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The effects of climate change on the hydrology, salinity, and biota of Kerala's estuaries

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Abstract
This review focuses on the significance of estuaries in Kerala, a state located on the southwest coast of India, and explores the challenges they face due to climate change. Estuaries are crucial ecosystems that support biodiversity, fisheries, tourism, and human well-being. However, their vulnerability to the impacts of climate change threatens their sustainability. We synthesize the existing literature on four major estuaries in Kerala, namely Ashtamudi, Vembanad, Chettuva, and Periyar, examining the effects of climate change on their hydrology, salinity, and biota. These estuaries are influenced by factors such as monsoon rainfall, river discharge, and tidal fluctuations. While they possess abundant natural and cultural resources, they encounter diverse environmental and socio-economic challenges. By analyzing different climate change scenarios, we investigate how these estuaries' physical and chemical characteristics are affected and the resulting implications for ecological processes and functions. Furthermore, we discuss the potential impacts of climate change on the ecosystem services provided by these estuaries and the livelihoods of the communities reliant on them. By identifying knowledge gaps and research needs, we aim to contribute to the effective management and conservation of these estuarine ecosystems in the face of a changing climate. Through this comprehensive review, we provide an overview of the present condition and prospects of the studied estuaries, emphasizing their role in sustaining the socio-ecological systems of Kerala.

Keywords: Climate, hydrology, salinity, biodiversity, fisheries

Introduction
Estuaries are dynamic ecosystems that provide important ecological and economic services, such as biodiversity, fisheries, tourism, and human well-being. However, they are also vulnerable to the impacts of climate change, which can alter their physical and chemical characteristics and affect their ecological processes and functions (Nair and Aziz, 1987) [4]. Kerala, a state on the southwestern coast of India, has several estuaries that are influenced by monsoon rainfall, river discharge, and tidal fluctuations. These estuaries are rich in natural and cultural resources, but they also face various environmental and socio-economic challenges, such as coastal erosion, sand mining, wetland destruction, saline intrusion, water quality degradation, and livelihood insecurity (Padmakumar and Murugan, 2022) [6-7]. According to Padmakumar and Murugan 2022 [6-7], Kerala's population density, geography, changing land use, urbanization, and development activities all contribute to climate change. There is very little more than 120 km (35 km in certain locations) separating the eastern and western regions of Kerala. There are locations above 2,695 meters above the coastline (Anamudi, Idukki region) as well as below sea levels (Alappuzha and Kottayam regions) within this 120 km. This creates a steep gradient for the water flow from the hills to the coast, which can be interrupted by various human interventions. Kerala's forty-one rivers that travel westward must empty into the sea after 120 kilometers. Kerala is thought to be home to 58 dams, which limit the inherent velocity of waterways and aquifers while also having the ability to regulate flooding. People utilize the riverbanks for domestic and agricultural reasons when the water recedes. When the dams are lowered during the season of precipitation, the people who live closest to the riverbanks are the most impacted. For homes and agriculture, people have also moved to the Western Ghats' foothills. These sections of the Western Ghats are the source of numerous rivers in Kerala. Construction, roads, buildings, and agriculture all impede rainwater's natural flow. About 331,904 kilometers make up Kerala's road network. If we presume that a road's typical width is five meters, then the span of the region is approximately 165,952 hectares.

In a similar vein, Kerala has 7.8 million households overall. Assuming that a house measures approximately five cents in size, this corresponds to an area of 157,827 hectares with concrete structures that are permanent obstructions. As a result, precipitation cannot infiltrate the earth as quickly (Kandasamy, 2017) [8]. Kerala is home to an estimated 5,924 quarries, which worsen the coastal region's environmental conditions.

The coastal areas, lagoons, maritime wetlands, and habitats that border the coastline all show signs of potential climate change effects on Kerala's aquatic and coastal environments. The primary factors contributing to these effects are rising sea levels, changes in precipitation patterns and the ensuing flow of freshwater, nutrients, and sediment; elevated sea surface temperatures; rising ocean acidity; modifications to distribution trends; and rising atmospheric CO2 concentrations (Rajendran *et al*., 2021). Modifications in the timing and volume of freshwater, nutrients, and sediment input may have an impact on estuarine production. Due to comparative increases in sea levels, the state's coastal areas, particularly the low-lying ones like Kuttanad, may suffer negative effects such as immersion, coastal flooding, and coastal erosion. The food production and water security in the coastal ecosystems would be further impacted by this. Climate change would also affect the highly profitable ecosystems along the Keralan coast, such as the seaweed and mangrove ecosystems (Suresh *et al*., 2020) [10]. According to Abdulla Bava and Seralathan (1996) [1], Kerala's shallow waters are nutrient-rich because rivers transport nutrients and organic matter through estuaries. The beachfront in Kerala is fruitful due to ocean currents that follow the winds and bring in cold, nutrient-rich water that upwells along the coast, ensuring a healthy biomass of fish. However, climate change may have an impact on these variables.

In this paper, we review the existing literature on the effects of climate change on the hydrology, salinity, and biota of four major estuaries in Kerala: Ashtamudi, Vembanad, Chettuva, and Periyar. We examine how different climate change scenarios affect these estuaries and their implications for the ecosystem services and livelihoods of the people dependent on them. We also discuss the knowledge needs and research needs for the effective management and conservation of these estuarine ecosystems in a changing climate. Our review provides a comprehensive overview of the current state and prospects of these estuaries and their role in sustaining the socio-ecological systems of Kerala.

Materials and Methods

Study area

The study focused on four estuaries in Kerala, India: Ashtamudi, Vembanad, Chettuva, and Periyar. These estuaries were selected based on their ecological significance, representation of different hydrological regimes, and availability of relevant data. Each estuary exhibits unique characteristics in terms of size, freshwater inflows, and connectivity to the sea, providing a range of scenarios to assess the impacts of climate change.

Data collection

Multiple sources of data were used for this review paper, including peer-reviewed scientific articles, government reports, and other relevant literature. Data on hydrological parameters, salinity levels, and biotic communities were collected from these sources. Hydrological parameters included river flow rates, water level fluctuations, and freshwater inflows. Salinity levels were measured at various locations within the estuaries, including near the river mouths and deeper into the estuarine channels. Biotic data encompassed surveys of fish populations, macroinvertebrates, and vegetation, as well as studies on the distribution and abundance of mangroves and other estuarine flora.

Data analysis

The collected data were analyzed qualitatively to identify trends and patterns in the hydrological characteristics, salinity levels, and biotic communities of the estuaries. Information from different estuaries was compared to detect commonalities and differences in their responses to climate change. The findings were then synthesized and interpreted to understand the overall impacts of climate change on the estuarine ecosystems of Kerala.

Results and Discussion

Hydrological changes

The review revealed significant alterations in the hydrological regimes of the studied estuaries. Increased temperatures and altered precipitation patterns, attributed to climate change, have led to changes in river flow patterns and freshwater inputs to the estuaries. These alterations in hydrology have had cascading effects on the estuarine ecosystems, influencing salinity levels and biotic communities. For example, reduced freshwater inflows during dry periods have led to decreased river flow rates, lower water levels, and reduced flushing of the estuaries, ultimately affecting the distribution and abundance of estuarine species (Jannerjahn *et al.*, 2008) [3].

Salinity dynamics

Changes in freshwater inputs and altered tidal dynamics have resulted in shifts in salinity levels within the estuaries. Higher salinity intrusions from the sea have been observed, leading to increased seawater influence on estuarine environments (Padmakumar and Murugan, 2022) [6-7]. These changes in salinity have affected the distribution and abundance of various estuarine species, including fish, crustaceans, and mangroves. Some species that are sensitive to salinity changes have shown declines in abundance, while others have exhibited shifts in their distribution ranges, seeking more suitable habitats within the estuaries. Additionally, increased salinity levels have also impacted the productivity and composition of estuarine vegetation, such as mangroves, which are important habitats and provide valuable ecosystem services (Anil *et al.*, 2023).

Biotic responses

The review also highlighted the impacts of changing hydrological and salinity regimes on the biota of the estuaries. Alterations in freshwater inflows and increased salinity have affected the reproductive cycles, growth rates, and distribution patterns of numerous species. For instance, changes in river flow rates and salinity levels have disrupted the breeding and spawning behaviors of fish species that rely on specific hydrological conditions (Zhang *et al.*, 2009) [9]. Reduced freshwater inflows and increased salinity have also negatively impacted the abundance and diversity of

macroinvertebrates, which serve as an important food source for fish and other aquatic organisms. Furthermore, changes in salinity levels have directly influenced the distribution and health of mangrove forests, with some areas experiencing dieback or reduced growth due to increased salinity stress.

Climate change adaptation

The findings of this review emphasize the need for effective adaptation strategies to mitigate the impacts of climate change on Kerala's estuaries. Integrated management approaches are crucial for maintaining the ecological integrity of these estuarine systems. One key aspect is the restoration of freshwater flows, which can be achieved through measures such as water diversion projects, regulated releases from reservoirs, and land-use management practices that prioritize maintaining natural flow patterns. By ensuring sufficient freshwater inflows, the adverse effects of increased salinity and altered hydrology can be mitigated, supporting the health and resilience of estuarine ecosystems (Shibu *et al.*, 2022) [5].

In addition to freshwater restoration, protecting critical habitats is essential. Conservation efforts should focus on preserving and restoring mangrove forests, as they play a vital role in providing nursery areas, stabilizing shorelines, and sequestering carbon. Establishing protected areas and implementing sustainable management practices can help safeguard these valuable ecosystems and enhance their capacity to adapt to changing environmental conditions.

Long-term monitoring programs are also recommended to better understand the complex interactions between climate change, hydrology, salinity, and biota in estuarine ecosystems. Regular monitoring of hydrological parameters, salinity levels, and biotic communities can provide valuable data for assessing the effectiveness of adaptation measures and identifying emerging trends or new challenges. Moreover, continued research efforts are needed to deepen our understanding of the specific mechanisms and thresholds through which climate change impacts estuaries, as well as to explore the potential synergistic effects with other stressors, such as pollution or habitat degradation.

In conclusion, the review highlights the significant impacts of climate change on the hydrology, salinity, and biota of Kerala's estuaries. The observed alterations in freshwater inputs, salinity dynamics, and biotic responses underscore the vulnerability of these ecosystems to changing environmental conditions. However, by implementing integrated management strategies, restoring freshwater flows, protecting critical habitats, and promoting long-term monitoring and research, it is possible to enhance the resilience of Kerala's estuaries and mitigate the adverse effects of climate change. These efforts are crucial for ensuring the continued ecological health and functionality of these valuable and fragile coastal ecosystems.

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