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Institute of Water and Flood Management
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HE 6206:Coastal Disaster Mitigation Engineering

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HE 6206: Quantitative effectiveness of nature-based solutions for coastal disaster mitigation: Global and local evidences

Term Paper

Introduction: Coastal areas worldwide are becoming more susceptible to natural calamities, particularly tropical cyclones, due to various variables like the rising sea levels caused by climate change, the increasing intensity of storms, and the growing populations residing in coastal zones. The profound consequences of these occurrences on coastal populations, infrastructure, and ecosystems emphasise the pressing requirement for efficient disaster mitigation techniques. Although traditional engineering-based methods have been the foundation of coastal safeguarding efforts, they can involve substantial costs, limited long-term viability, and negative effects on the ecosystem. There has been an increasing interest in Nature-Based Solutions (NBS) as alternative or additional methods for mitigating coastal disasters. Nature-based solutions utilise the inherent ability of natural ecosystems to adapt and withstand disasters, hence decreasing the likelihood and consequences of such events. Restoring coastal wetlands, reforesting mangroves, restoring dunes, and building and maintaining coral reefs are a few examples.Nature-Based Solutions (NBS), provide several additional advantages such as habitat restoration, erosion control, carbon sequestration, and enhanced water quality. In addition, they frequently offer more economical and environmentally friendly solutions in comparison to conventional methods, which makes them more appealing to politicians, practitioners, and communities dealing with coastal vulnerability. The study aims to explore the quantitative efficiency of nature-based solutions in reducing the effects of tropical cyclones on coastal communities and ecosystems. The study seeks to assess the effectiveness of Nature-Based Solutions (NBS) in reducing the negative impacts of cyclones, including storm surges, coastal erosion, and habitat destruction, by combining evidence from both global and local sources. This term paper seeks to enhance the understanding of the role of Nature-Based Solutions (NBS) in reducing the risk of coastal disasters by reviewing relevant research, analysing quantitative data, and engaging in critical discussions of the findings. Ultimately, our goal is to promote resilient, sustainable, and nature-based solutions for managing coastal areas in the face of increasing risks from climate change.

Some of the Nature Based Soluton considering the tropical cyclone disaster are :-

- Mangrove Restoration
- Coral Reef Protection
- Oyster reefs
- Dune Restoration
- Saltmarsh Creation
- Seagrass Bed Restoration
- Coastal wetland

This term paper examines the effectiveness of Nature-Based Solutions in mitigating tropical cyclone disasters by reviewing three research papers.All of these cases involved discussions on both local and global examples in order to comprehend the influence of NBS.

Quantifying the protective capacity of mangroves from storm surges in coastal Bangladesh"[1]

Objective: The objective of this study is to evaluate the ability of mangroves to provide protection from cyclonic storm surges in the coastal areas of Bangladesh. The study utilises a hydrodynamic model, specifically the MIKE21FM system, to evaluate the decrease in storm surge height and water flow velocity that is attributed to the presence of mangroves at specific locations along the Barisal coast during hurricane Sidr in 2007. By varying forest widths and planting densities, the study aims to provide location-specific information on the effectiveness of mangroves in mitigating storm surge impacts. The ultimate goal of the findings is to enhance the effective utilisation of mangroves for the purpose of mitigating coastal hazards and minimising harm to coastal embankments and infrastructure.

Materials and methods:

Studdy Area: Three research areas, comprising seven sites with existing polders, were selected in the southwest coastal region of Bangladesh, specifically in the districts of Bagerhat and Barguna. These areas are recognised for their high poverty rates, which are caused by frequent cyclones. The selection of these places was based on their susceptibility to cyclonic occurrences and the presence of appropriate data.

Species Selection:The selection criteria included evaluating the vulnerability to storm surges and analysing the tidal characteristics. The selection of mangrove species was based on high-resolution distribution maps given by the Department of Forests in Bangladesh. The selection criteria encompassed tidal feat ures, existing and predicted future salinity tolerance of species, and water salinity for each study site. A selection was made of seven mangrove species that are expected to thrive with the existing levels of water salinity. The final selection was determined through on-site visits and discussions with local ecologists and residents.

Estimation of Manning's roughness coefficients: The Manning's coefficients were determined for fully developed mangrove trees using field measurements of trunk and root diameter, root height, and tree spacing. Regional specialists offered advice on viable planting density. Estimations were conducted for various water levels in both the root and trunk systems of each species, which were used as substitutes to measure water-flow resistance in future hydrological study.

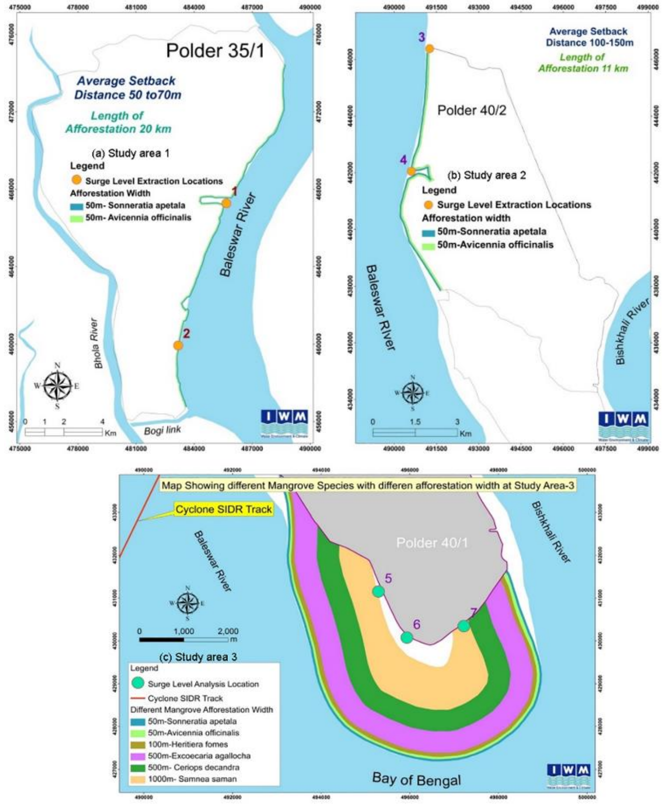

Figure 1 Afforestation area for analysis (a)Study area 1,(b)Study area 2,(c) Study area 3

Model Setup:A hydrodynamic model was developed for the Bay of Bengal, and improvements were made to increase the accuracy of the grid resolution. Additionally, location-specific data was included for the research locations. The study region was demarcated by open bounds, extending from Baruria on the Padma River to 16˚ north latitude in the Bay of Bengal.

Cyclone Simulation: The hydrodynamic model simulated Cyclone Sidr using historic cyclone data to generate cyclonic wind and pressure fields. The simulation was conducted with and without mangrove trees. Areas for afforestation were designated along the shorelines, and computer simulations were conducted to evaluate the effects of different widths and densities of afforestation. The recorded data on surge height and water flow velocity were used to determine afforestation strategies that effectively enhance the protective capability of mangroves.

Result :. The evaluation of mangrove species' resistance to water flow at different planting densities and forest widths, as quantified by Manning’s roughness coefficients, yields crucial insights into nature-based disaster risk management strategies The study reveals notable differences in resistance levels based on species, tree density, and water depth. Significantly, S. apetala is identified as the most obstructive species, with A. officinalis and H. fomes following closely behind. On the other hand, E. agallocha demonstrates greater resilience than C. decandra at all water depths.

Moreover, the study emphasises the direct relationship between resistance and planting density, indicating that denser mangrove plants often provide more effective hindrance to water flow. Suggested planting densities for different mangrove species are recommended based on reported resistance patterns. These recommendations offer useful direction for effective nature-based disaster mitigation activities.Regarding the lowering of surge height, study area 3, which has a coastline orientation and a less steep topography, exhibits more attenuation of surge height compared to areas located along riverbanks. The measured decrease in surge height varies from 4 to 16.5 cm among the examined locations, demonstrating different levels of effectiveness in reducing the impact of surges. Similarly, the decrease in the velocity at which water flows varies at different locations, with certain areas observing drops ranging from 29% to as high as 92%. The results highlight the various ways in which mangrove belts can reduce the height of surges and the speed of water flow, emphasising the need of carefully choosing the type and density of plants when building strong coastal protection methods.

Discussion: Mangroves are known in the field of tropical ecology for their ability to protect coastal communities and assets from a variety of natural dangers, including wind, waves, cyclones, and erosion.Studies indicate that mangroves can offer substantial defence against tropical storm surges. Storm surges, which are waves with concentrated force at the water surface, are more easily prevented by mangroves.

Mangrove forests are believed to efficiently reduce the intensity of shorter waves by obstructing the movement of water through their complex root systems, trunks, and leaves, according to theoretical models. Moreover, thorough evaluations and examinations of wetland ecosystems suggest that even small regions with vegetation might have a vital impact in reducing the intensity of waves. The presence of vegetation in these places results in significant resistance, causing the dissipation of wave energy.

Nevertheless, the ability of mangroves to reduce the force of waves differs based on variables such as geographical position and changes that occur throughout the year. Additional research is needed in order to get a more profound comprehension of the operational mechanisms of mangroves in particular coastal environments and how they can be efficiently supervised and conserved. Through the implementation of more focused research, we may expand our understanding of coastal forest ecosystems and their capacity to alleviate natural disasters, therefore providing valuable insights for improved conservation and management strategies.

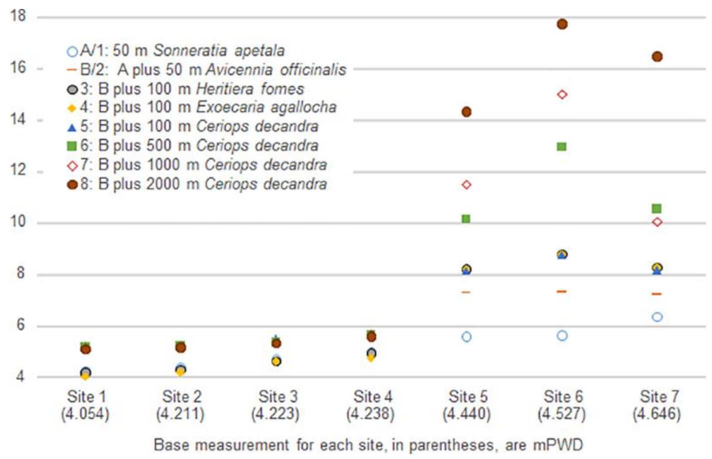

Figure 2Attenuation of Surge heights (cm) from afforestation of mangrove species at fm spacing

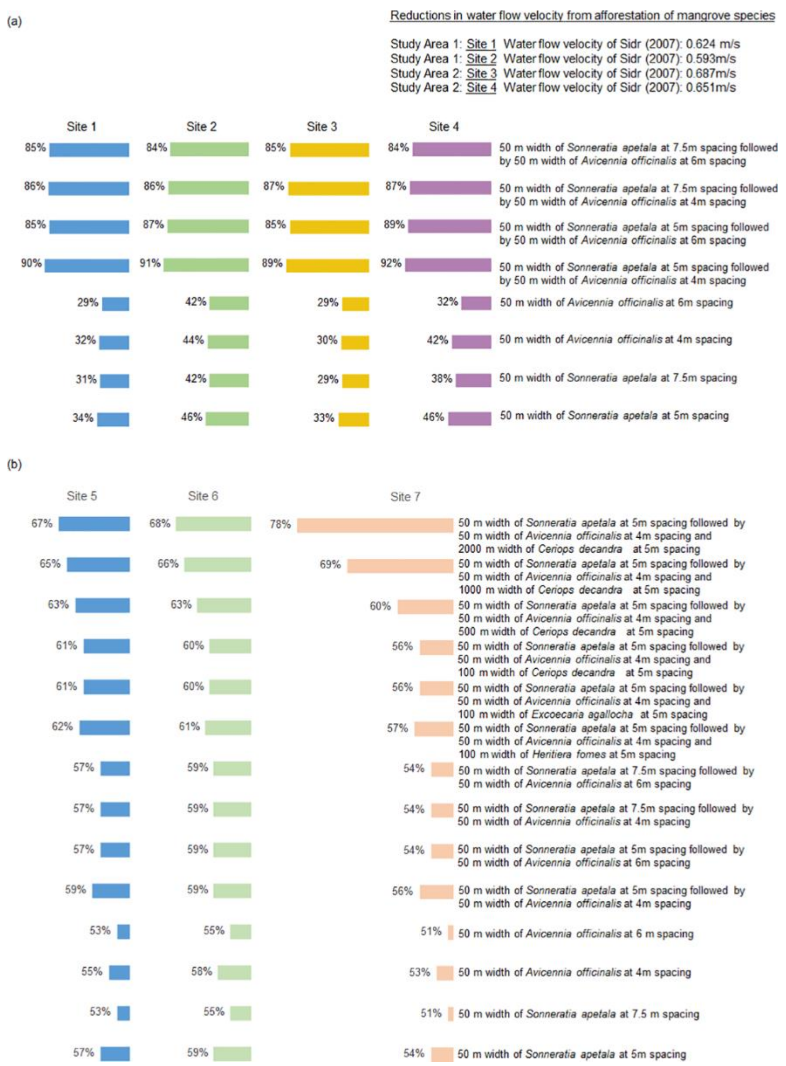

Figure 3Reduction in Cyclone SIdr water flow velocity (m/s) from afforestation with mangrove speicies

" The effectiveness of coral reefs for coastal hazard risk reduction and adaptation[2]"

Coral reefs serve as natural barriers against tropical cyclones through the process of wave energy dissipation, resulting in the reduction of storm surges and the safeguarding of coastlines against erosion and flooding. The intricate formation of their structure serves as a protective barrier, mitigating the force of powerful winds and waves during cyclones, so ensuring the safety of coastal communities and infrastructure. In addition, coral reefs that are in good health contribute to the preservation of biodiversity, which in turn strengthens the ability of ecosystems to withstand and recover from extreme occurrences. Coral reefs enhance shoreline stability by stabilising coastlines and effectively retaining sediments, hence lowering the vulnerability to damage caused by tropical storms. Nevertheless, human activities like as climate change, overfishing, and pollution pose a significant danger to the efficacy of coral reefs in disaster mitigation. Preserving and repairing coral reef ecosystems is crucial to guarantee their ongoing capacity to alleviate the effects of tropical storms on coastal regions.

Objective: This research aims to thoroughly analyse and evaluate the role and cost-effectiveness of coral reefs in mitigating coastal hazard threats on a global scale. The authors seek to offer an in-depth overview of the role of coral reefs in reducing natural disasters, specifically in context of the increasing occurrences of storms, flooding, and coastal development. Through meta-analyses, the paper demonstrates that coral reefs offer substantial protection by significantly reducing wave energy, with reef crests alone dissipating the majority of this energy. Additionally, the paper seeks to determine the population at risk that could benefit from protecting coral reefs or face higher costs for hazard mitigation if the reefs degrade. Furthermore, it aims to compare the risk reduction benefits of coral reefs to those of artificial coastal defence structures, taking into account both physical protection and economic cost-effectiveness. It highlights the significance of preserving and restoring coral reefs as essential elements of natural coastal defence systems.

Methodology: The methodology encompassed a systematic review of existing research, the synthesis of data through meta-analysis, statistical analysis, and a comparison between coral reefs and constructed coastal defences. The authors utilised this method to offer a thorough evaluation of the role and cost efficiency of coral reefs in mitigating coastal hazard hazards on a global scale.

Initially, a comprehensive literature search was conducted using Web of Science to identify relevant studies spanning from 1900 to 2013. Following that, the data extraction process concentrated on obtaining relevant data from selected research about wave attenuation measurements in various reef habitats, such as crest, flat, and whole reef. Meta-analyses were then performed using a random effects model to combine results from independent experiments and assess the magnitude of the difference between treatment and control groups. Effect sizes were calculated as log-response ratios, considering both wave energy reduction and wave height reduction as response variables. Additionally, the relationship between wave attenuation and incident wave energy, as well as reef characteristics such as width, was examined to understand the factors influencing coral reef effectiveness. Furthermore, a comparative analysis was conducted to evaluate the effectiveness and costs of coral reefs compared to artificial coastal defenses, focusing on low-crested detached breakwaters. Lastly, estimates of the population benefiting from coral reef protection were made by mapping and quantifying people living in low-lying areas near reefs, considering both direct exposure reduction benefits and indirect effects on coastal populations. In summary, our approach facilitated a thorough evaluation of the role and economic efficiency of coral reefs in mitigating coastal hazard hazards

Result:

The study conducted a comprehensive analysis on wave attenuation by coral reefs, drawing data from 255 studies and conducting meta-analyses based on 27 independent publications covering reefs across the Atlantic, Pacific, and Indian Oceans. The analysis focused on three reef environments: reef crest, reef flat, and the whole reef(Figure 4). Reefs significantly reduced wave energy across all three environments, with reef crests dissipating on average 86% of the incident wave energy and reef flats dissipating 65% of the remaining wave energy. The whole reef accounted for a total wave energy reduction of 97%. Reefs also significantly reduced wave height across all three environments, with the reef crest reducing wave height by 64%, the reef flat by 43%, and the whole reef by 84%. Wave energy in both swell and wind wave types was reduced across all three environments, although not always significantly. Reef crests significantly dissipated 70% of the incident swell wave energy, while the whole reef significantly reduced both wind and swell wave energy(Figure 5). The effects of the whole reef in dissipating wave energy were linear from small through hurricane-level waves, reducing a consistent 97% percent of the incident wave energy. After passing over the crest, waves were attenuated significantly across wider reef flats. However, most of the wave attenuation occurred in the first part of the reef flat. Furthermore, a comparison was made between coral reefs and artificial coastal defenses, revealing that the average wave height reduction achieved by reefs (64%) was comparable to low-crested detached breakwaters. Additionally, the study analyzed the costs associated with building tropical breakwaters and coral reef restoration projects, finding that restoration projects were significantly cheaper. In terms of coastal populations benefiting from reefs, an estimated 197 million people living below 10m elevation and within 50 km of a reef may receive risk reduction benefits, with Indonesia, India, and the Philippines having the highest number of at-risk individuals. Overall, the findings underscored the significant role of coral reefs in mitigating coastal hazards and their potential benefits for coastal communities globally

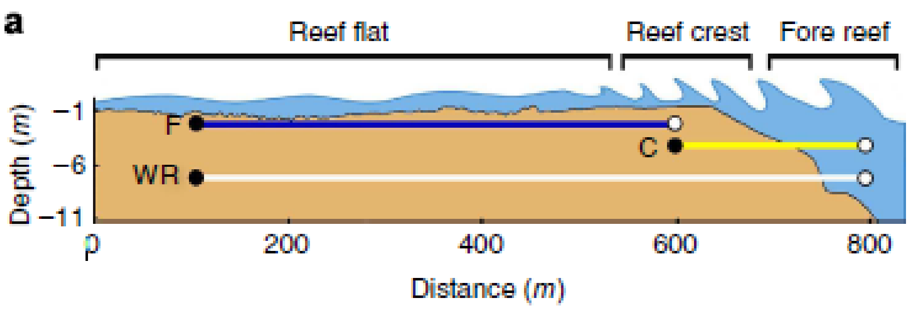

Figure 4 Example of coral reef environment

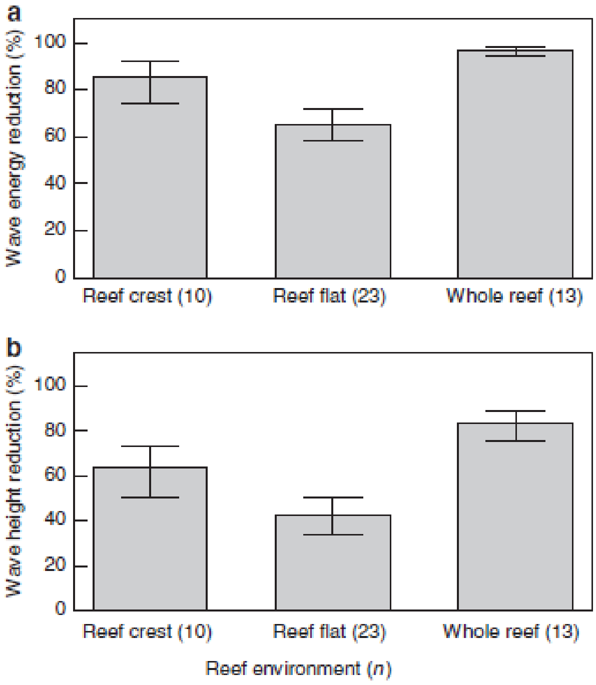

Figure 5 Coral reef and wave attenuation meta analysis

Discussion: The study offers a comprehensive examination of the ability of coral reefs to reduce wave energy across oceans, revealing significant findings.Coral reefs have been observed to effectively absorb and disperse an impressive 97% of wave energy. The reef crest, specifically, is responsible for a significant 86% of this reduction. Furthermore, the reef flat makes a significant contribution, especially within the initial 150 metres from the reef crest

The study highlights the importance of factors like bathymetry and bottom friction, where reef degradation, especially the loss of specific coral species, can impact wave attenuation. Moreover, reefs demonstrate effectiveness across various wave types and intensities, offering linear wave energy reduction and nonlinear amplification of attenuation with higher incident wave energy. Cost-effectiveness emerges as a key aspect, with reef conservation and restoration proving to be more economical strategies for coastal defense compared to artificial structures like breakwaters. However, despite their benefits, coral reefs face escalating threats from development and climate change, necessitating focused management efforts to prioritize reef restoration, particularly along the reef crest, for enhanced coastal resilience. This study underscores the critical role of coral reefs in coastal defense and emphasizes the urgency of conservation and restoration efforts to safeguard coastal communities against wave-related hazards.

The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature Based Defences[3]

Objective:

The primary objective of the research paper is to evaluate the effectiveness of various coastal habitats as natural defenses against coastal disasters. Through the analysis of field measurements from sixty-nine coastal habitats globally, including mangroves, salt marshes, coral reefs, and seagrass/kelp beds, the study aims to assess the potential of these habitats in reducing wave heights. The findings reveal significant variability in effectiveness across different habitats and sites. Notably, coral reefs and salt marshes emerge as particularly effective in wave height reduction. The evaluation of effectiveness also considers key biophysical parameters that influence habitat performance, such as the ratios of wave height to water depth and habitat width to wavelength in coral reefs, and the ratio of vegetation height to water depth in salt marshes. Additionally, the paper aims to synthesize the costs and coastal protection benefits of fifty-two nature-based defense projects, providing comprehensive insights into the cost-effectiveness of restoration projects designed for coastal protection.

Methodology:

The methodology employed in this study comprised several key components to comprehensively evaluate the effectiveness and cost-effectiveness of natural coastal defense measures. Firstly, two distinct datasets were utilized: one containing measurements of wave reduction in various coastal habitats, and the other comprising information on restoration projects aimed at coastal protection. The analysis of wave reduction involved compiling data from numerous studies measuring wave heights before and after the presence of different habitats. This enabled the researchers to assess the effectiveness of each habitat type in reducing wave energy. Additionally, the cost-benefit analysis of restoration projects involved examining fifty-two projects specifically targeted at coastal protection. To provide a basis for comparison, the costs of restoration projects were compared with those of alternative coastal defense structures, such as breakwaters. This comparison aimed to determine the cost-effectiveness of natural defense projects relative to engineered structures. Furthermore, the study investigated the mechanisms through which coastal habitats reduce wave energy, identifying wave-breaking and energy damping as primary mechanisms. A comprehensive literature search was conducted to gather data for analysis, focusing on studies reporting observed wave heights before and after the presence of coastal habitats. Field measurement analysis involved assessing data from sixty-nine studies measuring wave heights in various habitats, allowing for the calculation of percentage reduction in wave height due to habitat presence. Finally, cost estimation for breakwaters involved calculating the cost per meter coastline length based on the volume and construction cost per unit volume of the structures, providing insights into the relative costs of different coastal defense options.

Result:

The study analyzes sixty-nine field measurements to underscore the significant impact of coastal habitats on wave reduction. It demonstrates how specific engineering parameters influence wave reduction effectiveness and reviews the costs and benefits of fifty-two nature-based defense projects. Meta-analyses of sixty-nine studies across coral reefs, mangroves, salt marshes, seagrass/kelp beds reveal that these habitats significantly reduce wave heights, with coral reefs emerging as the most effective. The reduction varies with habitat and site, with coral reefs reducing wave heights by 70%, salt marshes by 72%, mangroves by 31%, and seagrass/kelp beds by 36%. The study also examines the influence of design parameters such as habitat width, width-to-wavelength ratio, and height-to-water level ratio. Wave reduction in each habitat is influenced by different parameters, highlighting the complexity of coastal dynamics. Additionally, cost-benefit analyses of thirteen nature-based defense projects in mangroves and salt marshes demonstrate that these projects can be several times cheaper than alternative submerged breakwaters, depending on water depth. The study emphasizes the need for consistent cost reporting and further comparative studies to inform the design and implementation of future nature-based defenses. Monitoring and evaluation procedures outlined within established coastal engineering frameworks should be followed when evaluating restoration projects for coastal protection. Such evaluations typically involve before-after comparisons of coastal hazards at the site, considering the multiple objectives of restoration projects.

Discussion:

This paper highlights several key points regarding the effectiveness and cost-effectiveness of nature-based defense projects for coastal protection. Firstly, the study underscores the significant potential of coastal habitats, particularly coral reefs and salt marshes, in reducing wave heights and providing shoreline protection. Secondly, it emphasizes that restoration projects, such as those in mangroves and marshes, can be cost-effective compared to traditional submerged breakwaters, especially in attenuating low waves and in areas with higher water depths.Furthermore, the effectiveness and cost-effectiveness of nature-based defense projects to enhance understanding of their viability. The availability of data from post-project monitoring is highlighted as crucial for assessing project success or failure, and for informing future project design and guidelines.The study also stresses the need for comprehensive assessments that consider variations in project costs with changes in water levels, wave conditions, and habitat characteristics. This becomes particularly relevant in the context of anticipated variations in sea-level rise rates and other environmental factors.Additionally, the paper suggests that better estimates of maintenance costs and the additional ecosystem services provided by both artificial and nature-based defenses are necessary for evaluating the overall costs and benefits of restoration projects aimed at coastal protection.

Finally, it suggests that inclusion of other habitats such as dunes and beaches would enhance the richness of existing nature-based defense databases, providing more comprehensive insights into their effectiveness.

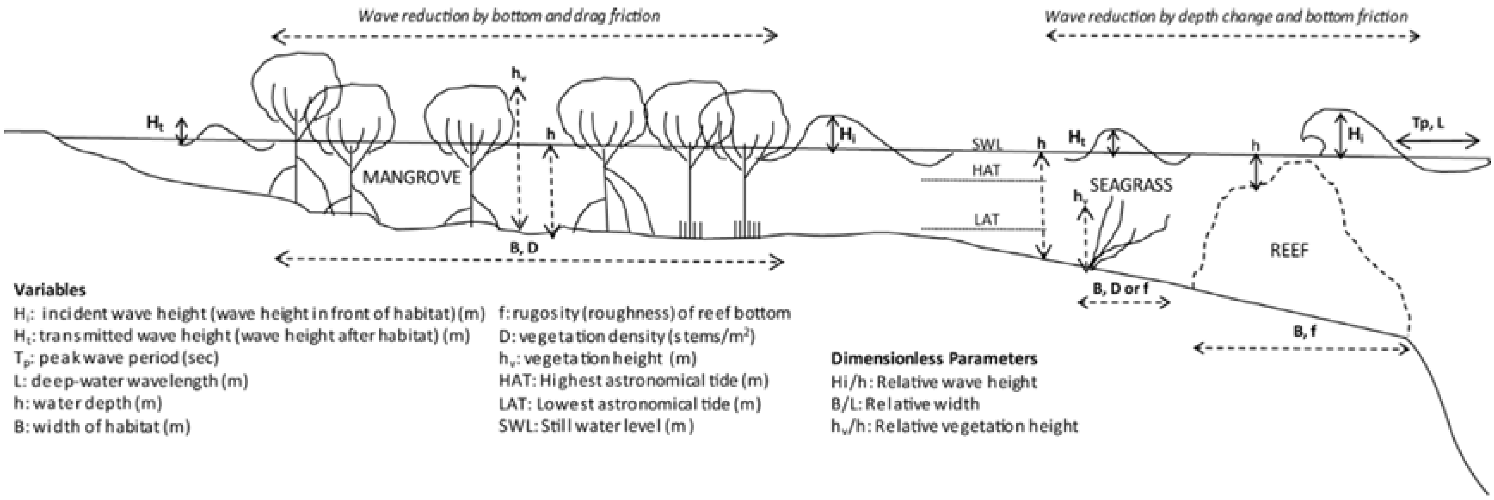

Figure 6 Schematic of wave height reduction acrosscoastal habitats.(schematic showing general mechanics of wave height reduction through habitats using the examples of coral reefs,seagrass beds and mangroves)

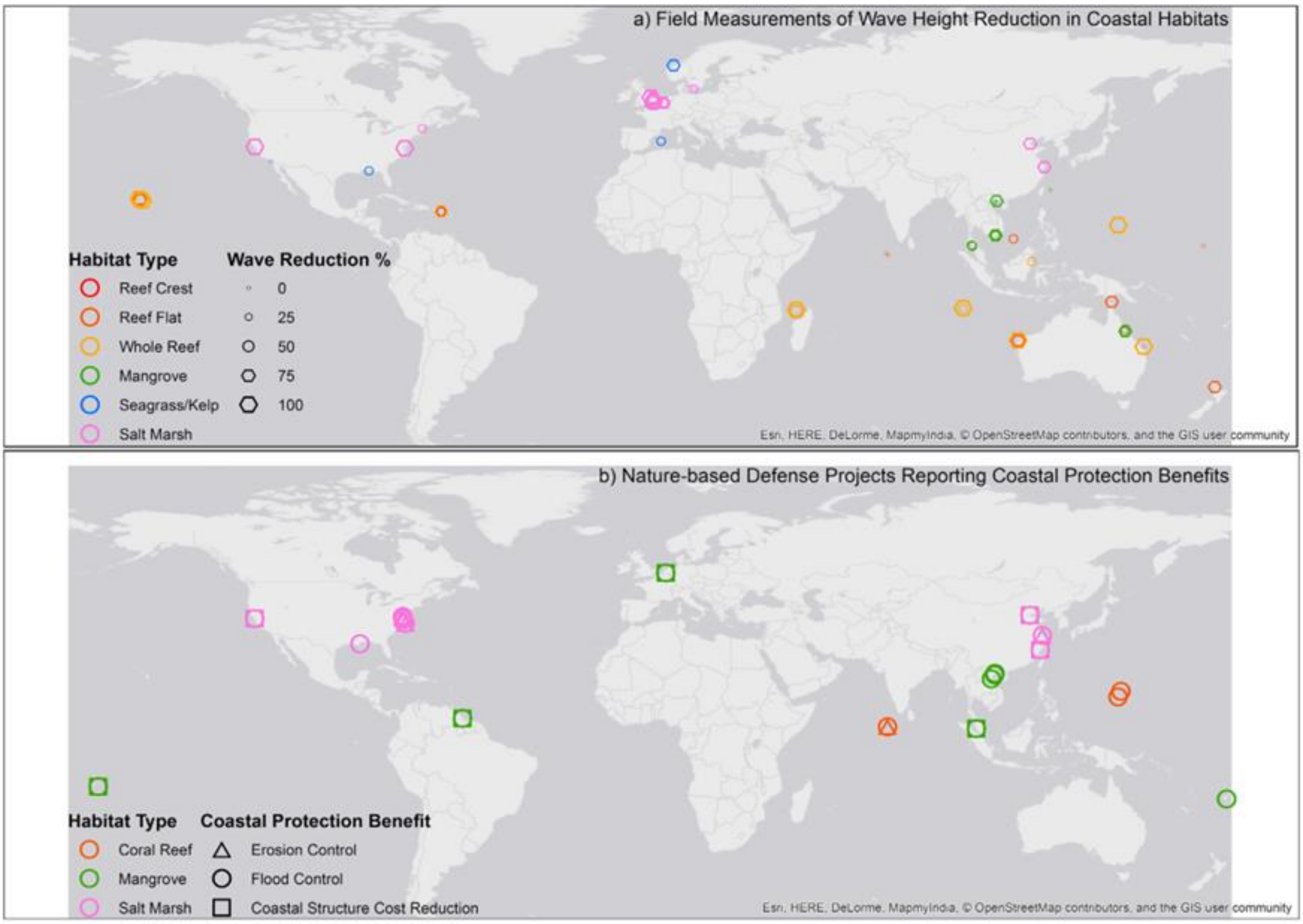

Figure 7 Global map pf (a) wave height reduction in natural defences and (b) Coastal protection benefits from restoration projects

Conclusion of the term paper:

In conclusion, this term paper has explored the effectiveness of nature-based solutions (NBS) in reducing the effects of coastal disasters, mainly tropical cyclones. By studying several Natural Based Systems (NBS), such as mangroves, coral reefs, and other natural systems, we have emphasised the capacity of these methods to improve coastal resilience and mitigate the effects of tropical storms on vulnerable communities.

The review of three research papers provided useful insights into the many methods by which Nature-Based Solutions (NBS) contribute to the mitigation of coastal disasters. From the protective functions of mangroves in attenuating storm surges to the role of coral reefs in dissipating wave energy and reducing coastal erosion, these studies collectively reaffirm the importance of conserving and restoring natural habitats as a frontline defense against tropical cyclones.

However, it is evident that the successful implementation of NBS requires overcoming various challenges, including limited funding, inadequate policy frameworks, and conflicting land-use priorities. Addressing these barriers necessitates interdisciplinary collaboration, community engagement, and evidence-based decision-making to ensure the effective integration of NBS into coastal management strategies As we face the growing dangers of climate change and more frequent tropical cyclones, it becomes clear that investing in nature-based solutions is a practical and cost-effective way to strengthen our ability to withstand and adapt to these changing risks. Through the utilisation of the inbuilt capacity of natural systems to rebound and the application of scientific research and local knowledge, we can empower coastal communities to withstand and recover from the impacts of tropical cyclones. This term paper highlights the importance of adopting nature-based solutions as a fundamental aspect of sustainable coastal management and reducing the risk of disasters. By conducting ongoing research, fostering innovation, and promoting collaboration, we can fully harness the capabilities of NBS (Nature-Based Solutions) and pave the way for a more resilient and fair future for coastal communities worldwide.

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