Effects of climate-induced salinity changes on estuarine ecosystems

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Abstract

This paper will discuss the impacts of climate-driven salinity changes on the ecosystems and ecology of estuaries. The purpose of the paper is to analyze how the drivers of climate change, such as sea-level rise, changes in precipitation intensity, and extreme weather regimes, alter salinity regimes and eventually impact biodiversity, ecosystem processes, and socio-economic services in estuaries. The methodology will involve the qualitative analytical review, conceptual model ecosystem analysis, and interpretation of secondary data. It was assessed using synthesized information from past empirical studies, ecological data, and simulation data to evaluate biological and ecosystem processes across varying salinity levels. Simulations of the changing salinity of the ecosystem, driven by species interactions, revealed tolerance and trophic responses. The results indicate that the patterns of ecological stability and biodiversity are dramatically altered by rising salinity levels. There are some statistical predictions regarding the extent of the ecosystem's adaptation to changes in salinity. Gradual change of +5 PSU gives rise to nutrient availability of 80, reduced primary productivity of 9 g C/m^2/day, and fish biomass of 300 kg/ha, which gives rise to the Human Livelihood Index of 70. With an extreme salinity (>10 PSU), the nutrient levels drop to 60 %, productivity goes down to 5 g C/m^2/day and the fish biomass declines to 180 kg/ha, meaning that there is extreme

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degradation. The decrease of nutrients to 85% and fish biomass to 280 kg/ha is caused by a freshwater surge (-5 PSU). These dynamics favor the halotolerant species and not the biodiversity that is freshwater-dependent, and also upset the trophic processes. The conclusion emerges with the reality that the salinity variable, as a result of climate change, is a decisive factor that influences the estuarine resilience, ecosystem services, and fisheries productivity. Thus, to minimize the loss of biodiversity, predictive ecological modeling and adaptive management strategies have to be implemented in the built-in monitoring of the estuarine ecosystem to alleviate a decrease in ecosystem services as well as augmentation of the long-term stability of the estuarine ecosystems under the rising climatic pressures.

Keywords: Estuarine ecosystems, Climate change, Salinity fluctuations, Biodiversity, Trophic dynamics, Ecosystem resilience, Sea-level rise

Introduction

Ecosystems located at the junction of freshwater river systems and marine environments; estuarine ecosystems are one of the most productive and diverse habitats available on Earth (Little, Wood and Elliott, 2017). Estuaries also provide critical ecosystem services, such as nutrient cycling, water purification, carbon storage capacity, and serve as nurseries or habitats for commercially important fish and shellfish species and wildlife habitats for migratory birds and other species (Yang *et al.,* 2025; Feyrer *et al.,* 2015). In addition to their critical and irreplaceable ecological value, estuaries provide the basis for socioeconomic activities such as fisheries, aquaculture, and tourism, and are thus intrinsically linked to biodiversity and human livelihoods. However, these ecosystems are sensitive to precipitation, hydrology, and salinity, two important factors that are both substantially changing the hydrology of all terrestrial and aquatic ecosystems due to climate change (Hall and Lewandowska, 2022). With respect to both the complexity and fragility of estuarine systems to climate change, it is the purpose of this study to examine the impacts of salinity change due to climate change, and biological-ecological-functioning responses of the estuarine ecosystems (Khujakulova *et al.,* 2025; Ghalambor *et al.,* 2021).

Being peculiar to the nature of transitions, estuaries are exposed to both freshwater and salinity, which play an important role in ensuring the sustainability of these systems in terms of their biodiversity and ecological processes. The salinity balance can be further complicated by the fact that the increase in the sea level will cause saltwater to intrude into freshwater zones, whereas the shift in precipitation patterns will cause droughts or floods of freshwater. As an example, species with limited salinity requirements might be forced out of habitat, and species with greater adaptability will be able to out-compete the less adapted species, causing changes in biodiversity. Such a changing nature can also affect the services which these ecosystems offer to human populations, such as the provisioning of food, fresh water, and recreation (Dixit and Raje, 2024; Nunes-Vaz, 2012).

The research will seek to examine the effects of salinity variation due to climate conditions in estuarine environments. In particular, the study will be concentrated on the effect of the changes in the salinity regimes on the biodiversity and species distribution, ecosystem processes, and socio-economic services (fisheries and aquaculture). Empirical research, ecological models, and secondary data will be used to assess the resilience of estuarine ecosystems at various salinity levels and also give insights into the adaptive management strategies.

The study will also assist in shaping the overall discussion on climate adaptive management because it will fill the existing gaps in the information on the salinity effects on estuarine ecosystems. This involves the knowledge of the critical salinity levels that the estuarine systems can withstand, and also the species and ecosystem services that are susceptible. Finally, the paper shall give practical suggestions to strengthen the resilience of the estuarine ecosystems in climate change conditions and to maintain the livelihoods that rely on these ecosystems. This study will uniquely address climate adaptive management and conservation of estuarine ecosystems in the context of climate change by acknowledging areas of existing knowledge and examples of current knowledge limitations.

Key Contribution of the Paper:

- Considering ecosystem services: assessment of estuarine ecosystems within the estuaries and their roles in diversifying, nutrient recycling, carbon storage, and nursery functions of economically and ecologically important species;
- Correlating climate change and salinity: climate change, through thermally induced precipitation increase, is the primary driver altering the weather system, and sea level rise is the consequence of climate change. These Factors Then Alter the Salinity and Hydrology of Estuarine Systems.
- Define in detail how these systems interact. Socio-Economic Consequences: Changes in ecosystems lead to changes in associated livelihoods. In particular, demonstrate these in relation to the estuarine-associated economies of fisheries and aquaculture.
- Identification of Knowledge Gaps: Addresses the need for further amalgamated research on salinity alteration and uptake.

The paper will be organized as follows: I will provide an introduction to estuarine ecosystems and the effects of climate change on salinity. Part II deals with salinity shifts brought about by climate. Section III discusses the impact of salinity on biota and biodiversity. Section IV considers the operation of the ecosystem at different salinities. In section V, the anthropogenic factors are discussed. Section VI provides the management and adaptation strategies. The last topic of section VII is major findings and recommendations.

Climate-Induced Salinity Changes

It is true that climate change is drastically changing the natural salinity regimes of estuarine ecosystems. These salinity variations are largely associated with the current climate-related phenomena like the elevation of sea level, the variations of precipitation, and more frequent and severe extreme weather. These drivers have complicated interactions, which cause tremendous changes in the salinity gradients on which estuaries rely to achieve ecological equilibrium.

Sea level rise as a result of global warming and polar ice melting is one of the greatest factors contributing to salinity change. Due to the rising sea level, intrusion of saltwater into the estuaries is increasingly becoming common, particularly in areas whose freshwater intake has already been affected. The result of this intrusion is high levels of salinity that interrupted the fine-tuning that the estuarine systems required, particularly in freshwater-dominated estuaries. Alteration of the salinity gradient in these systems has extensive consequences for distribution and biodiversity due to the inability of some of the species that are adapted to freshwater to endure in the present salty environment. Conversely, saltwater-tolerant species, or the so-called halotolerant species, are able to become more dominant, altering the biodiversity and ecosystem structure because of the invasion of saltwater (Varela and Drexler, 2021).

The change in the level of precipitation, e.g., prolonged droughts or heavy rainfall, is also contributing to the salinity changes in estuaries. The reduction in the amount of fresh water also has the potential to lead to high rates of salinity in the drought-afflicted regions because the rate of evaporation is more rapid than the rate of precipitation. Quite to the contrary, excessive rains can result in large quantities of freshwater, which can temporarily decrease the level of salinity in estuaries. These severe shifts between the hypo-salinity (low salinity) and hyper-salinity (high salinity) put a lot of stress on living biota. This can cause a change in trophic organization, species evenness, and stability of the ecosystem, owing to such stressors.

As well, the changes in salinities are also caused by excessive climate activities such as cyclones, hurricanes, and heavy storms (Aghazadeh, Mazinani and Mahdavi, 2016). These events change the hydrodynamics of estuaries by changing the circulation pattern of water, sediment deposition process, and erosion rate of the coasts. As an illustration, storm surge could cause sudden salinity spurts as the seawater gets pushed further inland, and fresh water during a heavy rainfall can dilute the estuarine waters. It has been estimated that with the change of climate, the frequency and severity of such extreme events are also anticipated to increase, thus increasing the already fluctuating salinity levels in the estuarine systems (Rybczyk *et al.,* 2013).

These regional impacts, which are caused by global climatic trends, will lead to larger regional and global patterns of salinity (Kulkarni and Jain, 2023; Chang, McKown and Chen, 2023). Oceanic increase in salinity is becoming common in many estuaries in the world where sea-level rise and loss of freshwater are most pronounced (Xu *et al.,* 2012). In ungulates, the natural salinity balance is being destroyed by the intrusion of freshwater periodically as a result of irregular distribution of precipitation in other areas (Mohammed and Scholz, 2018). Estuaries are not equally prone to changes; the vulnerability of the estuary to changes depends on a number of factors, including the geomorphology of the estuary, tidal inflow, and watershed characteristics. In particular, estuaries where the tidal range is small, or in places where there is a large volume of freshwater flow, may be less susceptible to saltwater intrusion, and estuaries with lower freshwater inflow or high evaporation rates may be susceptible.

Climate change agents, such as a rise in sea level, changes in precipitation patterns, and severe weather conditions, are causing the increasing levels of salinity variability in the estuarine ecosystems, pushing the ecosystems to the boundary of their salinity tolerance. These changes not only change the distribution of species, but also reduce the biodiversity and, in addition, undermine the ecosystems. The local environmental conditions define the ability of estuaries to adapt to such changes, and the consequent ecological imbalances put a strain on predictive models and adaptive management strategies to ensure that estuarine ecosystems and services to sustain that are maintained.

Impacts on Estuarine Biota

Species Distribution and Biodiversity Responses

Salinity variation caused by climate is one of the most significant environmental forces that can impact estuarine biota. Salinity changes the ecological niches of organisms and has a direct impact on the species distribution pattern in estuarine systems. Various species in estuaries have defined salinity tolerance levels (ranges) that define their existence and geographical distribution. When salinity changes outside these tolerance limits, species with freshwater affinities tend to decrease or move away to those species with greater adaptability, whereas phenotypically more flexible halotolerant or euryhaline species take over the habitat. Such a change in the composition of species brings a gradual reorganization of biological communities and a decline in the overall biodiversity. In the long run, ecological resilience may evolve into a less straightforward community structure as the specialized species may be replaced by fewer, more tolerant taxa, which may reduce the capacity of estuarine ecosystems to adapt to the disruption of environmental conditions.

Figure 1 explains how climate change affects the salinity levels that alter estuarine ecosystems. Climate change causes evaporation phenomenon and affects precipitation patterns, both hyper salinity and hypo salinity (extremely high and low salt levels, respectively, in water) in a body of water. The salt intrusion also modifies the salt content of the water, which is necessary for a salt wedge, and is vital for estuarine zonation. The osmotic and physiological equilibrium (homeostasis) of fish, shellfish, and other estuarine organisms is compromised in salinity, hyperosmosis (dehydration, also called estuarine organisms is osmotic stress), and habitat loss. The trophic structure and species assemblage are changed; lesser salt marshes, degraded mangroves, and seagrass beds.

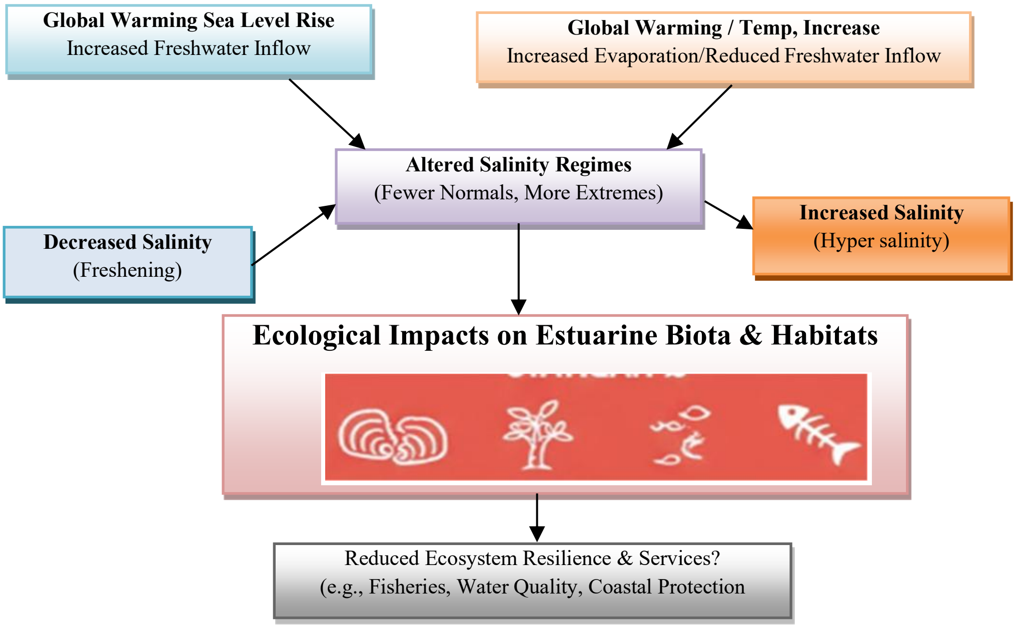

Figure 1: Climate change impacts on estuaries of the salinity shifts.

Physiological and Reproductive Stress in Aquatic Organisms

Fluctuations in salinity are also very stressful to estuarine species. Various species of water depend on the effective osmoregulatory processes to balance ionic equilibrium in the body and stability in metabolism. Acute or chronic variations in salinity disrupt these physiological systems, raising the amount of metabolic energy needed to ensure homeostasis. Because of this, the organisms can undergo slowed growth rates, compromised metabolic activities, and disrupted biochemical activities. Severe cases of salinity stress may result in reproductive failure via the production of gametes, fertilization, and development of larvae. The net effect is a decrease in population stability and long-term species survival in the estuarine ecosystem due to low larval survival and recruitment. Therefore, chronic upheavals of salinity can cause population reductions and changes in the life-history strategy of subjects.

Trophic Interactions and Ecosystem Stability

The changes in salinity regimes also have an additional impact on the trophic interaction and energy flow of estuarine food webs. The dynamics in the quantity or efficiency of the primary producers (phytoplankton and aquatic vegetation) can be spread to the upper trophic levels and impact herbivores, zooplankton, and predatory fish species. An example is that when primary productivity decreases due to salinity-related stress, it may decrease food supply available to herbivorous organisms, consequently decreasing prey availability to upper-trophic predators. These disturbances may disrupt the food web processes and disturb predator-prey interactions, and cause the cascading ecological effects within the ecosystem. Finally, these systems of trophic imbalance led to a decreased stability in the ecosystem, a change in nutrient cycling, and a decrease in the overall ecological balance in the estuarine waters.

Metrics

- **Biodiversity Index (Shannon–Wiener Index)**

This metric measures species diversity and ecosystem stability in estuarine ecosystems.

$$H' = -\sum_{i=1}^{S} p_i In(p_i) \quad (1)$$

In equation (1), where:

H'= Shannon diversity index
S= total number of species
p_i= proportion of individuals belonging to species i

- **Ecosystem Productivity Index**

This measures primary productivity changes under salinity stress.

$$P_e = \frac{C_f}{A} \quad (2)$$

In equation (2), where:

P_e= ecosystem productivity
C_f= carbon fixation rate (g C/day)
A= area of the ecosystem (m²)

- **Salinity Stress Index**

This metric quantifies the deviation from optimal salinity levels.

$$SSI = \frac{|S_O - S_t|}{S_O} \quad (3)$$

In equation (3), where:

SSI= salinity stress index
S_o= optimal salinity level
S_t= observed salinity level

- **Fish Biomass Productivity Metric**

This measures fisheries productivity within estuarine ecosystems.

$$B_f = \frac{W_t}{A} \quad (4)$$

In equation (4) Where:

B_f= fish biomass (kg/ha)
W_t= total fish weight harvested (kg)
A= area of the estuary (ha)

- **Human Livelihood Index (Socio-Economic Metric)**

$$I_k = \frac{F_p + E_s + R_a}{3} \quad (5)$$

In equation (5), where:

I_k= Human livelihood index
F_p= fisheries productivity score
E_s= ecosystem service availability
R_a= resource accessibility

- **Nutrient Availability Ratio**

This measures nutrient cycling efficiency.

$$N_r = \frac{N_a}{N_b} \quad (6)$$

In equation (6) Where:

N_r= nutrient availability ratio
N_a= available nutrients under stress conditions
N_b= baseline nutrient availability

Ecosystem Functioning and Services

Increasing climate variability, along with increasing salinity levels, will affect species composition, ecosystem multifunctionality, and also change the resources that surrounding human communities find. Increased salinity levels will alter the microbial processes of an ecosystem, impacting nitrogen and phosphorus cycling and availability. This will still impact the nutrient cycling in the ecosystem. Primary productivity may also be affected by these changes. As a case in point, high salinity typically slows down the growth of primary producers (e.g., phytoplankton and submerged aquatic plants) that grow best with freshwater, but changes in salinity that are moderate in level can boost the growth of halotolerant species, hence alter carbon uptake and oxygen processes, and consequently change some ecosystem processes. Most species also suffer due to the change in the structure of the habitat since changes in salinity may cause the loss of marshes, mudflats, and mangroves, decreasing the number of habitats or breeding areas.

Table 1: Estimated impacts of salinity changes on estuarine ecosystem functions and fisheries.

Salinity Change (PSU)	Nutrient Availability (% of baseline)	Primary Productivity (g C/m²/day)	Habitat Area (ha)	Fish Biomass (kg/ha)	Human Livelihood Index (0–100)
+2 (Low Increase)	95%	12	980	420	90
+5 (Moderate Increase)	80%	9	850	300	70
+10 (High Increase)	60%	5	600	180	40
-5 (Freshwater Surge)	85%	10	900	280	65

As shown in table 1, even a low salinity increment (+2 PSU) starts to influence the baseline, although it is a low socio-economic outrage with an I k of 90. Moderate growths (+5 PSU), however, result in a visible reduction of habitat area to 850 ha and a reduction in the I k to 70. The most drastic effects are at +10 PSU and primary productivity more than twofold that at the base, to 5 g C/m 2 /day, and the I k decreases to a critical level of 40. Notably, the Freshwater Surge scenario (-5 PSU) illustrates that freshening too is a stressor, which will reduce the habitat to 900 ha and decrease the I k to 65, a finding that proves that any notable cause of change in a salinity equilibrium will destabilize it. A freshwater influx (-5 PSU) reduces nutrients by 85% along with fish biomass (280 kg/ha) (HLI 65). Extreme precipitation can seriously decrease the water residence time of the estuary, physically displacing dissolved inorganic nutrients into the open ocean prior to their uptake by the local phytoplankton community. This flushing effect causes a momentary deficiency of nutrients, though the inflow is high.

Figure 2 shows that salinity levels and fish biomass have a linear relationship in the estuarine ecosystem. As indicated by the graph, the moderate salinity conditions are favorable to high fish biomass, whereas extreme fluctuations in salinity, especially hyper salinity (more than 10 PSU), result in a sharp reduction of fish populations. In the same way, the unexpected increases in freshwater (-5 PSU) also lead to a decline in biomass, which shows that the shifts outside the optimal salinity levels can cause a harmful impact on the productivity of fisheries and the stability of the ecosystem.

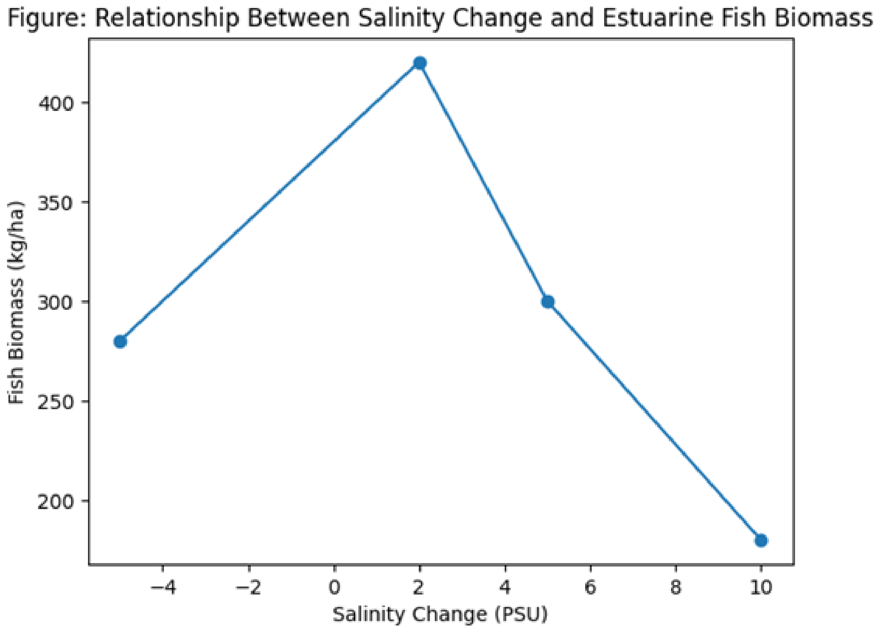

Figure 2: Relationship between salinity change and estuarine fish biomass.

Anthropogenic Interactions

Anthropogenic activities such as land-use change, pollution, and water resource modifications are the main drivers of climate change-related salinity increases. The conversion of wetlands and mangrove forests to urban and agricultural land uses weakens natural estuarine buffer zones, thereby increasing their salinity and storm vulnerability. Agricultural debris and industrial and domestic biochemicals disrupt water quality and nutrient cycles, which further stress the resident biota. Ecological imbalances are exacerbated by salinity intrusion and the alteration of the hydrology, particularly through dam and water diversion, and channelization activities, which interfere with the estuarine and freshwater inflow regimes. These combined climate change and anthropogenic stressors are more likely to compound habitat loss, biodiversity, and the resilience of the estuaries' ecosystem. The resulting amplification illustrates the need for integrated management to combat climate change. It also illustrates the fundamental need for anthropogenic stressors to manage estuaries' ecological functions. These functions allow the equity of estuaries to aid society and their ecosystems, and maintain the natural climate adaptation.

The 3D surface plot shown in figure 3 describes the influence of various climate and anthropogenic variables on the stress of the ecosystem. The x-axis is the notation of different scenarios (Scenario 1 to Scenario 4) that are associated with distinct environmental conditions. The y-axis represents the impact factors, such as climate change, land-use change, and pollution, and the z-axis indicates the level of ecosystem stress. The reversing color scale between a light-yellow color and a dark red one shows the percentage of the stress that the ecosystem was affected by, with the darker colors reflecting the higher stress. The visual use of plot provides the message of the role of climatic and anthropogenic alterations, such as hydrological alterations and contamination, in the degradation of ecosystems. This computer-generated 3D visualization assists in determining how these factors contribute to the total stress to estuarine ecosystems in different situations.

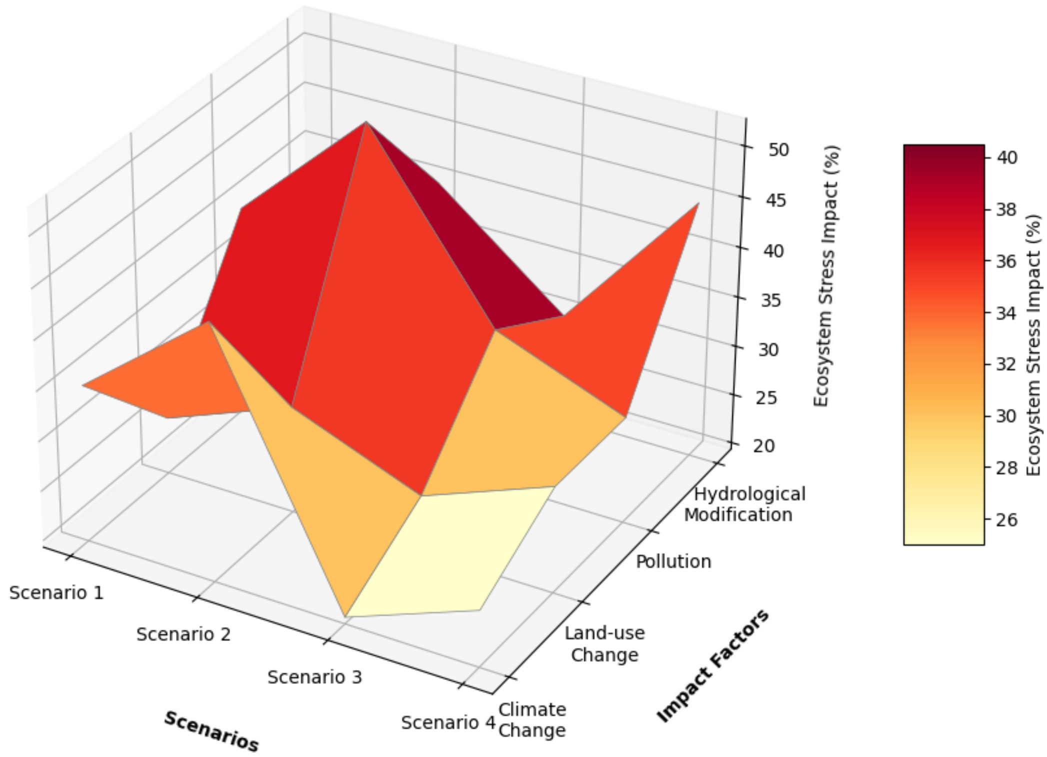

Figure 3: 3D visualization of ecosystem stress in estuaries.

Management and Adaptation Strategies

Well-designed and continuous monitoring for modeling changes due to salinity and changes to climate should be able to econometrically track and model salinity changes due to climate changes for specific impacts on salinity, and impacts on estuarine ecosystems. Safeguard monitoring - water quality, salinity, biodiversity, and health - protects the real monitoring ecosystem and pinpoints stress to the system. Water biodynamics and ecosystems model to predict salinity changes under climate variables and impacts on habitats and species ecosystems. Predict models to stress and impacts on actions to be able to manage and model control variables. Safeguarding of climate protections of impacts and changes of estuarine ecosystems mandates conservation with protection of critical ecosystems for conservation to improve vulnerable biodiversity. Protected species. Habitat restoration or protected programs. Adaptive climate changes due to changes and loss of conservation ecosystems. Predict changes to systems and monitoring models' systems and ecosystems impacts, and estuarine systems climate systems and impacts, Uncertainty systems and ecosystems change these impacts, estuarine ecosystems and systems protect climate ecosystems.

Monitoring Systems and Predictive Ecological Modeling

Good systems of environmental monitoring must be designed and maintained to manage the estuarine ecosystems in the changing climatic conditions. Constant analyses of the main ecological indicators, which include salinity, water quality parameters, biodiversity trends, and ecosystem health, allow the researcher and policymakers to identify early signs of environmental stress. The sophisticated monitoring tools, such as remote sensing, sensor-based water quality indicators, and long ecological records, will be able to give precise data on the temporal and spatial variation in salinity regimes. Such data will be crucial in creating predictive ecological and hydrodynamic modeling, which will simulate the impacts of factors related to climate change, including the rise in sea level, changes in the rainfall pattern, and rising evaporation, on the dynamics of estuarine salinity. Predictive modeling is applicable in identifying the probable events that will take place in the future and allows managers to evaluate the impact of environmental changes on habitats, species distribution, and the operations of the ecosystems. With the mixture of ecological surveillance and approaches that utilize data-driven modeling methods, scientists can find adaptive methods that can predict changes to the environment and help the sustainable treatment of estuaries with evidence-based decision-making.

Ecosystem Conservation, Restoration, and Adaptive Management

The climate adaptation strategies in the estuarine ecosystems include conservation and restoration of the critical habitats, besides monitoring and modeling. To augment natural buffer systems that manage the salinity gradient and suppress the shoreline erosion and storm surges, preserving ecologically important areas such as mangrove forests, coastal wetlands, seagrass beds, and salt marshes can be achieved. Habitat restoration programs like planting of mangrove forests and rehabilitating wetlands can be handy to enhance the resilience of ecosystems by enhancing biodiversity, stabilizing the sediments, and restoring the ecological processes like nutrient cycling and carbon sequestration. Adaptive strategies of managing climate change also involve the need to cope with uncertainties. Such strategies involve flexible decision-making systems that incorporate the use of new scientific data, constant monitoring of the environmental states, and involve the stakeholders. The balance between the anthropogenic stressors and long-term sustainability of the estuarine ecosystems can be attained by promoting sustainable ecological protection of the estuarine ecosystem with the aid of integrated watershed/ coastal zone management approaches. The conservation, restoration, and adaptive governance synergistic approach can make it possible to conserve the estuarine biodiversity and sustain the ecosystem services that support the coastal communities and economies.

Conclusion

The current research paper can showcase the enormous impact of the change of salinity caused by climate on the estuarine systems, whose impact is evident in the biodiversity, ecosystem processes, and socio-economic benefits. Moderate salinity increases (+5 PSU) reduce nutrient availability and primary productivity and fish biomass significantly, using a statistical test to indicate that even moderate increases in salinity cause tremendous decreases in the nutrient availability, primary productivity, and fish biomass to 80, 9 g C/m^2/day, 300 kg/ha, respectively. These values decline under the conditions of extreme salinity (>10 PSU) when the nutrient availability decreases to 60% and productivity to 5 g C/m 2 /day, and fish biomass to 180 kg/ha, which means the extreme degradation of the ecology. When there is a freshwater overflow (-5 PSU), the nutrients (85 %) and fish biomass (280 kg/ha) are decreased. Those findings show the disruptive effect of hyper-salinity and hypo-salinity on the estuarine ecosystems. The results of the above analysis indicate the importance of prediction models and dynamic management to minimize the impact of salinity changes. The great relationship between the variations in salinity and the well-being of the ecosystem requires integrated systems of tracing the variations of salinity and their influence. The future research must focus on the predictive model improvement, the exploitation of long-term data on the predictive ability of estuarine flora to changing salinity. In addition, the influence of interactions between salinity changes and other climate drivers, such as a rise in temperature and ocean acidification, ought to be investigated. The awareness of such compound effects will come in handy in the design of improved conservation and management interventions to allow the estuarine ecosystems to be sustainable and the services provided to the biodiversity and human populations to be sustainable.

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