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Ecosystem-Based Valuation to Enhance Climate-Resilient Governance of Coastal Wetlands: The Case of the Kol Ramsar Site, India

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Abstract

Wetlands are vital ecosystems that provide critical provisioning, regulating, cultural, and supporting services that underpin biodiversity conservation and local livelihoods. Despite their importance, ecosystem service valuation is often overlooked in coastal wetland restoration, limiting recognition of their contributions to the United Nations Sustainable Development Goals (SDGs). To address this gap and overcome methodological fragmentation in wetland assessments, this study develops the Integrated Ecosystem Valuation and Management of Wetlands (IEVMW) framework, which integrates the Millennium Ecosystem Assessment (MEA), Drivers–Pressures–State–Impact–Response (DPSIR) framework, IPCC climate risk assessment, and Total Economic Value (TEV) approaches into a unified methodology. The framework was applied to the Kol Wetlands in India to identify ecosystem services, assess climate-related risks, estimate economic values, and develop management recommendations. Results indicate that provisioning services contribute the highest economic value, followed by regulating and cultural services. Climate change was estimated to place approximately 11.7% and 13.0% of ecosystem service value at risk in North Kol and South Kol, respectively, corresponding to a combined economic value at risk of ₹42.9 crore, with provisioning services being the most vulnerable. The IEVMW framework provides a practical and scalable approach for linking ecosystem service valuation, climate risk assessment, and governance, thereby supporting climate-resilient wetland management and biodiversity conservation across diverse socio-environmental contexts.

Keywords: DPSIR; ecosystem services; Kol Wetlands; Millennium Ecosystem Assessment; risk assessment; Total Economic Valuation; Wetland management

1. Introduction

Wetlands are natural transition zones between terrestrial and aquatic systems, covering approximately 6% of tropical land areas [1]. Despite their limited spatial extent,

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wetlands provide a disproportionate range of ecosystem services critical to environmental functioning and human well-being. Ecosystem services are broadly defined as the benefits that ecosystems provide to society, encompassing both material goods and non-material functions [2]. These services include flood regulation, water quality improvement, support for food chains, carbon sequestration, and the preservation of cultural values [3, 4]. At the same time, wetlands serve as biodiversity hotspots, supporting high levels of plant and animal diversity [5]. In recent years, the health of wetlands has been compromised by land-use change, pollution, overexploitation, invasive species, and climate change [6]. These pressures pose significant risks to the integrity of wetlands and the ecosystem services essential to human societies. The Ramsar Convention, signed in Ramsar, Iran, in 1971, aims to promote the conservation and sustainable use of wetland ecosystems [7, 8]. India officially adopted the Ramsar Convention on February 1, 1982, to protect its designated Ramsar Sites. As of June 2026, there are 100 recognized Ramsar Sites in India [9].

To effectively conserve wetlands, it is essential to understand their susceptibility to disturbances [10]. Assessing ecosystem vulnerability helps to identify the magnitude and extent of risk. In its Sixth Assessment Report (AR6), the Intergovernmental Panel on Climate Change (IPCC) redefined climate change adaptation to emphasize risk, focusing on the interactions among hazards, exposure, and vulnerability [11]. Accordingly, vulnerability was redefined as a function of sensitivity and adaptive capacity, separating it from exposure.

Over the past decade, a range of conceptual frameworks has been developed to assess wetland ecosystem services and to assist scientists and policymakers in quantifying their ecological and socio-economic benefits. Among the most influential is the Common International Classification of Ecosystem Services (CICES), developed by the European Environment Agency. This widely adopted and flexible framework organizes ecosystem services into three principal categories: provisioning, regulating, and maintenance, as well as cultural services. Despite its comprehensive and hierarchical structure, CICES is sometimes regarded as relatively complex to operationalize in applied assessments [12].

Another landmark initiative is the Millennium Ecosystem Assessment (MEA), launched in 2001 and published in 2005, which evaluates the consequences of ecosystem change for human well-being. Compared with CICES, the MEA framework is often considered more holistic and conceptually accessible. It identifies four major categories of ecosystem services: provisioning, regulating, cultural, and supporting services [13]. The overarching goal of the MEA is to strengthen ecosystem conservation and promote sustainable use to enhance the quality of life.

In India, the MEA framework has been applied to assess ecosystem services provided by mangroves in the Sundarbans, demonstrating their critical contributions to coastal protection, fisheries, and local livelihoods. Such assessments have played an important role in informing regional conservation and management priorities [14].

Understanding and conserving ecosystem services is also essential for sustaining both social and economic systems and for ensuring broader environmental protection and resilience. Valuing these services highlights the critical importance of preserving biodiversity and maintaining ecosystem functions [15]. The Drivers–Pressures–State–Impact–Response (DPSIR) framework is a widely used approach for organizing environmental, social, and economic indicators, providing a comprehensive framework for analyzing how human activities influence ecosystem health and societal well-being [16].

For instance, a DPSIR-based assessment in Uganda's Lake Kyoga basin highlighted significant degradation of land and water systems due to uncoordinated land-use practices and climate variability. These pressures have contributed to resource depletion and heightened livelihood vulnerability, highlighting the need for integrated natural resource management and adaptive policy interventions to reduce socio-environmental risks [17].

Similarly, Chilika Lake in India was successfully removed from the Ramsar Convention’s Montreux Record following targeted restoration efforts led by the Chilika Development Authority (CDA), demonstrating the effectiveness of coordinated conservation and restoration strategies in reversing ecosystem decline [18].

To effectively evaluate ecosystem services and inform policymaking, it is essential to integrate economic and ecological methods [19]. Economic valuation is a crucial tool for informing evidence-based conservation and resource management decisions [20]. Within this context, the Total Economic Value (TEV) framework has gained prominence as a comprehensive approach to assessing ecosystem services, integrating monetary and non-monetary dimensions to reflect their full societal value and support informed policy development [21]. The TEV framework is widely recognized for identifying and quantifying the contributions of ecosystem services to human well-being.

Governance plays a pivotal role in promoting sustainable resource management, restoring wetlands, and supporting local livelihoods [19, 22]. Despite multiple management policies, wetland governance remains largely ineffective due to the absence of an integrated framework that accounts for ecological, climatic, and socio-economic dimensions. As a result, policy decisions often prioritize short-term economic gains while overlooking the broader value of wetland ecosystem services. Integrating both economic benefits and ecosystem service values into governance and decision-making processes is therefore essential. Existing frameworks, including the MEA, DPSIR, TEV, and IPCC risk assessment, provide important conceptual and analytical insights. Yet they address these challenges in isolation, failing to capture the interconnected nature of wetland systems. Consequently, there is a pressing need for a consolidated, operational approach that links wetland research outcomes to practical management and policy actions to support effective and sustainable wetland governance.

This study addresses a critical research gap by developing an integrated analytical framework that combines the MEA, DPSIR, and TEV frameworks, along with elements of the IPCC's risk assessment model. By integrating ecological classification, causal analysis, climate risk assessment, and economic valuation, the study establishes a comprehensive structure for evaluating ecosystem degradation under changing climatic conditions.

The research focuses on the Kol Wetlands and pursues three main objectives: (1) to analyse its ecosystem services and prevailing environmental challenges using the MEA and DPSIR approaches; (2) to assess the Total Economic Value (TEV) of identified ecosystem services to capture both market and non-market benefits; and (3) to identify and evaluate potential climate-related risks through the IPCC risk framework, culminating in policy recommendations and a practical action plan to support sustainable management.

In doing so, the study contributes to the objectives of the Ramsar Convention on Wetlands by advancing the conservation and sustainable use of tropical coastal wetlands.

2. Materials and Methods

The Integrated Ecosystem Valuation and Management of Wetlands (IEVMW) framework was developed by combining the MEA, DPSIR, TEV, and IPCC frameworks. It consists of four phases (Fig. 1). Phase 1 establishes the system context and defines the problems to be addressed. In this phase, we conducted a comprehensive exploration of the characteristics of the Kol Wetlands and systematically identified their ecosystem services. We also analyzed the drivers and pressures affecting the system using the DPSIR framework. Phase 2 involves indicator-based IPCC risk assessment. Indicators were selected after careful examination of the system's drivers and pressures. Indicators of hazard, exposure, and vulnerability were normalized and used to assess the ecosystem's risk to climate change. Additionally, the state and the system's impact were determined. Phase 3 integrates the derived risk with the economic valuation of each ecosystem service to quantify the system's losses. In Phase 4, policy implications were identified, and adaptation management strategies are recommended.

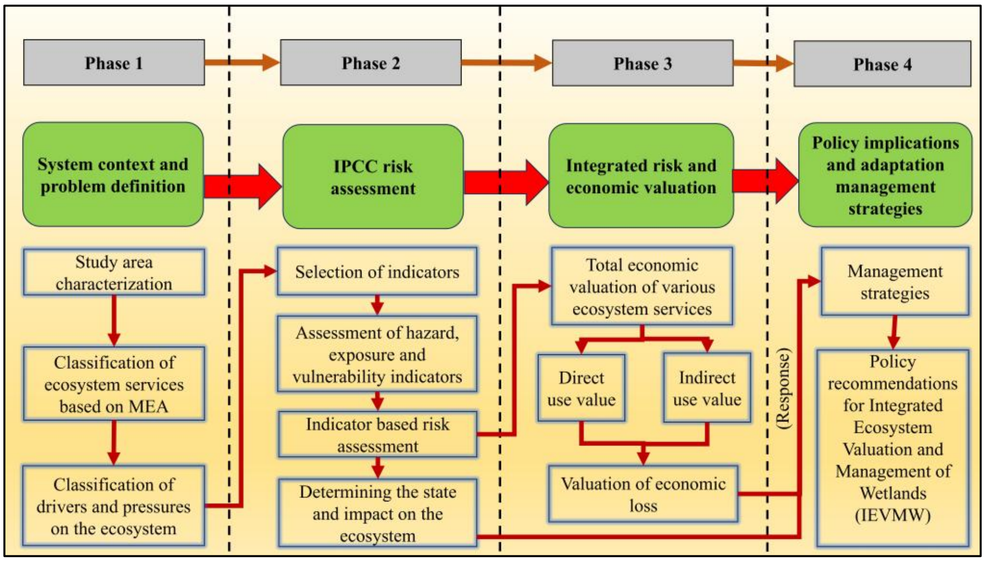

Figure 1. The four phases of the IEVMW framework

The IEVMW framework was conceptualized to overcome the methodological limitations of existing frameworks, which lack a systematic approach for quantifying the economic risks to wetland ecosystem services under climate change. First, the MEA framework was used to identify the ecosystem services provided by the wetland. Subsequently, the DPSIR framework was used to identify the major drivers and pressures affecting the ecosystem and to specify changes in the state and associated impacts driven by climatic risks. Climatic risks to the ecosystem were evaluated using the IPCC index-based risk assessment, employing indicators of hazard, exposure, and vulnerability derived from it. The TEV approach was then used to estimate the economic value at risk from climate change. Finally, in response to the findings, targeted climate adaptation strategies and management action plans were formulated for the wetland ecosystem.

The components of the risk index were selected based on the IPCC risk assessment framework, which defines risk as a function of hazard, exposure, and vulnerability. For each risk component, multiple indicators were selected based on their relevance to ecosystem functioning. Since this study focuses on a coastal agricultural wetland ecosystem, hazard indicators were selected to represent the climatic stressors relevant to this ecosystem, e.g., rainfall, flooding, and sea-level rise. Exposure indicators were selected to reflect the extent to which ecosystem services and ecological components are affected by climate change, e.g., agricultural area, human and cattle populations. Vulnerability indicators were structured to capture the system's sensitivity (e.g., salinity intrusion) and adaptive capacity (e.g., literacy rate), i.e., the system's ability to recover. Sections 2.2 and 2.3 provide a detailed explanation of the risk index's conceptualization, including its indicators and measures.

2.1. Study Area

The Kol Wetlands are among the largest and most productive humid tropical wetland systems in the region and were designated a Ramsar site on 19 August 2002. Located in the Thrissur and Malappuram districts of Kerala, they are locally known as the

Thrissur-Ponnani Kol and extend from the southern banks of the Bharathapuzha River to the northern banks of the Chalakudy River [23]. Situated at an elevation of approximately 0.5-1.0 m below mean sea level (MSL), the wetlands lie along the Central Asian Flyway, an important migratory corridor for numerous bird species [24].

Owing to their low topography, the Kol Wetlands remain inundated for more than half the year during the monsoon season [25]. Despite these challenging hydrological conditions, the system is highly fertile and supports exceptionally high rice productivity, with yields reaching up to 8 tons per hectare, significantly above the Kerala state average [26]. Rice cultivation typically begins after the monsoon, following the dewatering of flooded fields by pumping, with the extracted water retained in canal networks for irrigation [27]. During the summer months, additional irrigation water is supplied from the Chimoni and Peechi irrigation reservoirs to supplement agricultural demand [28].

The region receives an average annual rainfall of about 2685 mm and experiences temperatures ranging from 26° to 33.5°C. [29, 30]. The soils of the Kol Wetlands are highly acidic and are classified under agro-ecological unit 6 (AEU 6) by the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) [31]. This study focuses on the portion of the Kol Wetlands in Kerala's Thrissur district, covering 119.96 km^2 and divided into the North Kol and South Kol regions (Fig. 2).

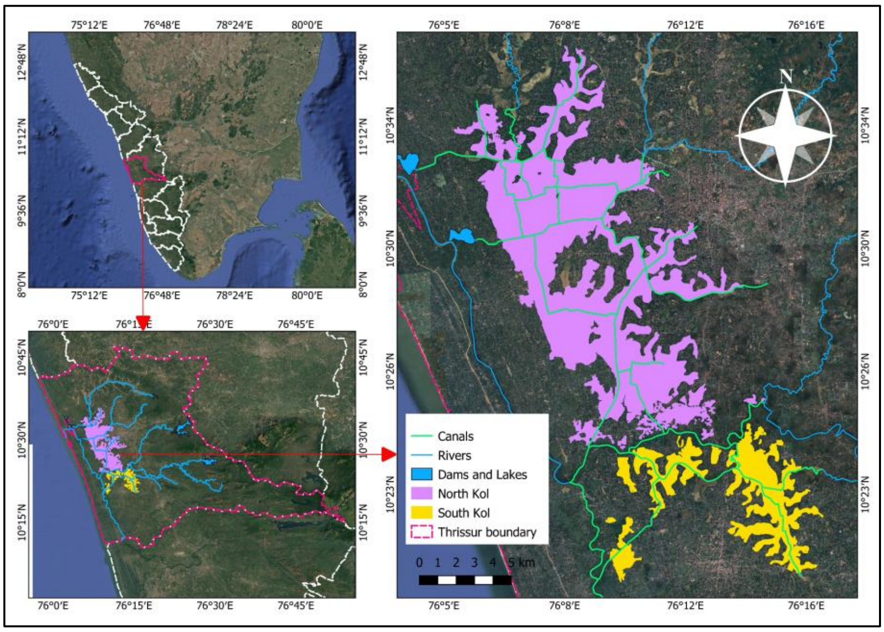

Figure 2. Study area

2.2. *Selection of indicators for the IPCC risk assessment*

This study employs an indicator-based risk assessment approach, given its established use in regional-scale studies and its effectiveness in enabling systematic prioritization [32]. Because the Thrissur Kol Wetland is an agricultural ecosystem, the indicators selected to evaluate each risk parameter were carefully chosen to reflect this context. The Thrissur Kol Wetland is divided into North and South regions, so this risk assessment has been conducted separately for each region to determine which is more vulnerable to climate change. The assessment systematically quantified hazard, exposure, and vulnerability using 21 indicators: 11 to characterize hazard, five socioeconomic indicators, and five physical indicators.

Socio-economic indicators include population density, crossbred cattle population, literacy rate, livestock density, and electricity availability. Physical indicators include changes in plantation, cropland, and settlement areas, as well as the study area's elevation and groundwater salinity. To ensure consistent quantification across livestock categories, cattle populations and livestock densities were standardized to adult cattle units (ACU) using the recommended animal unit values for the southern region of India [33]. This approach enables systematic comparison of livestock pressure across areas and supports integration with other socio-economic and environmental indicators in the assessment.

$$\text{ACU} = \text{livestock population in each category} \times \text{standard animal unit} \qquad (1)$$

2.2.1. Hazard indicators

The 11 selected climatic indicators relevant to agriculture are consecutive dry days (CDD), consecutive wet days (CWD), diurnal temperature range (DTR), total precipitation (PRCPtot), maximum 1-day precipitation (R×1 day), maximum consecutive 5-day precipitation (R×5 day), summer days (SU25), mean maximum temperature (TMAXmean), and mean minimum temperature (TMINmean) [34], inundation due to pluvial flooding and sea-level rise. Because the areal extent of the Thrissur Kol Wetland is very small, climatic data are available only from a single weather station. The analysis focused on historical data and future climate-change projections. Additionally, the impact of sea-level rise was examined for synthetic scenarios of 0.5 m and 1 m increases in sea level. Rainfall, minimum temperature, and maximum temperature data were collected for the baseline period from 1984 to 2023, and for the future SSP2-4.5 and SSP5-8.5 emission scenarios from 2031 to 2090. Historical climate data were obtained from the NASA POWER Data Access Viewer. Future climate change projections were derived from 13 bias-corrected, downscaled CMIP6 models compiled by Mishra et al. [35].

We utilized the ensemble mean of 13 climate models. Pluvial flood modeling and analysis in the Kol Wetlands were conducted using HEC-RAS (Hydrologic Engineering Centre’s River Analysis Software). The study incorporated historical and projected rainfall data along with a high-resolution digital elevation model (DEM). A 1-arc-second SRTM (Shuttle Radar Topography Mission) DEM was used to represent the topography in flood simulations. These datasets were integrated into the Rain-on-Grid (RoG) hydrological model, with rainfall inputs constrained to the wetland boundary to ensure spatially explicit flood predictions.

2.2.2. Exposure indicators

Exposure refers to the elements of the human and natural systems that are at risk of being adversely affected by climate-related hazards. High population density indicates more people are exposed to climate change. Crossbred cattle are more sensitive to climate change and require greater management investment than indigenous cattle. Hence, the more crossbred cattle there are, the greater the exposure. We have collected population density data from the 2011 census and crossbred cattle data from the 2011 panchayat-level statistics report for Thrissur, published by the Department of Economics and Statistics, for the 18 villages where the Kol Wetlands are located. A 4 km buffer around the Kol Wetlands was used to analyze changes in cropland, settlement, and plantation areas between 2010, 2015, and 2020, using Landsat 5, Landsat 8, and Sentinel-2 imagery, respectively, all resampled to 30 m resolution.

2.2.3. Vulnerability indicators

Vulnerability is a system's likelihood of being adversely affected by climate change. It includes the system characteristics that affect its sensitivity and its ability to cope or adapt. Vulnerability consists of two main components: sensitivity, the extent to which climate-related factors influence a system, and adaptive capacity, the system's ability to adjust to actual or anticipated climate changes and their effects.

In assessing vulnerability, we selected factors such as elevation and groundwater salinity to analyze system sensitivity, literacy rate, livestock density, and electricity availability to assess system adaptive capacity. Data on literacy rate, livestock density, and electricity availability were collected from the District Census Handbook [36]. The higher the literacy, the greater the ability to adapt; thus, literacy enhances people's ability to diversify and improve their livelihoods. Livestock density is an indicator of livelihood and agricultural diversification, which tends to increase the ability to cope with changes in livelihood. For this analysis, the indigenous crossbred breed and exotic cattle and buffalo were considered. Electricity denotes a positive overall development that enhances adaptability.

Since low-lying regions are highly susceptible to waterlogging, DEM is used to assess the study area's elevation. Kol Wetlands are also vulnerable to saline intrusion due to their proximity to the sea. Saltwater intrusion occurs when saline water infiltrates freshwater sources, degrading water quality. This process threatens food security and economic stability, particularly in agricultural areas where crop yields are adversely affected. We used the GALDIT index to evaluate groundwater salinity in the system using the six parameters: groundwater occurrence (G), aquifer hydraulic conductivity (A), groundwater level above sea level (L), distance from the shoreline (D), existing seawater intrusion impact (I), and aquifer thickness (T).

2.3. Conceptualizing Risk

The IPCC defines risk (R) as a function of hazard (H), exposure (E), and vulnerability (V):

$$R = f\,(H, E, V) \tag{2}$$

The risk index ranges from 0 to 1. It is categorized into five levels, from 'very low' to 'very high,' ensuring consistent interpretation, with higher values reflecting greater risk. Since the indicators varied in range and scale, to simplify arithmetic operations and comparisons, all indicators were normalized to a dimensionless scale from 0 to 1. This normalization ensures consistency across indicators, enabling their integration into risk indices. Based on the indicator’s direct or inverse relationship, two standardization approaches were applied for the index categories of hazard, exposure, and vulnerability [37]. The calculation of dimensionless hazard, exposure, and vulnerability index for each of the indicators is shown below:

$$Z_i \frac{X_i - MinX_i}{MaxX_i - MinX_i} \tag{3}$$

where Zi is the normalized value of indicator ‘i’, MaxXi denotes the maximum value, and MinXi the minimum value, of the indicator i. In case an indicator has an inverse relationship with hazard, exposure, or vulnerability, the index is calculated using the following alternative formula:

$$Z_i = \frac{MaxX_i - X_i}{MaxX_i - MinX_i} \tag{4}$$

Hazard, exposure, and vulnerability indices were calculated by aggregating the indicators (Fig. 3). We used the equal weighting method, as principal component analysis (PCA) may underestimate the risk, and expert judgment can be biased [38]:

$$\text{Index} = \frac{\sum_{i=1}^{n} I_i}{n} \tag{5}$$

where I represent the index indicators; n represents the number of indicators.

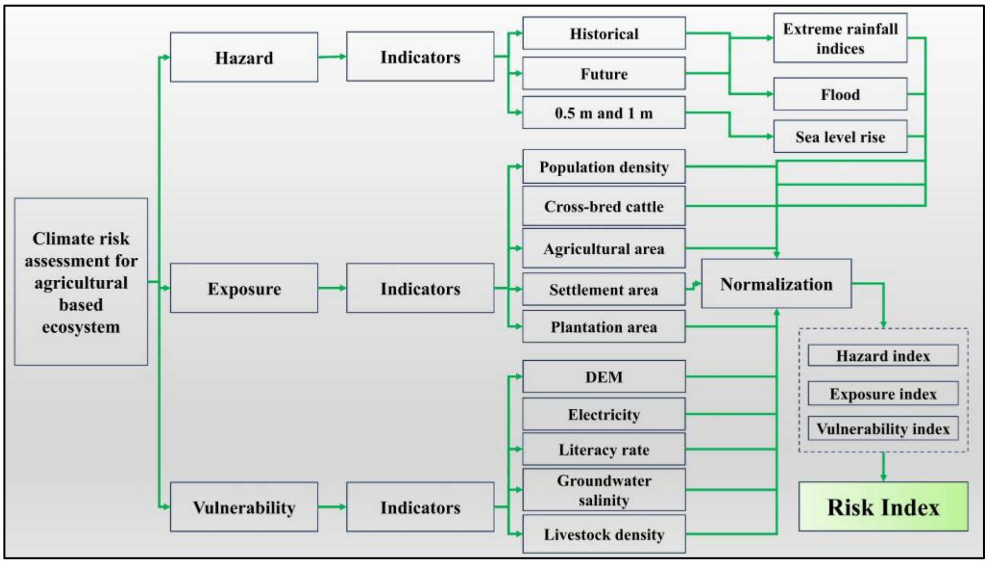

Figure 3. Development of Risk Index

2.4. Total Economic Value

The TEV framework employs a standardized unit of account, most commonly monetary terms, to quantify the benefits derived from ecosystem goods and services, including both use and non-use values. The concept of "use value" is classified into direct and indirect components. Direct use values include rice cultivation, fish farming, lotus cultivation, duck rearing, and tourism, while indirect use values encompass ecosystem functions such as floodwater storage, carbon sequestration, and groundwater recharge. In addition, non-use values include existence value, defined as the value derived from the mere existence of the ecosystem, independent of any direct use. The formula for TEV from Dushin & Yurak [39] is as follows:

$$\text{TEV} = (\text{use value}) + (\text{non-use value}) \tag{6}$$

To quantify potential losses in the Kol ecosystem attributable to climate risk, we adopted the TEV of the Kol Wetlands as estimated by Tamhankar and Nameer [40]. This aggregate value was subsequently disaggregated for the North and South regions of the Thrissur Kol Wetland, based on their respective spatial extents. The estimated economic value of ecosystem services encompasses the use values associated with provisioning, regulating, cultural, and supporting services. The economic value-at-risk was then calculated by multiplying the estimated ecosystem service values by the corresponding regional risk index.

3. Results: Application of the framework

3.1. Phase 1: System context and problem definition

3.1.1. System characteristics

The wetland remains submerged for more than six months of the year because it lies below sea level and has historically served as a floodplain. It plays a vital role in the regional rural economy by providing fertile agricultural land and supporting the local population. This ecosystem offers valuable resources, including fish, food, fodder, timber, and medicinal plants. Furthermore, it serves as an essential habitat for wildlife, particularly migratory birds [41].

Although there are many farming societies to facilitate cooperative farming operations within the Thrissur Kol Wetland, human activities and climate change are causing declines in diversity, agricultural output, access to drinking water, flood patterns, and aesthetic appeal [42].

3.1.2. Ecosystem services of the system

The ecosystem services of the Kol Wetlands, as identified by the MEA, are as follows:

- Provisioning services: rice cultivation, fish farming, lotus farming, and duck rearing
- Regulating services: flood storage, carbon sequestration, and groundwater recharge
- Cultural services: tourism
- Supporting services: the provision of habitats that sustain a wide range of biodiversity

3.1.3. Drivers in the ecosystem

Several factors affect ecosystem services and contribute to increased vulnerability. This study focuses on those that degrade the ecological character of wetlands, leading to declines in habitat quality, biodiversity, and ecosystem services. Within a DPSIR framework, natural drivers of environmental change include variations in solar radiation and climate, pest and disease outbreaks, and inherent ecological processes such as flooding and ecosystem succession. Human-induced drivers, including urbanization, land reclamation, intensive agriculture, and population growth, also significantly affect this ecosystem.

3.1.4. Pressures on the ecosystem

In recent days, shifts in temperature and rainfall patterns in the Kol Wetlands have adversely affected farmers and fishermen, as both flooding and drought, exacerbated by climate change, disrupt livelihoods and ecosystem services. According to Ajithkumar & Riya [43], the maximum temperature in Kerala has risen by 0.03°C per year from 1980 to 2020. Urbanization has increased municipal solid waste and industrial and domestic wastewater, which flow through the Kokkala canal to the Kol Wetlands. This contamination negatively impacts agricultural lands and water bodies with oil, grease, and suspended solids [44, 45].

3.2. Phase 2: IPCC Risk Assessment

3.2.1. Assessment of hazard

(a) Extreme climatic indices

Figure 4 presents box plots of the annual averages of nine extreme rainfall indices for both historical and future periods. The projections indicate an increase in CWD and a corresponding decrease in CDD, suggesting a shift toward persistently wetter conditions. Notably, the historical maximum CWD of 104 days is projected to exceed 200 days under future climate scenarios. Total annual rainfall is also expected to increase by 2071–2090, rising from a historical average of 2913.8 mm to 3457.5 mm under SSP2-4.5 and 3794.4 mm under SSP5-8.5. Although DTR values are higher in future periods than in the historical baseline, the overall trend indicates a gradual decline. Both annual mean daily maximum and minimum temperatures increase consistently under higher emission scenarios. In contrast, maximum rainfall intensity indices (Rx1day and Rx5day) are projected to decline in future scenarios. The SU25 index further indicates that daily temperatures exceed 25 °C for most of the year, highlighting sustained warming conditions across the study area.

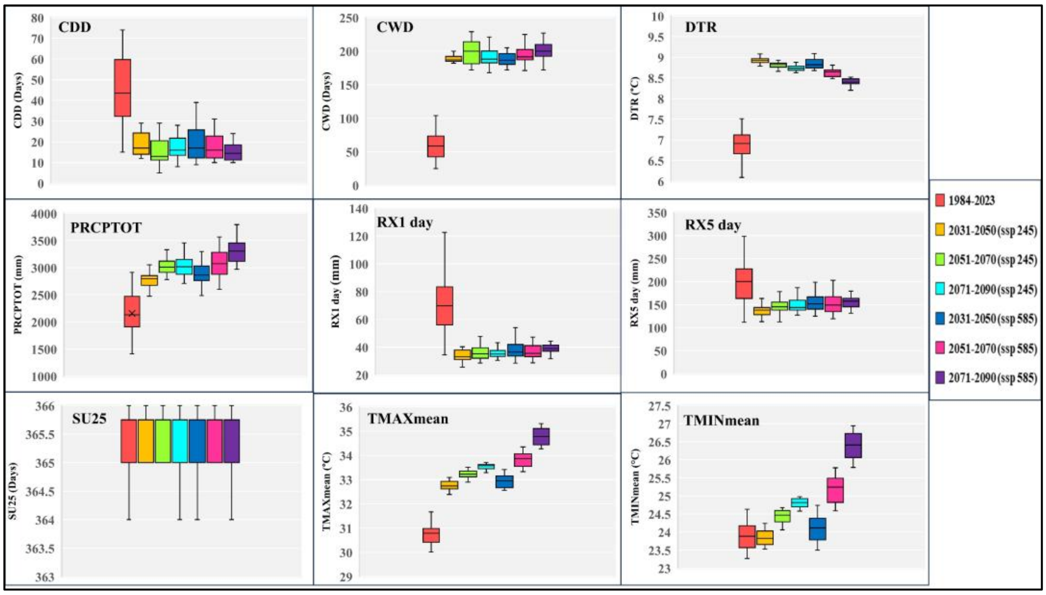

Figure 4. Extreme climate indices

(b) Inundation due to pluvial flood

A radar plot was generated to visually compare the percentage of submergence in both North and South Kol during a recent flood event (2018) and for future emission scenarios (SSP2-4.5 and SSP5-8.5) for 2031-2050, 2051-2070, and 2071-2090. For future scenarios, the 20-year average rainfall during the south-west monsoon season (June-September) was used, while for the 2018 flood, the actual rainfall data during June–September 2018 was used.

The results, depicted in Figure 5, indicate that the South Kol region is more prone to flooding compared to the North Kol region. In South Kol, the percentage of submergence exceeded 90% during the study period, and in North Kol, more than 60% of the area was submerged during the southwest monsoon season. The submergence percentage in the North Kol reached 74.5% in 2018. We also observed that the North Kol may experience severe future flooding, with 65% of the area submerged in both scenarios. In the case of South Kol, the area of submergence will increase up to 94.69% during 2071-2090.

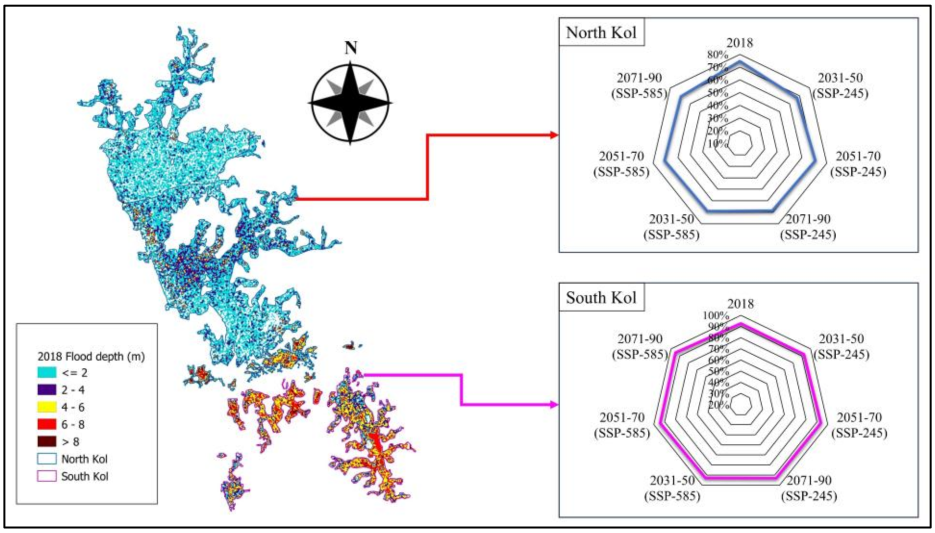

Figure 5. Inundation due to rainfall for various greenhouse gas emission scenarios in the Kol wetland

(c) Inundation due to sea level rise

The rise in sea level impacts the salinity in the Kol wetland. This analysis aims to determine the submerged areas of the North and South Kol regions at 0.5 and 1 m of sea-level rise. Figure 6 shows the percentage of areas submerged for sea level rises of 0.5 m and 1 m. The results indicate that the North Kol region is more susceptible to sea level rise than the South Kol region. For a 0.5 m sea level rise, 85.15% of North Kol and 71.33% of South Kol will be submerged. For a 1 m sea-level rise, the submerged area increased to 92.72% and 80.29% in North and South Kol, respectively.

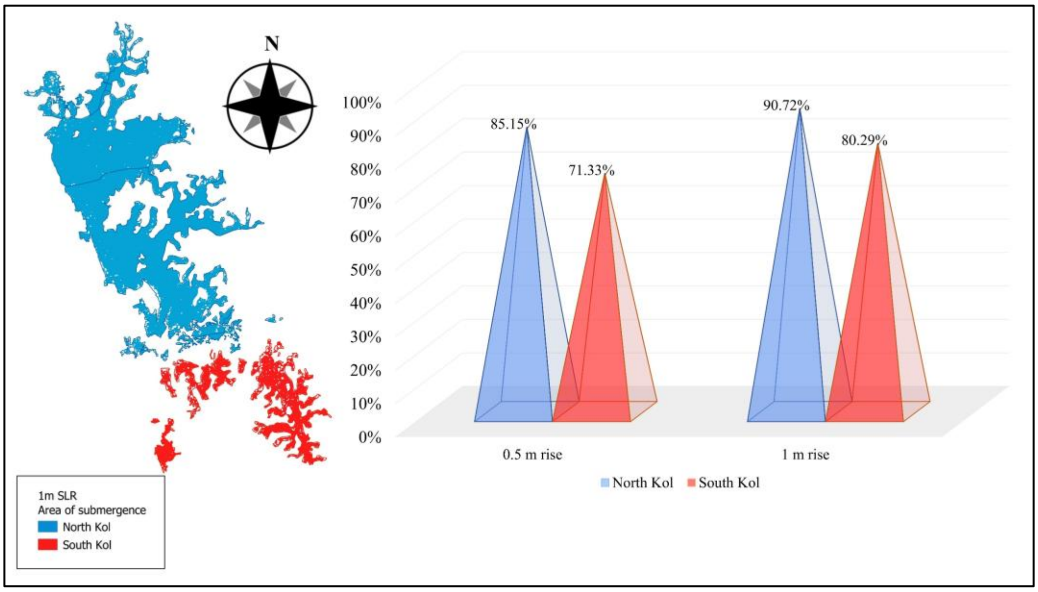

Figure 6. Inundated areas when the sea level rises to 0.5 and 1m.

3.2.2. Assessment of exposure

(a) Population density

The North Kol and South Kol regions of the Kol Wetlands encompass several villages. The North Kol region comprises 12 villages, with Avinissery having the highest population density at 2,981 persons/km2. In contrast, Adat has a lower population density of 828 persons/km2. In the South Kol region, comprising seven villages, Irinjalakuda has a high population density of 2,557 persons/km2. In contrast, Parapukkara has a lower density of 802 persons/km2.

(b) Cross-bred Cattle

The number of cross-bred cattle is higher in Parapukkara village (2008.32 ACU) and lower in Manalur village (161.86 ACU). Overall, the average ACU of cross-bred cattle for the North Kol region is lower (809 ACU) than the South Kol region (880 ACU).

(c) Land use change

Changes in the surrounding area of the Thrissur Kol wetland are affecting the ecosystem's health; therefore, a 4 km buffer was included in the LULC analysis. This analysis assessed exposure indicators, focusing on three main parameters: settlement area, cropland, and plantation. Plantation covers the largest area, followed by cropland and settlement in both the North and South Kol regions (Fig. 7).

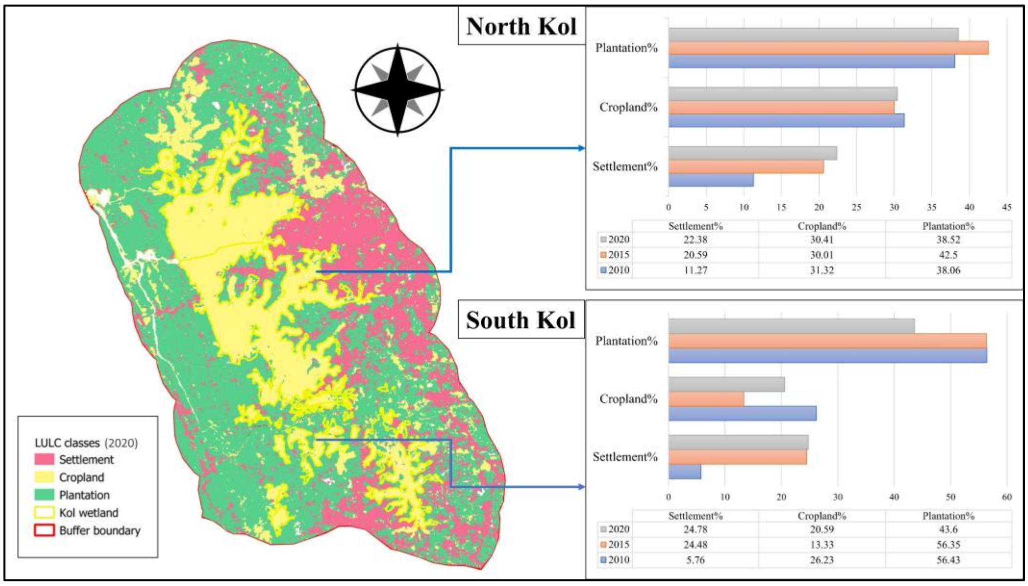

Figure 7. LULC analysis during 2010, 2015, and 2020

3.2.3. Assessment of vulnerability

(a) Literacy rate

Avinissery village in the North Kol region has a high literacy rate of 97.38%, whereas Cherpu village has a lower rate of 93.9%, compared with other villages. Villages in both North and South Kol have average literacy rates above 96%, with South Kol slightly higher than North Kol.

(b) Livestock density

Avinissery village is estimated to have a higher livestock density (203.25 ACU), while Manalur village is estimated to have a lower livestock density (34.54 ACU). The average livestock density was higher in the South Kol region (110.26 ACU) than in the North Kol region (100.58 ACU).

(c) Availability of Electricity

Four villages in North and South Kol have more than two electrical connections; therefore, we assumed 100% electrical connectivity in these four villages, thereby increasing their adaptability. Among all villages, Paralam village has the fewest electricity connections per household (84.38%). Overall, 93.94% of North Kol villages and 96.7% South Kol villages had domestic household electricity connections.

(d) DEM and Groundwater Salinity

DEMs of both North and South Kol were analyzed. Since the Kol Wetlands are located below mean sea level, they are vulnerable to waterlogging. In the case of Thrissur Kol Wetland, the North Kol elevation ranges from -109 m to 1 m, and the South Kol elevation ranges from -108 m to 1 m. Regarding elevation, both the North Kol and South Kol regions are vulnerable to waterlogging.

Figure 8 illustrates the vulnerability to salinity intrusion in groundwater across various blocks within the Kol Wetlands for 2019 and 2021. The analysis indicates that a significant area of the Thrissur Kol wetland is at considerable risk of saltwater intrusion because it lies below MSL. It was observed that salinity has advanced landward towards the east from the coast, with many regions classified as ‘less vulnerable’ in 2019 shifting to 'highly vulnerable' and 'extremely vulnerable' by 2021. In the North Kol region, the area of lower vulnerability decreased in 2021 compared to 2019. At the same time, the areas classified as extremely vulnerable and highly vulnerable have increased in 2021.

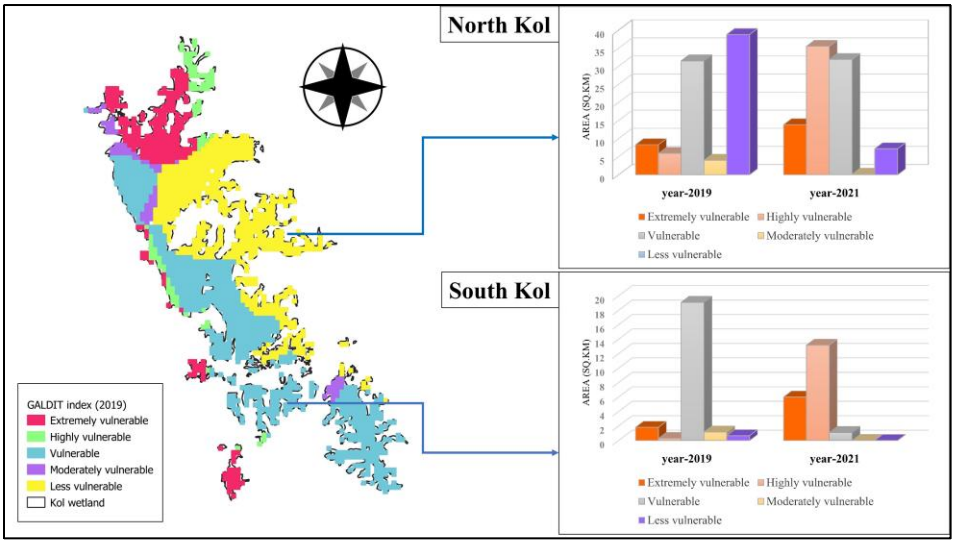

Figure 8. GALDIT index for the Kol wetland during 2019 and 2021

Table 1 presents the development of the risk index for the North and South Kol regions. These results show that South Kol is at a higher risk than North Kol.

Table 1. Risk index development using normalized indicator values.

Component	Indicator (I)	Indicator relationship with the component (Zi)	Time period (Historical/ Present)	Time period (Future - SSP245 & SSP585)	Normalized averaged indicator value		Index Value $(\frac{\sum_{i=1}^{n} I_i}{n})$		Risk index R=(H*E*V)	
					North Kol	South Kol	North Kol	South Kol	North Kol	South Kol
Hazard	Extreme rainfall indices (TMAXmean, TMINmean, SU25, DTR, RX1day, RX5day, PRCPtot, CDD and CWD)	Direct (DTR – Inverse)	1984-2023	2031-2090	0.379	0.379	0.44	0.52	0.117	0.130
	Flood	Direct	2018	2031-2090	0.09	0.95				
	Sea level rise (0.5 m and 1 m rise)	Direct	-	-	0.86	0.23				
Exposure	Population density	Direct	Census 2011	-	0.38	0.31	0.49	0.48		

	Cross-bred cattle	Direct	Census 2011	-	0.35	0.39				
	Area of cropland	Direct	2010, 2015, 2020	-	0.66	0.65				
	Area of settlement	Direct	2010, 2015,2020	-	0.96	0.37				
	Area of plantation	Direct	2010, 2015,2020	-	0.09	0.77				
Vulnerability	DEM	Direct	-	-	0.77	0.76	0.54	0.52		
	Literacy rate	Inverse	Census 2011	-	0.45	0.41				
	Electricity	Inverse	Census 2011	-	0.39	0.21				
	Groundwater salinity	Direct	2019 and 2021	-	0.49	0.66				
	Livestock density	Direct	Census 2011	-	0.61	0.55				

3.2.4. State of the ecosystem

Regulators at the major estuarine mouths prevent salinity intrusion in the Kol Wetlands from the Chettuva and Enamakkal backwaters. The effectiveness of the regulators is uncertain due to their need for updates and improvements.

The Kol Wetlands are increasingly lying fallow due to several factors, including high wage rates, labor shortages, low rice prices, and challenges associated with mechanized farming on certain lands. As a result, rice cultivation has become uneconomical. In recent years, climate change has caused successive droughts and floods, as well as saline incursion due to rising sea levels. The Enamakkal barrage, built 50 years ago, prevents salinity intrusion, and the minor regulator at Kottenkottuvalavu acts as a spillway for floodwaters.

Results of the study show a 90% increase in inundation in the Kol Wetlands, with water levels rising to an average of 5 m during the 2018 floods in Kerala [46]. Due to the lack of Sewage Treatment Plants (STPs), untreated sewage, along with the indiscriminate use of pesticides, contributes to pollution in the Kol wetland ecosystem [47, 48].

Cabomba furcata, often called "Pink Bloom" for its color, is an invasive aquatic plant native to South America that has become a significant ecological threat in the Kol Wetlands. Together with *Salvinia molesta* and water hyacinth (*Eichhornia crassipes*), *Cabomba furcata* has been proliferating in specific zones of the wetland, disrupting water flow and creating ecological and economic issues (Fig. 9). Its swift growth and ability to propagate vegetatively through stem fragments allow it to create dense mats, hindering light penetration and affecting native aquatic plant life.

Figure 9. Proliferation of invasive plants in the Kol Wetlands

3.2.5. Impacts on the ecosystem

Over the past four decades, rice cultivation in the Kol Wetlands has declined markedly. This trend has been largely attributed to climate change, particularly reductions in rainfall and rising temperatures, which have adversely affected rice productivity [49]. In addition, fluctuations in salinity levels have altered the ecological dynamics of the backwaters, influencing fish growth and species composition. A study conducted in the Chettuva backwater reveals that salinity declined sharply during the southwest monsoon, from 35.7 ppt in May to 23.6 ppt in June and 23.2 ppt in July, resulting in an increased freshwater influence and a corresponding decline in estuarine fish species [50, 51].

The Enamakkal regulator is the primary outlet for floodwater in the southern Kol Wetlands, and it also controls saltwater intrusion into rice polders. However, local farmers report that leaks in the regulator allow saline water to seep into agricultural fields, leading to soil salinization and reduced rice yields.

The Kol Wetlands are experiencing a decline in beneficial microorganisms, birds, and reptiles. Traditional subsistence fishing has shifted to commercial methods, affecting local fishing communities. Many species are threatened: *Kooral* is ‘Endangered’ [52] while Günther’s Catfish and giant sheatfish are ‘Vulnerable’ [53, 54]. Among birds, the Spot-billed Pelican is ‘Near Threatened’ [55]; the Steppe Eagle and Black-billed Tern are ‘Endangered’[56, 57]; and the River Tern and Greater Spotted Eagle are ‘Vulnerable’ [58, 59]. Reports of bird poaching and mangrove loss near the Chettuva estuary have also been documented.

From September onwards, the brackish-water habitat gradually re-emerges, and marine fish tolerant of salinity reappear in the lower reaches of the estuary. The loss of biodiversity can weaken the ecological integrity and resilience of ecosystems. This loss is a common consequence of intensified agricultural practices [60]. In the Kol Wetlands, declines in farmer-friendly microorganisms and in populations of various bird and reptile species have been reported.

3.3. Phase 3: Integrated risk and economic valuation

3.3.1. TEV of the provisioning services (Direct use value)

Rice cultivation, fish farming, lotus cultivation, and duck rearing are the primary provisioning services provided by the Kol Wetland ecosystem; however, these services are increasingly at risk due to environmental and human-induced pressures, as discussed earlier. Additionally, this study estimates the economic values of the provisioning services of North Kol and South Kol at ₹1,13,48,81,849 and ₹27,02,99,660, respectively. The economic value-at-risk was calculated by multiplying the ecosystem service's use value by the corresponding regional risk index (Table 1). The percentage value-at-risk was then derived by dividing the estimated economic value-at-risk of the ecosystem service by the total use value, i.e., ₹2,89,97,57,688 for North Kol and ₹69,06,47,682 for South Kol.

(a) Rice Cultivation

There are four main cropping seasons in the Kol Wetlands: *Virippu* (April – August), *Mundakkan* (September – January), *Kadum Krishi* (October – February), and Puncha (December/January – April/May). When the risk index is integrated with the economic value of rice cultivation, 4.21% (₹12,21,47,587) of the total use value in North Kol and 4.68% (₹3,23,24,903) of the total use value in South Kol were estimated to be at risk due to climate change.

(b) Fish Farming

Fishing is a crucial livelihood in the wetland, especially during the monsoon months. When water is pumped from the rice polders into the canals, large fish can be caught as the water level drops. Based on risk assessment value conducted on fish farming, 0.34% (₹98,98,402) of the total use value in North Kol and 0.38% (₹26,19,494) in South Kol are estimated to be at risk.

(c) Lotus Farming and Duck Rearing

Owing to strong cultural and religious demand, more than 6 ha of the Kol Wetlands are currently dedicated to Lotus (*Nelumbo nucifera*) cultivation, with an average annual yield of 1 lakh flowers per ha [40]. Kol Wetlands also play an important role in duck rearing. For lotus farming and duck rearing, 0.004% (₹1,23,312) and 0.021% (₹6,11,876) of the total use value in North Kol and 0.005% (₹32,633) and 0.023% (₹1,61,926) in South Kol are at risk, respectively.

3.3.2. TEV of the Cultural services (Direct use value)

(a) Tourism

The Kol Wetlands are a popular tourist destination with lush foliage and an abundance of bird and fish species. In the case of tourism, the risk assessment indicates that 0.27% (₹78,57,595) of the total use value in North Kol and 0.30% (₹20,79,419) in South Kol are at risk, respectively.

3.3.3. TEV of the Regulating services (Indirect use value)

Flood storage, carbon sequestration, and groundwater recharge fall under the category of regulating services and are also considered indirect use value of the Kol Wetlands. The estimated economic values of the regulating services for North Kol and South Kol were ₹1,69,77,16,910 and ₹40,43,52,492, respectively.

(a) Flood Storage

One of the most essential functions of the Kol Wetlands is flood storage. It is a natural buffer between the Western Ghats and the Lakshadweep Sea. The wetland can store 305.61 Mm3 of water with an average depth of 3 m under completely submerged conditions. Kol

Wetlands provide natural storage, like an artificially constructed reservoir. The risk estimation indicates that 5.36% (₹15,53,26,197) of the total use value of flood storage in North Kol and 5.95% (₹4,11,05,227) in South Kol are at risk due to climate change.

(b) Carbon Sequestration

Carbon sequestration plays a vital role in wetland function. Studies show that mangroves can store more carbon than tropical forests, helping combat climate change by sequestering it. Varghese et al. [61] estimated carbon stocks in the Chettuva mangroves at 569.3 t C/ha. These carbon stocks were equivalent to 2,089.33t CO2 per ha. The risk estimation indicates that 1.21% (₹ 3,51,12,729) of the total use value of flood storage in North Kol and 1.35% (₹ 92,92,165) in South Kol are at risk due to climate change.

(c) Groundwater Recharge

The presence of water in the wetland helps to retain the groundwater level. The risk estimation indicates that 0.28% (₹ 81,93,952) of the total use value of flood storage in North Kol and 0.30% (₹ 21,68,432) in South Kol are at risk due to climate change.

3.3.4. TEV of the Supporting Services

(a) Habitats for a wide range of biodiversity

The Kol Wetland is rich in biodiversity and supports numerous indigenous fish species. However, due to human activities and the presence of invasive species, populations of many native fish are declining. According to a 2019 study conducted in Pullazhi Kol, the number of native fish species declined significantly after a flood. This decline is attributed to the presence of an invasive fish species, *Pygocentrus nattereri* [62].

4. Discussion

The Discussion follows the four-phase structure of the IEVMW framework, enabling a structured interpretation of drivers, risks, and economic implications within the Kol Wetlands system.

4.1. Phase 1

Population growth increases food demand, which drives land conversion and the intensification of agricultural practices, placing increasing pressure on wetland ecosystems. Intensive agriculture exerts considerable pressure on the Kol Wetlands, prompting engineering interventions to enhance drainage and water management for double cropping.

The construction of farm roads has facilitated the movement of tillers and tractors, thereby reducing the cost of transporting seeds and fertilizers. However, these developments have also contributed to land-use conversion for non-agricultural purposes and to associated activities such as mining, thereby altering natural habitats and accelerating ecosystem degradation [63].

Overuse of agrochemicals, such as pesticides and fertilizers, leads to water pollution and disrupts ecosystems. Rapid population growth and urbanization have driven unscientific land reclamation in parts of the Thrissur Kol Wetland, reducing its area from 41% to 28% between 1969 and 2008, thereby accelerating ecosystem degradation [63]. Increasing temperature and pollution associated with climate change may lead to habitat loss for birds in the Kol Wetlands [64].

These findings demonstrate that anthropogenic drivers, particularly agricultural intensification and land-use change, are the primary forces shaping ecosystem degradation in the Kol Wetlands, reinforcing the need for integrated governance responses.

4.2. Phase 2

Excessive flood duration negatively affects rice crop harvests, particularly during the *Virippu* season (April–May to September–October), illustrating how climatic hazards directly affect provisioning services. It also delays cultivation in subsequent seasons, such as *Mundakkan* (September–October to December–January) and *Puncha* (September–October to December–January), since dewatering will take longer, resulting in significant production losses.

Furthermore, higher DTR during critical growth stages, particularly flowering, can adversely affect crop development and lead to yield reductions. A study conducted in the Thrissur-Ponnani Kol Wetlands by Sunil et al. found that every 1°C increase in maximum temperature during the flowering season was associated with a significant reduction in rice yield [65]. Similar studies report yield declines of 10%–20% under high temperature stress during the flowering stage [66,67].

Flooding strongly influences the economy, human health, water resource management, and ecosystem services, underscoring its role as a key hazard that links climatic variability to socio-economic impacts [68]. Flood depth assessment and analysis of flood events across climate change projections are essential for coastal wetlands. The flood analysis further emphasizes how increasing rainfall variability and intensity influence flood dynamics in the Kol Wetlands.

Inundation due to sea-level rise is another cause of coastal wetland degradation resulting from climate change.

Given that the Kol Wetlands are located below mean sea level, even moderate sea-level rise scenarios (e.g., 0.5 m) can result in extensive submergence, highlighting their inherent physical vulnerability.

Also, salinity modeling identified salinity intrusion as an additional critical stressor, driving rapid shifts in vulnerability between 2019 and 2021. This underscores the need to incorporate climate forecasts into flood management and wetland conservation planning. Many studies indicate that under high-emission scenarios, 20% to 90% of existing coastal wetlands may be lost by 2100, depending on the extent of sea-level rise and the wetland's capacity for inland migration [69,70].

Groundwater salinity results show that, even though the areal extent of South Kol is lower than that of North Kol, it is still vulnerable to salinity intrusion. Out of the six blocks that cover Kol Wetland in Thrissur district, most parts of the Irinjalakuda block (South Kol) and the Anthikkad block (North Kol) have shifted from ‘less vulnerable’ to ‘highly vulnerable’ and ‘extremely vulnerable’ during 2019–2021. It can be inferred that the area under the vulnerable category decreased, while the areas in the extremely vulnerable and highly vulnerable categories increased across most blocks.

LULC analysis shows an increase in settlement areas, reflecting rising exposure of socio-economic systems to climate risks. In contrast, the decline in cropland and plantation areas indicates both climatic stress and ongoing land-use transformation [71].

Reduction in cropland area in 2015 may be linked to rainfall deficits. Overall, the interaction between hazard, exposure, and vulnerability highlights the systemic nature of climate risk in the Kol Wetlands, emphasizing the need for integrated adaptation strategies.

A reduction in cropland area was observed in 2015 across both regions, possibly due to temporary fallowing induced by monsoon rainfall deficits. Thrissur experienced a 24%

deficit in southwest monsoon rainfall and a 15% deficit in annual rainfall that year, which may have affected cultivation.

According to the IPCC risk assessment, the higher hazard index was observed in South Kol, indicating that this region is more prone to hazards, one reason being high flood submergence. Although the exposure index showed only minor differences between the two regions, North Kol has a slightly higher value, suggesting more elements are at risk than in South Kol. Furthermore, the higher vulnerability index in North Kol highlights the region's lower capacity to cope with hazard events. Although North Kol has a higher exposure and vulnerability index, the overall value indicates that South Kol is more prone to climate risk than North Kol. Therefore, risk reduction strategies should focus more on South Kol and on enhancing adaptive capacity and resilience in both North and South Kol to minimize overall risk across the Kol ecosystem.

Parvathy & John [72] indicated that anthropogenic activities, such as the discharge of domestic sewage, the runoff of fertilizers and pesticides from rice polders, and the use of ichthyotoxic substances for fish capture, critically harm water quality, leading to a decline in fish diversity.

The 2018 flood significantly affected the Kol Wetlands, resulting in income losses for many individuals due to declines in fish diversity.

The Enamakkal regulator is a vital part of the Kol Wetlands and was built to prevent the mixing of freshwater and saltwater. Leakage in this regulator leads to salinity intrusion, which destroys crop cultivation [73]. This is being temporarily prevented by constructing an earth bank in front of the regulator each year. Though these earth banks may provide short-term protection against salinity, the restoration and maintenance of the Enamakkal and the Idiyanchira regulators are essential for improving the resilience of the Kol Wetlands ecosystem and supporting sustainable agricultural activities.

Invasive aquatic plants like *Cabomba furcuta* massively affect freshwater fish populations, resulting in economic hardship for local communities dependent on fisheries. A similar case can be observed in Australia, where another species of Cabomba (*Cabomba caroliniana*) has invaded water bodies, affecting aquatic life by displacing native vegetation [74].

Within the IEVMW framework, these findings collectively demonstrate the interaction between hazard (flooding and sea-level rise), exposure (land-use change and population), and vulnerability (salinity intrusion and adaptive capacity), which together determine overall climate risk.

4.3. Phase 3

Climate variability has increasingly affected the Kol Wetlands through frequent floods and droughts, with significant implications for ecosystem services and livelihoods [75]. Saseendran et al. [76] estimated a 6% reduction in rice yield in the Kol Wetlands due to climate change. Future climate scenarios indicate that extreme rainfall is projected to increase, leading to higher-intensity and longer-duration floods in the Kol Wetlands.

The dewatering process begins in August, as the wetlands appear as a large body of water following the monsoon season. This is when migratory birds start visiting Kol. After the rice harvest in the Kol Wetlands, duck farmers bring their ducks to the rice polders, where they wade for about a month. Once the rice has been cultivated, the ducks are allowed to wade for an additional 2 to 3 months. In return, the landowners receive a small income from the duck farmers as compensation

The Kol Wetlands provide important cultural ecosystem services. Its outstanding scenic value attracts many visitors. Boating is another popular pastime in the Kol from July to February. Pullu and Vilangan Hills are two main tourist destinations. The tourists visit

Pullu to see the sunset. The Thrissur district administration considered the Pullu-Manakkody Kol Wetlands for an ecotourism project in 2017. This plan includes bait fishing, boating, a treehouse for birdwatchers, an eco-museum, and educational agricultural tours [77].

As stated by Mitsch et al. [78], the average sequestration rate for tropical wetlands is 1.29 tons of carbon per hectare (ha) per year (t-C ha^{-1} $year^{-1}$). Additionally, a study by Ricke et al. [79] found that India's social cost of carbon emissions is the highest globally, at $86 per ton of CO2. One ton of carbon equals 3.67 tons of CO_2 [80]. A study conducted across the entire Kol Wetlands estimated that the maximum organic soil carbon (SOC) was stored in the 90-120 cm soil range and that the 150 cm topsoil layer can sequester around 229.63 Tg of organic carbon [81]. Mangrove forest or *kandal kaadukal* is available in the Chettuva mouth of the Kol Wetlands, spreading over an area of 2.025 ha.

According to reports, groundwater levels have remained relatively stable over time despite rising water demand driven by population growth and urban expansion [82]. This stability can be attributed to the wetland’s capacity to recharge groundwater, highlighting the importance of regulating ecosystem services.

One of the most essential values of the Kol Wetlands is its diverse avifauna. Like many other tropical wetlands, Kol provides birds with food and shelter. However, according to Asian Waterbird Censuses, there has been a significant decline in bird populations, indicating biodiversity loss, likely due to pesticide use and waste dumping [83].

These findings indicate that climate change poses a substantial economic threat to ecosystem services in the Kol Wetlands, with provisioning services being particularly vulnerable due to their direct dependence on climatic conditions. This demonstrates that the impacts of climate change are not evenly distributed across ecosystem services; rather, livelihood-dependent services such as agriculture and fisheries are disproportionately affected. By linking ecosystem service valuation with climate risk indices, the study provides a clearer understanding of how environmental change translates into economic loss, thereby strengthening the relevance of integrated assessment frameworks for climate adaptation planning.

4.4. Phase 4

The findings highlight the need to develop targeted management strategies and policy recommendations, informed by assessments and outcomes across all phases of the IE-VMW framework, to address the key issues facing the wetland system. These strategies directly respond to the drivers and pressures identified in Phase 1, the climate risks quantified in Phase 2, and the economic vulnerabilities highlighted in Phase 3.

Table 2 outlines the issues facing the Kol Wetlands along with their corresponding causes.

Table 2. Underlying causes of observed phenomena in the Kol Wetlands

Issues	**Causes**
Agricultural Modernization	State policies promoted the modernization of rice cultivation through irrigation infrastructure and subsidies from 1960 onwards [84].
Water Supply Infrastructure	Peechi and Chimmoni reservoirs were commissioned to meet crop irrigation requirements [85].
Mining Activities	Mining during the construction boom has impacted wetlands. Regulations exist but are poorly implemented [85]
Urban & Industrial Reclamation	Land reclamation driven by population growth for food production, housing, and aquaculture intensifies pressure on wetlands [24].
Fish Farming	Although fish farming can be conducted without altering wetlands, it increases pollution and land-preparation costs [86, 87].
Ecological Changes	Changes in biophysical processes affecting the wetland's ecological character and natural resource baseline have been observed [64].
Urban Sewage & Solid Waste	Untreated sewage and solid waste from the urban periphery are dumped into wetlands. Puzhakkal thodu shows the highest BOD (0.1131 tons/day) [88].
Soil & Water Quality Decline	Overuse of fertilizers and pesticides, along with poor bund and canal design and maintenance, has degraded soil and caused waterlogging [89, 90].
Sedimentation Issues	High sediment yield (26 t/ha/yr) is observed in the catchment area of the wetlands; the estimated total sediment yield in the Kol Wetlands is 4 million tons [91].
Fallow Land Increase	Factors such as high wages, labor shortages, low rice prices, and difficulty with mechanization have left more land uncultivated, increasing the proportion of fallow land [65, 92].
Post-Mining Degradation	Lands affected by mining remain unsuitable for agriculture, resulting in more fallow land [24].
Biodiversity Loss	Agricultural intensification has reduced biodiversity, thereby affecting the ecosystem's resilience [93].

4.5 Management action plan

Decentralized water governance, involving cooperation between Kol farmers and government agencies, is crucial for managing both agricultural productivity and drainage in the region and forms a key component of integrated wetland management.

To prevent salinity intrusion from the Enamakkal and Chettuva backwaters, significant estuarine regulators, including the Enamakkal and Idiyanchira structures, have been built. Suggested measures for enhanced wetland management include establishing sewage treatment plants (STPs), maintaining and improving salinity-control systems, encouraging farmers to use fertilizer effectively, improving market access, and implementing targeted climate action strategies.

These measures directly address the drivers, pressures, and risks identified across Phases 1–3 of the IEVMW framework and aim to enhance system resilience.

A network of monitoring stations must be in place to assess salinity levels and water quality for the scientific operation of upstream reservoirs and salinity structures. A data management system can be established to facilitate monitoring, investigations, and research on this vital ecosystem.

Based on the framework, this study recommends implementing the following measures to enhance sustainable development and ecosystem services in the Kol Wetlands.

a) Given the salinity conditions in the wetland and the need for freshwater for rice cultivation and other ecosystem services, it is essential to implement effective reservoir operation policies for both the Chimoni and Peechi irrigation projects. These policies should also account for water availability and requirements beyond wetland areas.

b) The regulators that connect the wetland to the Canolly Canal should utilize data from the monitoring stations. Some of these regulators need repair and proper maintenance.

c) Effective operation and maintenance of salinity control structures are essential for regulating salinity levels while ensuring the sustainable use of wetlands.

d) The main structures that need renovation are the Enamakkal, Idiyanchira, Koothumakal Regulators, and the Karanchira Lock. Key tasks include replacing shutters, reinforcing concrete, preventing salinity intrusion, and automating shutter operation with sensors and IoT technology.

e) There is a need to revisit and redesign the canal network, considering the requirements of irrigation and drainage and inland navigation, wherever applicable.

f) The unchecked discharge of sewage into the wetlands from densely populated areas, particularly the townships, must be stopped. It is essential to implement the necessary measures to treat sewage to acceptable standards before discharging it into the wetlands. Compliance with the standards set by the Central Pollution Control Board (CPCB) and the Bureau of Indian Standards (BIS) is mandatory.

g) The application of agrochemicals for rice cultivation in the wetlands is often not done scientifically but based on manufacturers' advice, whose commercial interest cannot be overlooked. Therefore, given the significance of the wetland's flora and fauna, agrochemicals should be reduced; natural manures should be used wherever possible; and organic farming should be encouraged. Organic farming is already practiced in a few localized pockets. Where feasible, multiple cropping systems may be adopted, with at least one crop other than rice, such as vegetables or pulses.

h) Fishery activities are ideal during the monsoon season, and these should be encouraged wherever possible; this will bring more income to the farmers and meet the protein deficiency among the population in and around the Kol Wetlands. The rice-cultivating farmers should also consider the needs of the local fishing community.

Exotic fish farming must be avoided, and the use of chemicals and fish feed should be minimized. Native fish species must be encouraged.

i) Speedy actions must be undertaken to weed out invasive species of plants and avoid activities leading to the introduction and growth of invasive species.

j) Plastic use within this Ramsar site's boundaries must be strictly controlled.

k) The reclamation or use of wetlands for purposes other than those for which they are presently used must be avoided. The Enactment of the Government of Kerala, namely, the Kerala Conservation of Paddy Land and Wetland Act 2008, must be strictly implemented.

l) Developing the Canolly Canal within the wetland, from Chethuva to Kottapuram, is possible for ecotourism purposes. The revenue could support biodiversity conservation in the wetlands, which are famous for their bird populations.

m) The mouths of the channels connecting the wetlands to the sea had rich mangrove forests from the point of view of species and area covered. In recent years, human activities have led to declines in species numbers and mangrove thickness. It is recommended that a detailed study be conducted to restore mangrove forests to their former state. The investigations have shown that mangrove areas contribute significantly to carbon sequestration.

n) Construction of Sewage Treatment Plants (STP) is required to control pollution. Proper solid waste management is also necessary to maintain the wetland's aesthetic value and further reduce ecosystem degradation.

o) The Kerala Land Development Corporation (KLDC) and the Kol Development Authority (KDA) should be strengthened and empowered with broader representation of stakeholders to support integrated management of this wetland system. India's Chilika Development Authority (CDA) may serve as a model. CDA serves as a governing body for multiple stakeholders, including various government departments, national agencies, research institutions, and local fishing communities, and is chaired by the state's chief minister. By bringing together diverse stakeholders, CDA effectively facilitates integrated resource management for the sustainable governance of Chilika Lake [94]. KLDC plays a crucial role in maintaining infrastructure, including canal networks, regulators, bunds, sluices, locks, and bridges, to support the farming and fishing communities in Kerala. They have constructed most of the irrigation canals [27]. Operation and maintenance, in collaboration with the farming community, are handled by KLDC. The State Irrigation Department maintains and operates the water sources (Peechi and Chimoni reservoirs) for the system. The State Wetland Authority, Kerala (SWAK), plays a major role in formulating policies and regulatory frameworks, and in implementing integrated wetland management. Also, SWAK tends to regulate the wetlands by managing plastic use, invasive species, agrochemicals, salinity, fisheries, and sewage treatment plants (STPs).

5. Conclusion

This study presents the development and application of the IEVMW framework to the Kol Wetlands, combining the MEA, DPSIR, IPCC risk assessment, and TEV approaches to analyze ecosystem services, associated risks, and their economic value.

In relation to objective 1, the application of the MEA and DPSIR frameworks enabled a systematic identification of ecosystem services and the key drivers and pressures affecting the wetland system. The findings highlight the combined influence of climate change and anthropogenic activities in degrading ecosystem health, with implications for biodiversity, agricultural productivity, and water resources.

Addressing objective 2, the TEV approach was used to quantify both market and non-market ecosystem services, demonstrating the substantial economic importance of the Kol Wetlands. Provisioning services were found to contribute the highest share of economic value, underscoring the dependence of local livelihoods on wetland resources.

For objective 3, integrating the IPCC risk framework enabled quantification of climate-related risks. The results indicate that approximately 11.7% and 13.0% of ecosystem service value in North Kol and South Kol, respectively, are at risk under changing climatic conditions, with provisioning services being the most vulnerable. This combined risk valuation approach provides a clearer understanding of the economic implications of climate change.

Building on these findings, the study proposes targeted adaptation and management strategies, including improved salinity control, wastewater treatment, sustainable agricultural practices, and enhanced monitoring systems. These measures are essential to strengthen ecosystem resilience and support sustainable livelihoods.

Overall, this study demonstrates that integrating ecological, climatic, and economic dimensions within a single analytical framework enhances the relevance of ecosystem service assessments for policy and decision-making. The IEVMW framework offers a transferable and scalable tool for wetland management, with the potential to support climate-resilient governance and contribute to multiple SDGs, including those related to water, climate action, and biodiversity conservation.

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