

Groyne designs for novel habitat creation with repurposed sediment within the Port of Gladstone

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Abstract

The intense modification of our coastlines over the past century has led to a concerning loss of the “services” provided to society by our coastal ecosystems. Irreversible changes in land use and a climate in flux mean that the recovery and preservation of these valuable ecosystem services may not always be best achieved simply by restoring existing habitats, but can also involve the creation of new, productive and resilient habitat – a “natural intensification”. While the coastal defences required for urban and industrial development, such as seawalls, breakwaters, and bund walls, are often associated with negative ecological impacts, these structures may also represent an opportunity to achieve environmental goals when combined with efforts to create new habitat. Here we discuss the design of a “living seawall” within the Port of Gladstone, that will create a new extensive intertidal sediment habitat for mangroves, oysters, and seagrass, adjacent to a major reclamation area being designed to house dredge spoils for future port development. Numerical modelling is used to assess the flow control structures that would be required to ensure that sediments placed on the outer face of the reclamation area seawall do not resuspend. Construction of the reclamation area is shown to lead to a local intensification of tidal flows adjacent to the seawall, demanding the use of flow control structures to prevent erosion of the placed sediments. The ability of a network of groynes to produce an accreting boundary layer adjacent to the seawall is investigated. The numerical modelling supports the use of regularly spaced groynes to prevent erosion of the placed sediment, and importantly shows that the groynes need only extend to the same height as the habitat.

Keywords: working with nature, sediment reuse, intertidal habitat restoration

1. Introduction

Vegetated coastlines provide a broad range of “ecosystem services” that are highly valued by society, such as preventing coastal erosion, improving water quality, sequestering carbon, and providing food, habitat and nursery for commercial and recreational fisheries and their trophic webs. It has been broadly recognised, however, that conservation of the remaining pristine coastal habitat is, by itself, not sufficient to preserve coastal ecosystem health in the long term [1,21]. The intense coastline modification that has occurred over the past century has compromised the delivery of these vital and valuable ecosystem functions, whose recovery has been deemed essential for meeting future human demographic challenges [10]. This has spawned efforts to reconcile society’s necessary and often irreversible use of the coastline with the pressing need to restore coastal ecosystem function. As such, “Working with Nature” (WwN) techniques have gained traction over recent decades as fundamental tools in conservation. WwN seeks to leverage positive ecological outcomes within coastal development projects. While WwN efforts may be aimed at the conservation of particular species or habitats, the emphasis may also be placed more generally upon recovery of the lost ecosystem services, seeking to produce ecosystems that are resilient to the

urbanised environment and to a climate in flux. Efforts to orient habitat restoration to create optimal delivery of ecosystem services have been termed “natural intensification”.

Traditional construction techniques for adding hard elements to the coastal zone, such as breakwaters, groynes, and seawalls, has commonly been associated with negative ecological outcomes. By replacing diverse natural habitats with monotone substrate, by altering sediment pathways, and by interrupting connectivity of the native populations, traditional rock or concrete structures in the coastal zone tend to give rise to depauperate ecosystems characterised by low biodiversity and dominated by invasive species [5,7,13]. Coastal defense works can, however, be designed to achieve positive ecological outcomes within urban and engineered habitats, such as maintaining biodiversity and ecosystem services [7,14,16,17,22]. Restored oyster, seagrass, saltmarsh and mangrove habitats have demonstrated quantifiable improvements in water quality, carbon uptake and coastline stability [8,15,28]. There are also numerous examples where the restored habitat contributes to the primary function of the structure [27] – often coastal defense - and can prove to be more cost effective than traditional construction techniques, even without quantifying the ecosystem benefits [12,18,19,25,26,29].

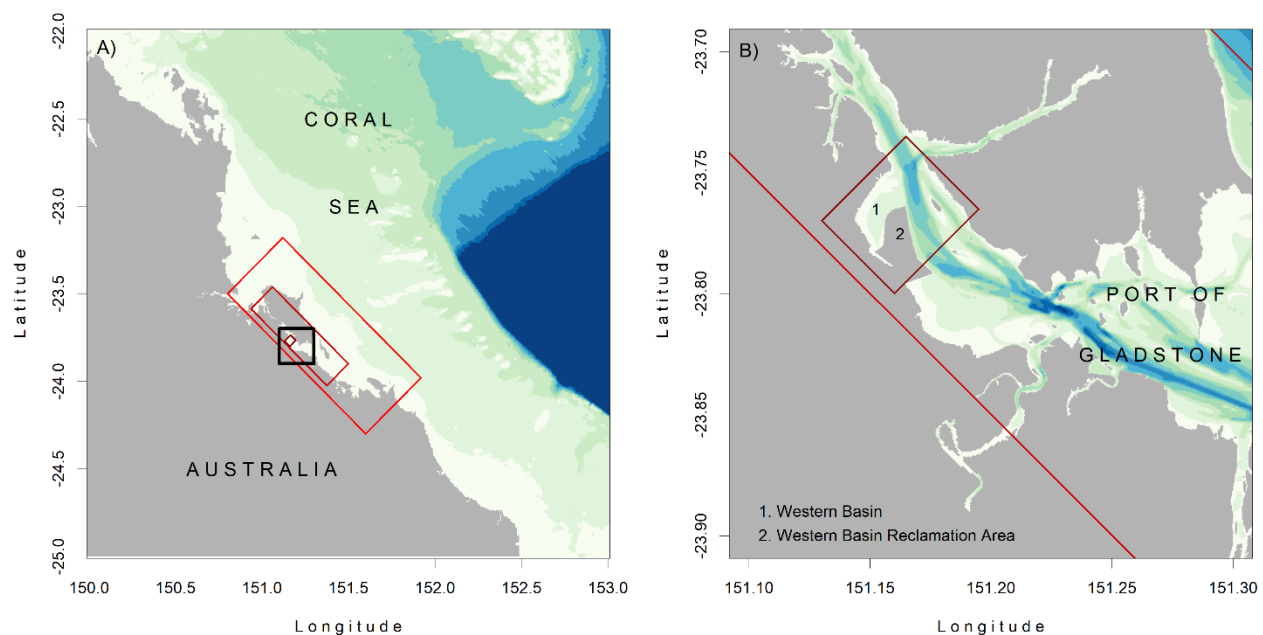


Figure 1 A) Location of the Port of Gladstone, in north-eastern Australia. The nested domains used for numerical modelling of the tidal circulation are indicated in red. B) Location of the Western Basin Reclamation Area within the Port of Gladstone. The innermost numerical model domain is shown.

When intertidal species are the target for coastal restoration, significant terraforming may be required to ensure that the substrate lies at a suitable elevation to provide immersion times within the physiological limits. This may be achieved by modifying the hydrodynamic conditions to encourage natural sedimentation [31], or through direct sediment placement [4,32]. The problem then becomes how to ensure that the newly created intertidal sediment habitat can resist erosion. Solutions include the construction of secondary hard structures, such as permeable dams, breakwaters or groynes, or modification of the primary structure, such as adding crenulations.

While successful examples exist of creating sediment habitats either intentionally or unintentionally [20,24], the design of structures to use for sediment management remains non-trivial and careful consideration of local conditions remains vital for a successful restoration. In the following we present such considerations for an industry-driven WwN project to create new intertidal habitat within a major industrial port.

2. The Port of Gladstone Living Seawall

Its proximity to the Great Barrier Reef World Heritage Area sets unique operational constraints on the major multi-commodity Port of Gladstone, located in north-eastern Australia (Fig. 1A), including the requirement for land disposal of all capital dredge material. The port's operator - the

Gladstone Ports Corporation (GPC) - is actively pursuing the incorporation of WwN concepts within their reclamation and dredging activities to achieve better environmental, social and economic outcomes [3]. One such project involves the creation of a “living seawall” adjacent to a planned expansion to an existing reclamation area to house dredge material. The living seawall has the objectives of encouraging the formation of mangrove, seagrass and oyster habitats, and providing safe roosting for the endangered Eastern Curlew. Given the physiological and ecological characteristics of the species concerned, the creation of a suitable substrate for mangroves will involve the placement of sediment to an elevation of 70 cm above mean sea level along the seaward face of one section of the reclamation area seawall. While various research questions exist concerning the type of sediment and seeding techniques best suited to encourage the development of mangrove habitat, this paper focusses on measures to prevent resuspension of the placed sediments prior to establishment of the new habitat.

The planned reclamation area extends from the existing Western Basin Reclamation Area in the northern portion of the harbour (Fig 1B), adjacent to a large intertidal mudflat containing sparse seagrass which is flanked by a mature multi-specific mangrove forest. The port is naturally well protected from wave energy, and the reclamation area expansion will further greatly limit the locally generated wave energy available to resuspend sediment. The dominantly semi-diurnal tidal range of 4.8 m, however, results in currents during flood and ebb that commonly exceed 1 m.s^{-1} . Moreover, due to the change in its geometry, the tidal currents within the Western Basin are expected to increase

following construction of the reclamation area expansion. As such, the dominant source of erosional bottom stress for a novel intertidal sediment habitat located adjacent to the inner bund wall would be tidal flow, and secondary hard structures would be required to ensure that the placed sediments are not eroded by the tidal currents prior to consolidating.

Given that the tidal flow runs tangent to the reclamation area seawall, an array of perpendicular-oriented elements has been proposed to create a low flow boundary layer that spans the width of the desired new habitat. The optimal geometry for the array of structures required to protect the placed sediments within this setting was investigated using numerical modelling, as discussed in section 3. Designs were sought that prevent erosion across the area to be restored at all substrate heights and phases of the tide. Such a constraint is necessary when natural sedimentation is desired, and in the case of placed sediments suggests that recovery should still occur following events of erosion. While there are ecological benefits from having the groynes extend only to the desired height of the sediment substrate, as peak tidal currents occur around mid-tide, numerical simulation was used to assess whether this is sufficient to avoid overtopping during periods of strong flow. The solid structures are required to withstand not only the substantial hydraulic stresses exerted by the peak tidal flows, in particular at their seaward extent, but also unbalanced static loadings during the placement of sediments, suggesting the use of solid structural elements such as rock groynes.

Groynes generally produce a region of reduced tangential flow for a distance downstream that exceeds their length. For practical reasons the maximum groyne extension from the seawall is limited to 20 m. Given the desirability of minimizing the number and height of the groynes, the numerical modelling focused upon determining the minimum spacing and minimum height of 20 m long groynes required to establish a permanent continuous accreting boundary layer adjacent to the seawall when exposed to tidal flows.

3. Numerical simulations of groyne-current interaction

Numerical simulations were performed of (1) the effect of the reclamation area extension upon the local tidal flow within the Western Basin, and (2) the effect of adding flow control measures upon peak tidal velocities within the zone earmarked for the novel sediment habitat. The COAWST numerical modelling framework [30], utilising the widely used ROMS ocean model [23], was used to simulate the hydrodynamics. This family of ocean models solves the primitive equations for fluid flow on a curvilinear

and vertically stretched grid, using state-of-the-art numerical schemes that provide accuracy and numerical efficiency. Importantly for this project, the COAWST model incorporates simulated tidal drying and wetting of the extensive mud flats, as well as a sophisticated sediment dynamics module that runs on-line together with the hydrodynamics [30].

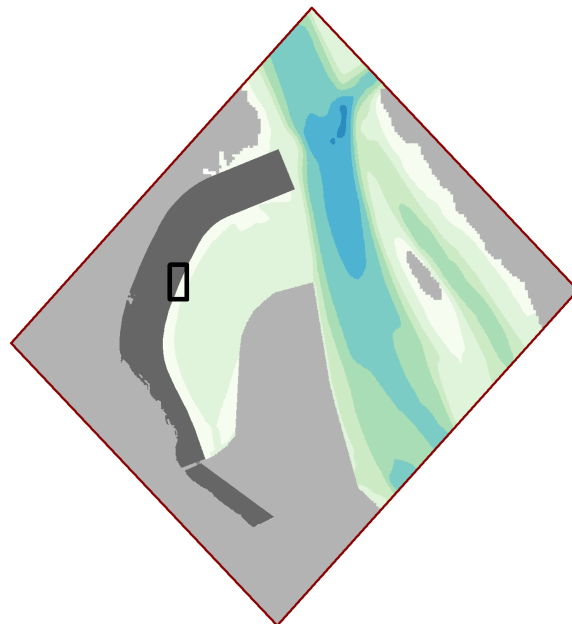


Figure 2 Representation of the domain of the curvilinear grid used for simulation of the groyne arrays with reference to the innermost of the domains used to simulate the regional tidal circulation.

3.1 Altered tidal flow

The construction of the reclamation area extension will significantly alter the geometry of the Western Basin, converting it from a broad embayment to a narrow channel akin to other natural channels located nearby, and thereby increasing tidal velocities. As the Port of Gladstone is near-resonant to the semi-diurnal tide, the tidal circulation exhibits sensitivity to errors in the bathymetry or basin geometry 2 (Aiken, 2008). It is particularly important to accurately represent the northern opening of the port at “The Narrows”. As a result, to adequately represent the tidal circulation, simulations were run on three telescoping grids of increasing resolution and decreasing geographical extent (Fig. 1). The horizontal resolution ranged from 100 m for the largest domain, encompassing the greater Port Curtis region, to 30 m for the domain restricted to the inner harbour, and to 10 m for the domain focused on the WBRA. The first two, lower resolution, simulations were used to provide accurate boundary conditions for the models of higher resolution. The boundary conditions for the outer domain were generated using tidal constituents from the TPX09 global tidal inversion [10].

3.2 Effect of groynes

A second configuration, employing a curvilinear grid that follows the inner seawall of the reclamation area, was used to represent different groyne array options (Fig. 2). In each simulation the groyne length and width are set at 20 m and 4 m respectively. Simulations were performed for separations between groynes of: 50 m to 1 km. For each groyne array separation, two simulations were performed, using (a) fully emergent or (b) partially submerged groynes, the latter protruding to 0.7 m above MSL – the desired height for the mangrove substrate. The open boundary conditions were obtained from the previous simulation encompassing the entire port.

4. Results

As a result of the modification in the Western Basin geometry, simulated peak tidal flows experienced by the inner seawall along the face of the bundwall exceeded 1.8 m.s^{-1} (Fig. 3). By comparison, actual peak flows within the Western Basin are simulated to reach 1.2 m.s^{-1} . It is possible that the coupled current-sediment system will adjust towards a steady state with even more intense currents occupying a narrow tidal channel that forms next to the seawall. As such, creation of the living seawall will also provide protection against undercutting by the tidal channel.

As discussed in [3], the primary determinant for natural mangrove establishment via propagule dispersal from adjacent mangrove stands is likely to be creating a stable substrate with an elevation of at least 70 cm above MSL – corresponding to the physiological upper limit of inundation time for the target species *Avicennia marina* and *Rhizophora stylosa*. This in turn depends upon ensuring constantly accreting conditions, even at peak tidal flows. While a substrate targeting seagrass restoration would extend only to the lower intertidal, the requirement for non-eroding flows is remains. As such, in either case – mangrove or seagrass – a groyne array design is sought that guarantees weak currents across the zone to be dedicated to the living seawall, even during peak tidal flow.

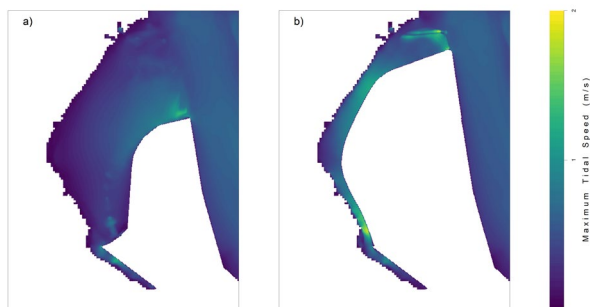


Figure 3 Peak tidal velocities for (a) the present geometry of the Western Basin, and (b) a possible design for an extension to the reclamation area. Narrowing of the Western Basin results in higher peak flows.

A leading order appraisal of the effectiveness of the groyne array designs was determined by their ability to achieve a continuous boundary layer of weakened currents adjacent to the seawall prior to the placement of the sediment. For the case of a mangrove habitat this represents a strict condition upon resuspension of placed sediments, which due to their elevation above mean sea level would not be exposed to tidal currents during peak flow. Future simulations will incorporate sediment dynamics, of most importance for assessing possible current-sediment feedbacks.

The results of the set of simulations representing different groyne array designs are summarised in Figure 4 for the section of the reclamation area inner seawall indicated in Figure 2. An inter-groyne spacing of 150 m was sufficient to establish continuous low flow conditions throughout the region destined to the sediment habitat. The use of groynes that only reach to the target elevation of the substrate – 70 cm above mean sea level – only moderately increased peak tidal flows within the boundary layer (Fig. 5). With such a design for the groyne array, repurposed sediment added between the groynes would be expected to resist erosion by tidal currents, regardless of the height of the substrate. In the case of mangroves, by using groynes that do not protrude above the substrate, these would be completely assimilated within the sediment, and subsequent natural accretion would allow them to eventually be incorporated within the new mangrove ecosystem.

The numerical modelling considers the interaction of the tidal flow with the array of groynes, but not the non-linear interactions between flow and sediment. Changes in the bottom depth due to accretion/erosion will, in turn, change the local patterns of flow. In nature, this process leads to the formation of tidal channels that may be highly dynamic, and the formation of such a tidal channel abutting the groynes is likely to occur. When the space between groynes is entirely filled with repurposed sediment, as would occur for mangrove habitat, erosion due to primary tidal flows is prevented, as inundation of the substrate occurs only during weak flows at high tide. The formation of erosional channels in the sediment driven by tidal percolation of the receding tide is, nonetheless, possible and may be intensified adjacent to the groynes. While such processes can be simulated numerically with coupled sediment-hydrodynamic models, empirical studies and monitoring remain essential to address problems of excessive secondary erosion as they arise.

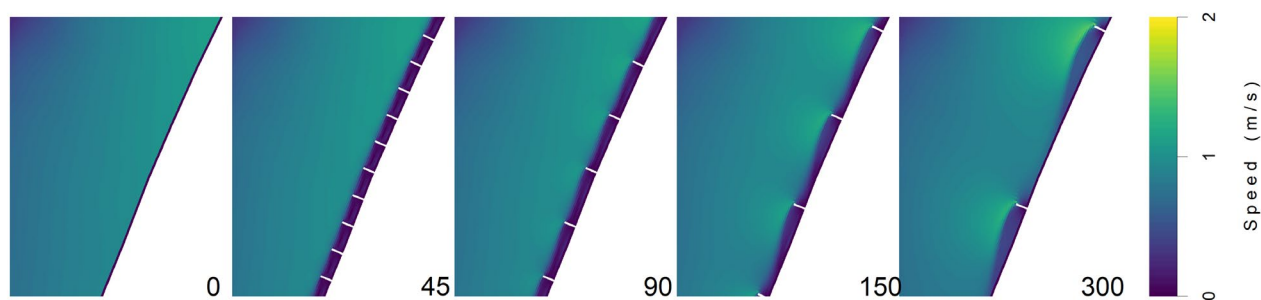


Figure 4 Simulated peak tidal velocities under different groyne spacing scenarios, for groynes that extend to beyond high tide. The separation between groynes in meters is shown in the lower right of each panel. A 150 m spacing between groynes maintains a continuous low flow boundary layer along the reclamation area seawall.

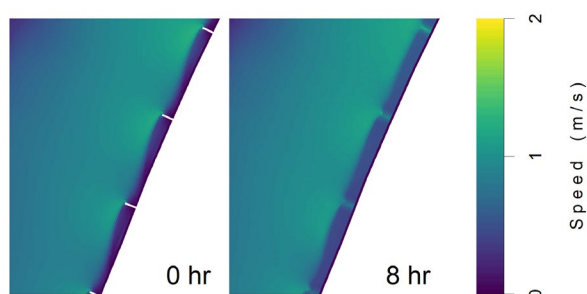


Figure 5 Simulated peak tidal velocities for groynes that extend to beyond high tide (left) and that reach only to 70 cm above mean sea level (right, 8 hour inundation time) for a spacing between groynes of 150 m. The use of lower groynes, which would eventually be incorporated within the new habitat, is still able to maintain a contiguous region of low flow in the region earmarked for habitat creation.

5. Conclusions

The importance to society of the services provided by our coastal ecosystems, and the pressing need to restore them, is now well appreciated. From the alimentary perspective alone, recovery of these highly productive ecosystems will be essential for meeting future demographic challenges. While urban development has commonly had an overwhelmingly negative impact upon coastal ecosystems, there is now evidence that the incorporation of suitable techniques can allow ecological goals to be addressed in new modifications of the littoral zone. In this context the rehabilitation of coastal habitats adjacent to seawalls through the reuse of sediments represents a promising opportunity to recover lost coastal ecosystem services.

In the case considered of the construction of a “living seawall” using dredge spoils to ameliorate loss of natural habitat by intervening a bund wall within the Port of Gladstone, low wave energy and strong tidal flows argue for the use of rock groynes to ensure that placed recycled sediments resist

erosion during inundation. The conservation targets considered are the endemic seagrass, oysters and mangrove populations, as well as providing habitat for the endangered Eastern Curlew. Numerical modelling was used to assess the peak velocities across the placed sediment and the dimensions of the groyne array. Importantly, it was found that groynes that extend only to the height of the substrate, set by the inundation tolerance of the target species, would shield the novel substrate from peak tidal flows on both ebb and flows. The possibility for the groynes to become incorporated within the sediment matrix and provide ecological dividends.

This example also highlights the opportunity to engage industrial users of the coastal zone in conservation efforts. By reconciling ecological goals with economic realities, WwN and related approaches are providing tools to achieve coastal rehabilitation at scale. There is now sufficient practical experience to have confidence that the dredge material produced as an unavoidable consequence of modern port operation can be repurposed to achieve positive outcomes for ecosystem services in the intertidal areas, even without a coastal defence objective.

6. References

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Australasian Coasts & Ports 2021 Conference – Christchurch, 30 November – 3 December 2021

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