EGU25-3855, updated on 14 Apr 2025
https://doi.org/10.5194/egusphere-egu25-3855
EGU General Assembly 2025

Nature-based solutions for attenuating hydrometeorological hazards in coastal regions: Effectiveness and quantification approaches

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Deltaic coasts, with their fertile soils and diverse ecosystems, are critical for agriculture, trade, fisheries, energy supply, and manufacturing. However, these regions are highly susceptible to hydrometeorological hazards, including storms, flooding, and extreme temperature events. Anthropogenic climate change has exacerbated the frequency and intensity of such hazards, posing significant societal and environmental challenges. While traditional hard engineering structures (e.g., levees, dykes, sea walls) have been the primary approach to coastal protection, these solutions often increase hazard complexity and risks while requiring substantial financial investments. In contrast, nature-based solutions (NbS) have emerged as cost-effective and sustainable alternatives or complements to traditional engineering approaches, demonstrating their potential to mitigate and adapt to coastal hydrometeorological hazards.
Quantifying the effectiveness and potential of NbS in attenuating hydrometeorological hazards in coastal regions remains challenging due to the complexity in spatiotemporal dynamics of hazards and variations in assessment methods (e.g., qualitative, quantitative, or mixed). Despite numerous studies on NbS in coastal and deltaic contexts, there is a lack of comprehensive evaluations addressing the types of NbS, their geographical applications, methodological robustness, and confidence in their effectiveness in addressing hydrometeorological hazards. This study bridges these gaps by systematically reviewing 330 peer-reviewed English-language articles published between 2008 and 2024, identified using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol. The review focuses on five key hydrometeorological hazards in coastal and deltaic regions globally: storms, floods, extreme temperatures, extreme precipitation, and droughts. NbS are evaluated as substitutes, complements, or safeguards to hard engineering structures, considering both real-world and hypothetical case studies. A comprehensive framework, adapted from the Intergovernmental Panel on Climate Change (IPCC),

is employed to evaluate NbS based on three criteria: (1) robustness of evidence (e.g., mechanistic understanding, model validation), (2) the level of agreement (e.g., consistency of findings supporting NbS effectiveness), and (3) confidence (integrating robustness and agreement).

The findings provide key typologies of NbS applications across different hydrometeorological hazards, with a predominant focus on storms and floods, while extreme temperatures and droughts receive comparatively less attention. Most studies evaluate the effectiveness of NbS options such as mangroves, coastal wetlands, dunes, and coral reefs in safeguarding coastal areas from hydrometeorological threats, often drawing insights from real-world case studies. Studies on floods and storms frequently employ numerical or hydrodynamic modelling, using indicators such as flood depth, extent, velocity, wave height, and wave energy. These studies consistently demonstrate high confidence in the effectiveness of NbS in attenuating storm and flood hazards in coastal and deltaic regions, attributed to their robust methodologies and consistent findings.

The study highlights the effectiveness of NbS in mitigating coastal hydrometeorological hazards varies geographically, influenced by local factors such as geomorphology, hydrology, and human activities. Numerical or hydrodynamic modelling, supplemented by cost-benefit analyses and validated with observational data, is recommended for robust quantification of NbS benefits and trade-offs. These findings provide a foundation for future research and offer actionable insights for policymakers and practitioners, facilitating the integration of NbS into coastal hazard management as viable substitutes or complements to hard engineering measures.