al.* (2018)
4.1.2.1	Ground (and subsurface) water for drinking	River Hooghly recharges groundwater; used for drinking	Soren *et al.* (2023); Jammel *et al.* (2023)
4.1.2.2	Ground water (and subsurface) used as a material (non-drinking purposes)	Cooking, cleaning, various domestic works and in irrigation	Soren *et al.* (2023)
4.2.1.2	Mineral substances used for material purposes, including geophysical support (foundations).	Riverine sediment-based brick kilns	Kanga *et al.* (2020)
4.2.2.1	Non-mineral substances or ecosystem properties used for nutritional purposes	Adequate sunshine, a source of Vitamin D	Goswami *et al.* (2022)
4.2.2.3	Wind energy	Wind farm project at Freserganj	Department of Power (2024); Sharma *et al.* (2012)
4.2.2.4	Solar energy	Solar power systems in Sagar Island	Haldar and Bhattacharya (2020); Das and Hazra (2020)

Table 5. *Regulation and Maintenance Services (Abiotic/geophysical) provided by HMES*

Code	Class	Services by	Source
5.1.1.1	Dilution or transport of wastes by freshwater and marine ecosystems	Dilution of wastewater	Bhadra *et al.* (2022)
5.2.1.1	Abiotic regulation of mass flows	Coastal dunes act as a wall of defence for inland areas against destructive sea waves and currents	Bhattacharya and Jana (1993)
5.2.2.1	Maintenance and regulation by inorganic natural chemical and physical processes of fresh or salt waters	Annual load of sediment out of the estuary to the NE coast of Bay of Bengal	Mukhopadhyay *et al.* (2006)
5.2.2.2	Maintenance and regulation by inorganic natural chemical and physical processes of atmosphere	Land breeze-sea breeze; maintenance of moderate temperatures along the coastal area	Ganguly *et al.* (2014); Subramanian *et al.* (2023)

Table 6. *Cultural services (Abiotic/geophysical) provided by HMES*

Code	Class	Services by	Source
6.1.1.1	Characteristics of geophysical systems that that enable activities promoting health, recuperation or enjoyment through active or immersive interactions	Recreational boating; walking along the riverside; picnic, boat ride and swimming; kayaking, speed-boating and other river-water sports; events like Hooghly River Swim	Jha *et al.* (2008); Das (2021); Saha (2022); Ghosh and Mandal, (2020); Koli (2021)
6.1.1.2	Characteristics of geophysical systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions	Panoramic views; sunset beach	Travel triangle (2024); Das (2015)
6.2.1.1	Elements of geophysical systems that enable scientific investigation or the creation of traditional ecological knowledge	Research on ecological risk; dynamic modelling of dissolved oxygen; estuarine acidification; water pollution and Its mitigation	Ghosh *et al.* (2019); Mandal *et al.* (2012a); Mitra and Zaman (2021); Mitra *et al.* (2020)
6.2.1.2	Elements of geophysical systems that enable education and training	Information about conservation of natural resources or climate-change issues.	Roy *et al.* (2023)
6.2.1.3	Elements of geophysical systems that are resonant in terms of culture or heritage	Cultural heritage; scenic beauty and salvation	Rai and Das (2022)
6.2.1.4	Elements of geophysical systems that enable aesthetic experiences	Poems on Hooghly and Matlah Rivers	Ramesh (2009); Chattopadhyay (2014)
6.4.1.1	Elements of geophysical systems that have symbolic meaning	largest estuary of India; world's largest delta; largest mangrove vegetation in India	Qasim (2003)
6.4.1.2	Elements of geophysical systems that have sacred or religious meaning	Hooghly is the Ganges at its most sacred river.	Ivermee (2017); Ivermee (2020)
6.4.2.1	Elements or features of geophysical systems whose contemporary existence or conservation is important to people	Namami Gange Projects in West Bengal	Namami Gange Programme (2020)

spots like Princep Ghat and Machranga Dwip in the estuary (Jha *et al.,* 2008; Anon, 2021; Saha, 2022). At the same time, events like the Hooghly River Swim draw people to feel the waters (Koli, 2021). These interactions also offer a direct connection to the river's cultural and historical significance (Das, 2015). Additionally, the estuary provides spectacular panoramic views of the Bay of Bengal, especially from locations in the Sundarban near Beguakhali. It is a popular location for nature lovers because of its breath taking views (travel triangle, 2024). Beautiful beaches like Bakkhali, Kalsa Dwip, and Freserganj are great places to see sunsets and stroll along the shore (Das, 2015).

Numerous scientific studies have been conducted in this regionto explore its geological and environmental complexity. Research on heavy metal pollution in estuarine sediments (Ghosh *et al.,* 2019), dissolved oxygen modelling in the creeks of Sagar Island (Mandal *et al.,* 2012a), and the broader issue of estuarine acidification (Mitra and Zaman, 2021) offers vital information for conservation and environmental management. In addition, research on water pollution and its mitigation strategies highlights the importance of this estuary to the region's sustainability (Mitra *et al.,* 2020). NGOs and conservation organizations also contribute to raising awareness about climate change and the conservation of natural resources (Roy *et al.,* 2023).

This estuary has been a source of inspiration for many poets and artists. The Matla and Hooghly rivers have influenced many literary works, like the poem by Chattopadhyay (2014) and another by Ramesh (2009), illustrating the estuary's aesthetic and emotional impact on writers and artists. It also has great spiritual and symbolic significance as India's largest estuary with the largest mangrove vegetation. It is also a portion of the largest delta in the world (Qasim, 2003). The Hooghly River is known for its spiritual significance and it is the sacred Ganges (Ivermee, 2017). Also known as the Bhagirathi, it symbolises its heavenly origin and highlights its historical and spiritual significance to the local population (Ivermee, 2020).

Both the country and local communities have serious concerns about preserving the HMES. This spiritually and environmentally significant water system is intended to be preserved by initiatives such as the Namami Gange Project in West Bengal, which has been approved for Rs 3,815.95 crore (National Mission for Clean Ganga, 2020). These initiatives highlight the river's significance as a natural resource and a cultural and spiritual symbol essential to millions of people's lives and well-being.

Issues and recommendations

Urbanization and human activities have significantly altered the HMES, fragmenting habitats and reducing biodiversity, undermining essential ecosystem functions (Culhane *et al.,* 2018). Industrial and agricultural pollution has further exacerbated the issue, causing eutrophication and hypoxic conditions threatening aquatic life and critical services like water purification and carbon sequestration (Sousa *et al.,* 2016). To address these challenges, sustainable management policies are essential. The ecosystem services identified in this study hold significant value and can guide policymakers in incorporating these benefits into planning processes. By doing so, they can also promote community involvement, encouraging local stewardship and a stronger sense of responsibility toward preserving these vital resources. These strategies are crucial for preserving the HMES's ecological integrity and supporting its vital role in human well-being.

CONCLUSION

In summary, the Hooghly-Matlah Estuarine System offers a wide range of ecosystem services essential for the region's ecological balance and social cohesion. Biophysical services such as agricultural production, biomass resources, and fisheries are vital for sustaining local economies. Following this are ecological processes, including carbon sequestration, waste water dilution, and coastal defences, which are essential for reducing environmental risks and maintaining ecosystem stability.It preserves cultural heritage and provides recreational opportunities while creating strong physical, intellectual, and cultural linkages between the people and the environment. Additionally, it provided geophysical services like resources and materials, renewable energy, potable water, climate regulation, and interactive and spiritual connections. These biotic and abiotic services collectively demonstrate the economic and ecological significance of the Hooghly-Matlah Estuarine System. Thus, sustainable management of this estuarine system is essential for preserving biodiversity and human life in this vital estuary. So, the benefits of these services can be sustained for future generations, too.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

ACKNOWLEDGEMENT

This research forms a part of the first author's PhD program, conducted with the fellowship and facilities provided by ICAR-Central Institute of Fisheries Education, Mumbai, to whom the author extends his gratitude for the fellowship and institutional resources made available throughout the degree program from 2021 to 2024.

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