

A MODEL APPROACH TO NATURE-BASED SOLUTIONS DESIGN IN ESTUARIES

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INTRODUCTION

The implementation of Nature-based Solutions (NbS) instead of conventional shoreline infrastructure is becoming increasingly popular because of the potential for NbS to trap sediment and reduce erosion, particularly in estuaries and on shorelines that are vulnerable to sea level rise and ongoing environmental change (Borsje et al., 2011). However, to provide confidence that the coastal protection services of NbS will be sufficient for long-term shoreline stabilisation and protection, technical guidance that quantifies the shoreline protection functionality with respect to biophysical changes is required. To this aim, a review of guidelines for the implementation of NbS in the intertidal zone of estuaries was undertaken. This review evaluated the available technical details and assessed whether existing standards and manuals can be used to quantify the NbS functionality (Dunlop et al., 2023).

Unlike static infrastructure, such as seawalls and dikes, NbS are dynamic, and establish, grow, die, and function in response to changing environmental and hydrodynamic conditions. For this reason, it is critical to develop predictions of NbS growth and coastal protection services to inform implementation and maintenance strategies. Following the review of existing NbS guidelines, a conceptual approach towards an integrated guideline was proposed to balance ecological and engineering principles and provide quantitative support to design. This approach was then incorporated within a coupled Python and Delft3D Flow-FM model to determine the functional specifications of NbS designed for shoreline protection.

GUIDELINE REVIEW

NbS guidelines in the form of books, reports, standards, and codes, were reviewed to assess their objectives, and to evaluate the availability and suitability of technical design details. This search was expanded to include ecological guidance for the establishment and restoration of intertidal NbS such as seagrass, oyster reefs, mangroves, and saltmarsh.

The outcomes of this review highlighted a lack of technical specifications that would enable practitioners to design NbS to the same level of detail and confidence as traditional engineering or ecological restoration projects. These guidelines were instead aimed at providing support for project delivery, and focused on project implementation frameworks, design principles, case studies, and qualitative concepts to inform NbS decision-making. These guidelines were often presented from either an engineering or ecological perspective, without

an adequate balance between the quantitative requirements of the two disciplines. As such, a conceptual approach towards an integrated eco-engineering guideline was proposed that considered the technical requirements derived through research to balance ecology and engineering.

CONCEPTUAL APPROACH TO DESIGN

Academic manuscripts related to four intertidal NbS, namely: seagrass, oyster reefs, mangroves, and saltmarsh, were reviewed to complement the design guideline review and inform the development of an integrated eco-engineering design approach. This approach was developed to balance the ecological requirements with the engineering values of a functional shoreline defence, and is based on four key stages of the NbS project lifecycle: i) establishment, ii) growth, iii) recovery and mortality, and iv) functionality (Fig. 1).

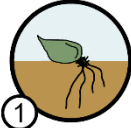
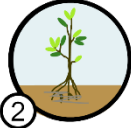
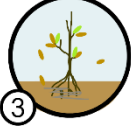
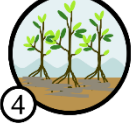
Stage	Current Research	Proposed Approach
 <p>1 Establishment</p>	<p>Ecology OR Engineering</p> <p>Parameters:</p> <ul style="list-style-type: none"> Environmental factors (e.g., salinity, pH) Limited coupling with hydrodynamics 	<p>Ecology AND Engineering</p> <p>Additional Parameters:</p> <ul style="list-style-type: none"> Inundation free period Current velocity Wave climate Erosion/Burial rates
 <p>2 Growth</p>	<ul style="list-style-type: none"> Static growth rate Allometric relationships Limited autochthonous accretion rates 	<ul style="list-style-type: none"> Allometry, growth, and autochthonous accretion rates as functions of hydrodynamics and NbS size
 <p>3 Recovery and Mortality</p>	<ul style="list-style-type: none"> Mortality thresholds for extreme events Erosion thresholds for juvenile species Limited thresholds for chronic conditions 	<ul style="list-style-type: none"> Thresholds (magnitude and duration) for mortality, linked to NbS size and age, for: inundation period, current velocity, wave climate, and burial/erosion depths
 <p>4 Functionality</p>	<ul style="list-style-type: none"> Relationships between drag / damping coefficient, and NbS size and age for mature species 	<ul style="list-style-type: none"> Relationships across all lifecycle stages and NbS types, linking NbS size and age to: <ul style="list-style-type: none"> Drag coefficient Damping coefficient Roughness

Figure 1 - The four stages of the conceptual approach towards an integrated eco-engineering design guideline. Parameters from existing research and the proposed approach are outlined (modified from Dunlop et al., 2023).

For each stage, several key parameters and concepts are recommended when designing NbS in the intertidal zone of estuaries. In cases when practitioners are unable to obtain long-term site-specific data, a simplified approach could be adopted. This approach might consider the parameter values associated with the chosen NbS species, those associated with similar species, or a fitness function that presents a proportional change in growth and damage associated with the intensity of environmental stressors. Alternatively, when practitioners have sufficient resources to conduct site surveys and record data across the lifecycle of the chosen NbS species, more detailed parameter relationships can be derived.

MODEL APPLICATION

To demonstrate the applicability of this NbS design approach, a hydrodynamic model was developed using Delft3D-Flexible Mesh (DFM) and coupled with a Python 3.10 script to evaluate dynamic changes across the four stages of the conceptual approach. The relationships between hydrodynamic conditions and biophysical processes, as derived in academic research for various NbS, were incorporated into the Python script. The Python script was coupled to the DFM model using the Basic Model Interface (BMI) module (Hutton et al., 2020), where parameters were exchanged at the beginning of each hydrodynamic and NbS timestep. Variables such as water level, bed level, wave height, flow velocity, and bed shear stress were retrieved by the Python code from the DFM model at the end of each hydrodynamic timestep and used to evaluate the changes to NbS presence, growth, mortality, and functionality. These NbS changes were quantified in terms of the required inputs for the modified Baptist bulk roughness formulae for vegetation (Baptist et al., 2007), namely vegetation diameter, density, bulk drag coefficient, and bare bed resistance. These parameters were exchanged with the DFM model before the next hydrodynamic timestep.

In this study, the coupled model was developed to assess the coastal protection services of mangroves, specifically *Avicennia marina*, across a range of estuarine conditions. Ongoing modelling is being conducted to reveal the key input parameters and thresholds that have the greatest impact on the predicted coastal protection services, such as shoreline erosion, and wave attenuation. By identifying the stages of the model with the most sensitive parameters, practitioners can prioritise research and site surveys in these areas.

Further, by modifying the initial density, width, size, and location of planted mangroves or an existing mangrove forest, within the model, the user can test different NbS designs to identify the most suitable solution for the project site. This optioneering capability can be combined with a range of incident hydrodynamic and morphological conditions to understand how different solutions will perform across estuarine contexts.

The inclusion of acute climate-induced hazards and environmental stressors that impact the biophysical processes of mangroves, can provide practitioners with

an understanding of the required size and age of NbS to withstand such events. Similarly, by including chronic climate change impacts in the model, such as sea level rise and increased water temperature, the user can evaluate the timeframes under which NbS would be expected to achieve the desired project objectives, and when adaptive management would be required. This could include the implementation of additional NbS as part of a multi-habitat approach, or the introduction of a conventional shoreline protection solution.

CONCLUSION

This study has demonstrated the importance of considering quantitative ecological and engineering parameters across the lifecycle of NbS to support the early optioneering and design stages of shoreline protection projects. By applying the proposed conceptual approach to a coupled numerical model, the key parameters influencing the coastal protection services of NbS can be determined. To improve the accuracy of the model predictions, practitioners can undertake site-specific surveys and research to obtain more detailed data for these influencing parameters.

This model presents a structured tool for ecologists and engineers to use when quantifying the long-term trajectory of NbS in the intertidal zone of estuaries, providing investors with informed predictions of the time required for NbS to sufficiently reduce erosion and protect shorelines. Quantifying the response of NbS to environmental change can also inform adaptive management strategies and the timing for the implementation of interventions.

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