A Living Shoreline Design for erosion mitigation in Main Beach, Byron Bay, NSW, AUS

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1. Introduction

In this study, we selected and designed artificial submerged reefs (ARs) as a living shoreline, one of natural-based solutions, for Byron Bay, and used another similar project in AUS to verify its performance.

Byron Bay is a tourist town on the northern NSW coast in the east AUS, and it is an area subject to coastal erosion in a long term. From 2023, Byron Shire Council has defined some preliminary options for the Main Beach Shoreline Project (MBSP), such as berm rock revetment and pathway, without any consideration of soft engineering, and the project aims to develop elevation to avoid surge storm disasters.

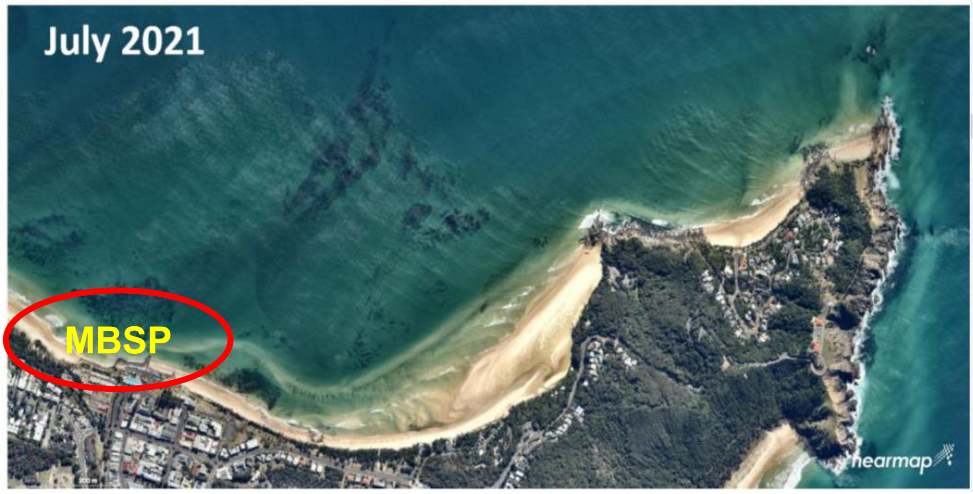

Fig 1. MBSP location and adjacent beaches

Fig 2. Structural condition rating based on visual and drone inspection on 2019.[1]

Therefore, we want to suggest some NbS measures (i.e., living shorelines) as a supplementary design, to attenuate wave energy in the surf zone and reduce overtopping effect in coast. The “living shorelines” approach focuses on balancing shoreline protection and habitat creation. Living shorelines are living, natural structures that support rather than degrade the surrounding ecosystem, by not only stabilising the shoreline, but also providing many ecological functions enhancing the ecosystem. [2]

2. Coastal Site and Risk Assessment

2.1. Geomorphology and reefs

Geological and seabed characterization mapping for the Byron embayment is shown in Fig 3. This map shows the embayment has extensive indurated sand (or coffee rock) lenses and bedrock outcrops including Julian Rocks and Middle Reef.

And the recent aerial images that show reefs within the embayment intermittently exposed and then covered with sand. Hard substrate also reduces the volume of sand that can be stored in the southern embayment.

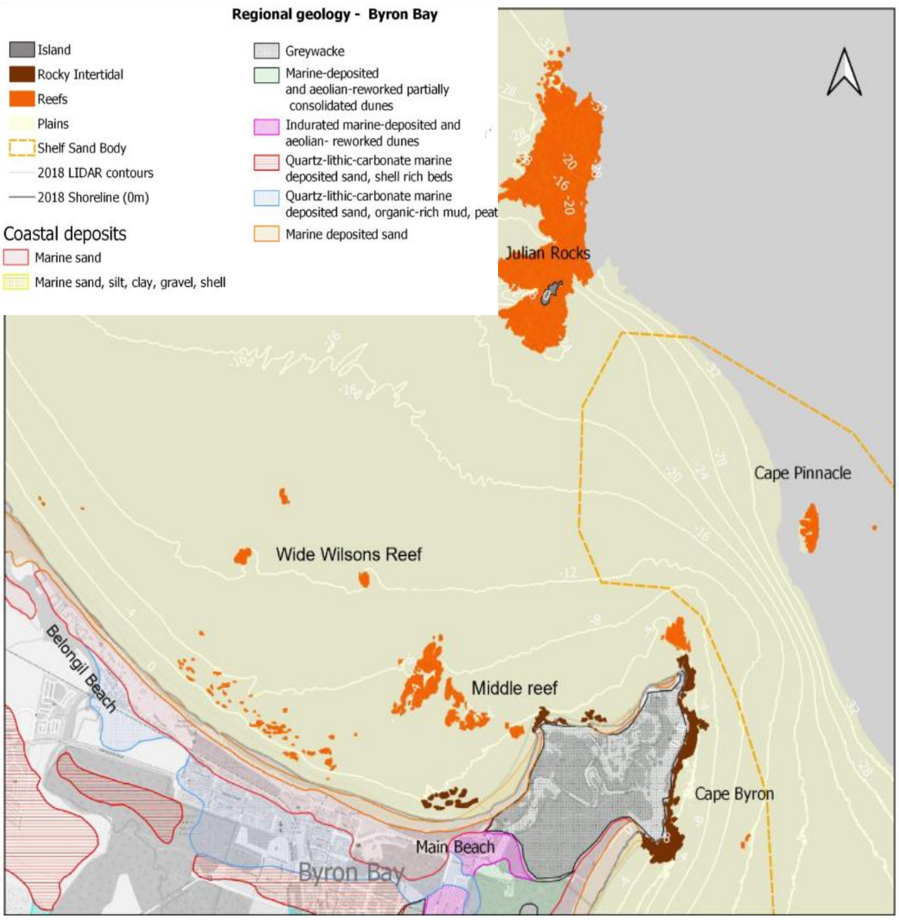

Fig 3. Byron Bay regional coastal geology and seabed characterisation map.

Considering the good condition of existing reefs, we can conclude that an artificial reef consisting of similar variety with local reefs can grow in this ocean environment.

2.2. wave transformation and site parameters

Simulated wave and hydrodynamics maps and statistics for a series of design scenarios are provided in *MBSP TechnicalReport* [3]. Modelled nearshore hydrodynamics results including wave properties and bathymetry are presented for the basecase in 8.1

Appendix I: Wave properties and baseline in MBSP, where the 90th percentile wave conditions were selected as representative of higher wave energy but regularly occurring event.

2.3. Erosion risk

In the main beach, groynes were built in the foreshore to block longshore transport, but it seems to be failing as the embayment was experiencing severe ‘natural’ erosion, and it was recorded around 1,382,000 m^3 sand loss during 3yrs, that means a significant volume longshore sediment transport bypassed groynes and the shoreline was not stable. And in agreement with the sand loss trend identified in the sand budget analysis, the embayment shows shoreline recession.

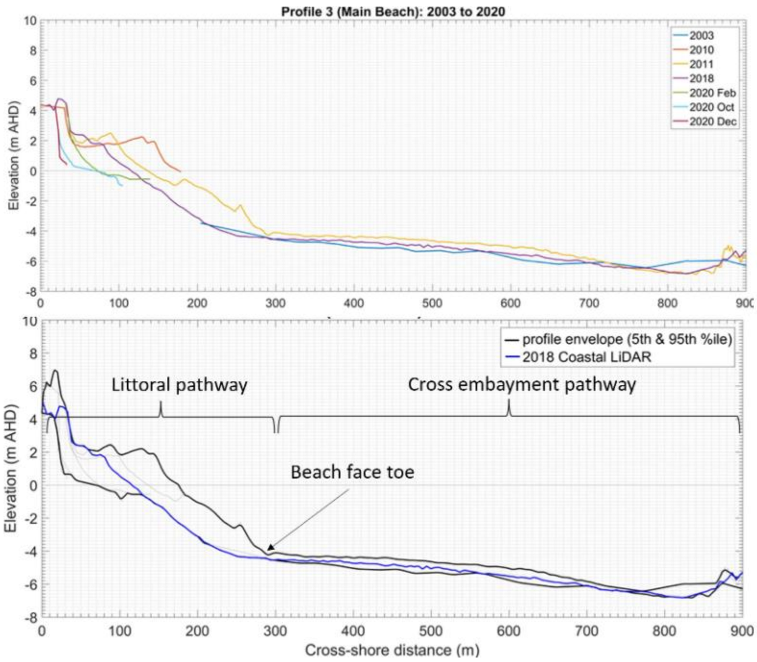

Fig 4. Coastal profile at Main Beach (top) with envelope of profile variation between 2003 and 2020 (bottom).

If using the Bruun Rule to evaluate shoreline recession, and assuming the adopted storm demand is 150m3/m (volume per unit length (meter) above AHD), the long-term shoreline recession is estimated at 0.09m/yr, with sea level rise (SLR) contributing around 15m of SLR recession until 2050 for the MBSP.
Also, we can see the significant instability of shoreline and recession in Fig 4.
Thus, we selected present erosion rate at 0.65m/yr considering the average impact, that is classified as ‘Moderate Erosion’.

3. Living shoreline function and design consideration

3.1. Wave attenuation by reefs

Shallow water coral reefs act as low-crested, submerged breakwaters, that can provide flood reduction benefits through wave breaking and wave energy attenuation, especially for the reef crests, and can attenuate up to 98% of the incoming wave energy. [4]
This wave attenuation function is evident in the inclusion of reef depth as a primary variable when developing empirical relationships to describe wave energy reduction on coral reefs [5]. From the Fig 5, it shows the reef crest significantly reduces the wave energy, and the subsequent transformation of residual energy leads to cross-shore sediment and shoreline changes.

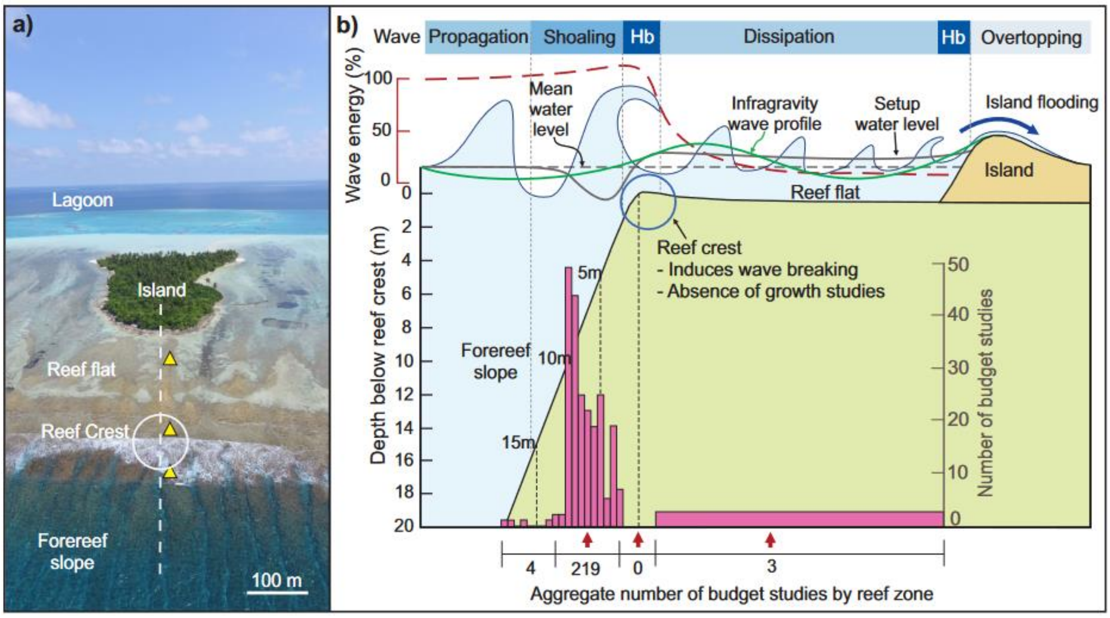

Fig 5. Summary of wave interactions with Indo-Pacific coral reefs and reef flats.

Thus, the performance depends on the underlying structure of reef, and the design location should consider the water depth in a low to moderate wave energy locations.

3.2. Critical parameters

We refer the criteria index (in 8.2 Appendix II: Critical ranges of different NbS structures in guideline) from Living Shorelines Engineering Guidelines in US[6] to evaluate the suitability of the living shorelines in the site.

To simplify the guidelines, the relevant parameters have been divided into 4 categories. It should be noted that the separation of these variables into groups is done for convenience and that there is some overlap. As a coastal engineer, we prefer to design to precisely defined geodetic datums, but the influence the growth and survivability of vegetation should be focused on like ecological derived datums. Specifically, the ocean acidification reduces reef growth and calcification rates, and long-term cold-water temperatures below 18° C damages their structures.

We extract the local parameters from 8.1 Appendix I: Wave properties and baseline in MBSP, and the comparison of local scenarios and critical index is presented in Table 1.

Table 1. Properties in MBSP baseline and evaluation by criterion

No.	Parameter	Baseline Value	Criterion	Local Class	Guideline Class - Living Reef
		1. System Parameters			
1.1	Erosion History	0.65m/yr and severe sand loss	2~4 ft/yr	Moderate	Low-Med
1.2	Sea Level Rise	0.01m/yr, where the selected sea level rise of 0.78m by 2100 is a mid-value between 50th percentile	0.2~0.4 in/yr	Moderate	Low-Mod
1.3	Tidal Range	1.7m, selected as ±15% of measured level (neap tide)	> 4 ft	High	Low-Mod
		2. Hydrodynamic Parameters			
2.1	Waves	Hs=1.5m (75th percentile wave)	>3 ft	High	Low-Mod

No.	Parameter	Baseline Value	Criterion	Local Class	Guideline Class - Living Reef
2.2	Wakes	NA info			Low-Mod
2.1	Currents	an average surf zone current speeds of 0.3m/s and a peak speed of 0.9m/s (0.583 kts)	< 1.25 kts	Low/Mild	Low-Mod
2.2	Ice	NA info			Low
2.1	Storm Surge	0.9m, 1.1m and 1.2m for present day, 2050 and 2100	>3 ft	High	Low-High
		3. Terrestrial Parameters			
3.1	Upland Slope	1/25 from the shoreline profile in 2018	1:30 to 1:10	Moderate	Mild-Steep
3.2	Shoreline Slope	1/10 from the shoreline profile in 2020	1:15 to 1:5	Moderate	Mild-Mod
3.3	Width	45m, including the main beach and groynes	>60 ft	High	Mod-High
3.4	Nearshore Slope	1/25 from the shoreline profile in 2018	1:30 to 1:10	Moderate	Mild-Mod
3.5	Offshore Depth	1.2m depth at a distance of 100m from the shoreline	2 ft to 5 ft	Moderate	Shallow-Mod
3.6	Soil Bearing Capacity	NA info			Mod-High
		4. Ecological Parameters			
4.1	Water Quality	good	-	Good	Good
4.2	Soil Type	Sediment soil survey: Hard setting duplex soils; Red podzolic soils of good structure.	-	Good	Any
4.3	Sunlight Exposure	for 5 hours/per between 10am–3pm	2 to 10 hrs/day	Moderate	Mod-High

Note: red text indicates that the baseline level exceeds the criterion specified.

According to the comparison, most of indicators in baseline are satisfied with the criteria, expect high tidal and wave conditions. Once the value of high tidal and wave conditions is up to a threshold level, it may affect the structure of ARs, and reduce the attenuation function of wave by ARs.

Thus, it is necessary to increase monitors to ensure ARs survival rates and constructability.

3.3. Specific considerations

Because of strict environmental restrictions, coral reefs generally require warm and clear water. While in the conceptual design phase, we need to consider more about environmental and ecological conditions. Thus, when developing a living marsh sill with oysters and mussels in a moderate or high wave energy environment, gabion baskets constructed from wire or geogrid material should be used to contain larger masses of shell to add increased stability to the structure [6].

And the water depth, water temperature varies with the distance from MBSP shoreline. Also, the structure of ARs defines the performance. A properly designed living reef project will contain windows or gaps along the structure to allow for circulation. While it is possible for water to access a marsh bordered by a living reef through overtopping or the macro-pores or spaces in the reef, gaps should always be included along larger projects to allow access for marine animals.

In generally, ARs have 4 types of structures [7], as shown in Fig 6. Behind ARs, circulation currents, in addition to the presence of longshore currents, reduce the rate of littoral drift and help accumulate sediments and stabilize shorelines.

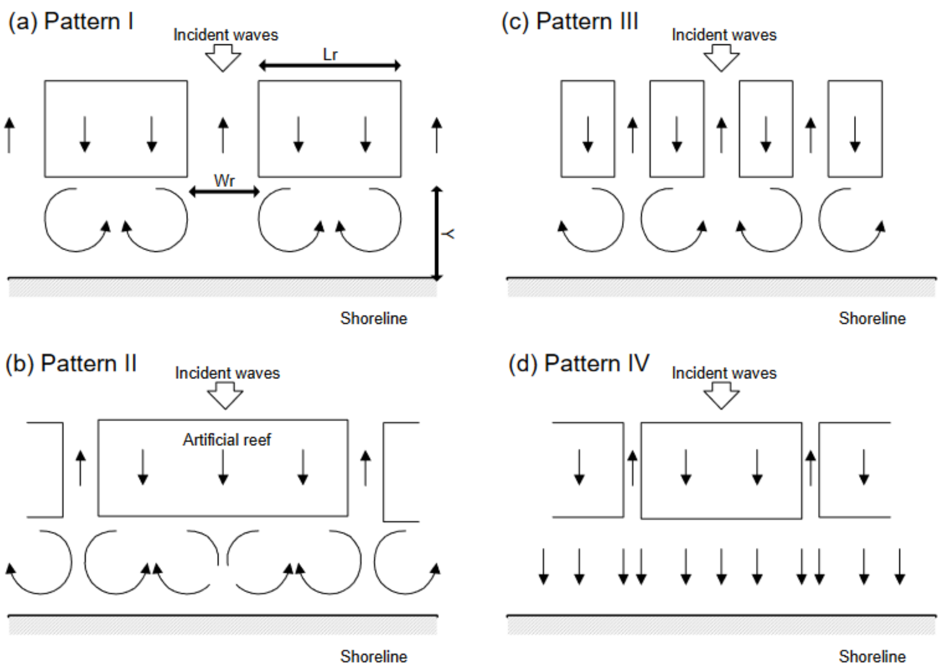

Fig 6. Current Patterns around Artificial Reefs

Besides, the constructability, project monitoring, native/invasive species also should be considered in design stage.

4. Conceptual design of living shorelines

The living shoreline project aim to increase beach and foreshore habitat and decreased erosion in shorelines.

It acts as an assistant soft measure with revetment, including the creation of reef habitat, and coastal native seagrass has re-established in the shallow waters. And the layout is shown in Fig 8.

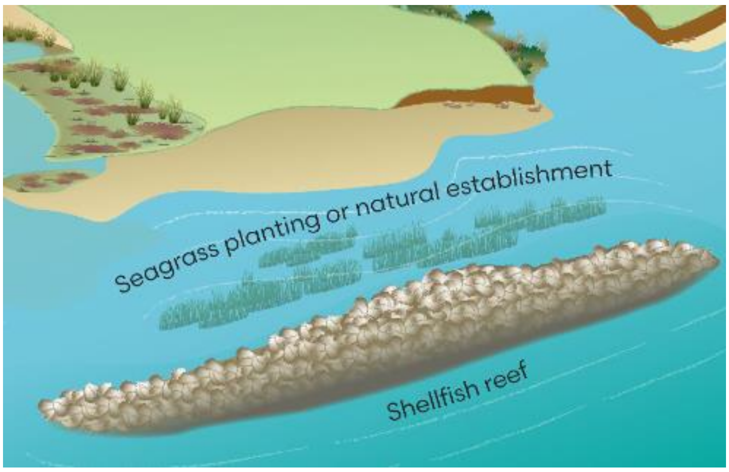

Fig 7. Conceptual design

1) Seagrass Vegetation Restoration

The native seagrass is restored to reduce residual wave energy, and also reduce wind-wave driven sediment resuspension in the onshore zone. [8]

In generally, it is avoidable to plant seagrass in swales, and the specie of seagrass should be consulted to identify appropriate plant species and planting zones.

Thus, swales, planted out with coastal native seagrass, can be introduced to contain some of the overtopping water during severe storm surges as providing additional protection.

2) ARs in foreshore

ARs are designed to reduce wave energy and erosion, mainly protecting the length range of MBSP shorelines where the severe erosion expanded.

The foreshore construction involves a semi-submersible breakwater in the form of an artificial reef 100m out (Y=100m) and with water depth at 1.2m, parallel with the shore, where reefs can grow well.

The size of ARs is 80m long (Lr<Y) and 8m wide, and the Pattern II in Fig 6 is applied. Although circulation currents only develop at the tips of the reefs, a relatively good coastal littoral drift control effect can be obtained by creating flow Pattern II. Evaluate the cross-shore distribution of longshore sediment transport by CERC [9], when Lr <Y, onshore currents flowing over the reef reach almost to the beach line and sometimes sand accretion does not develop behind the reefs. [7]

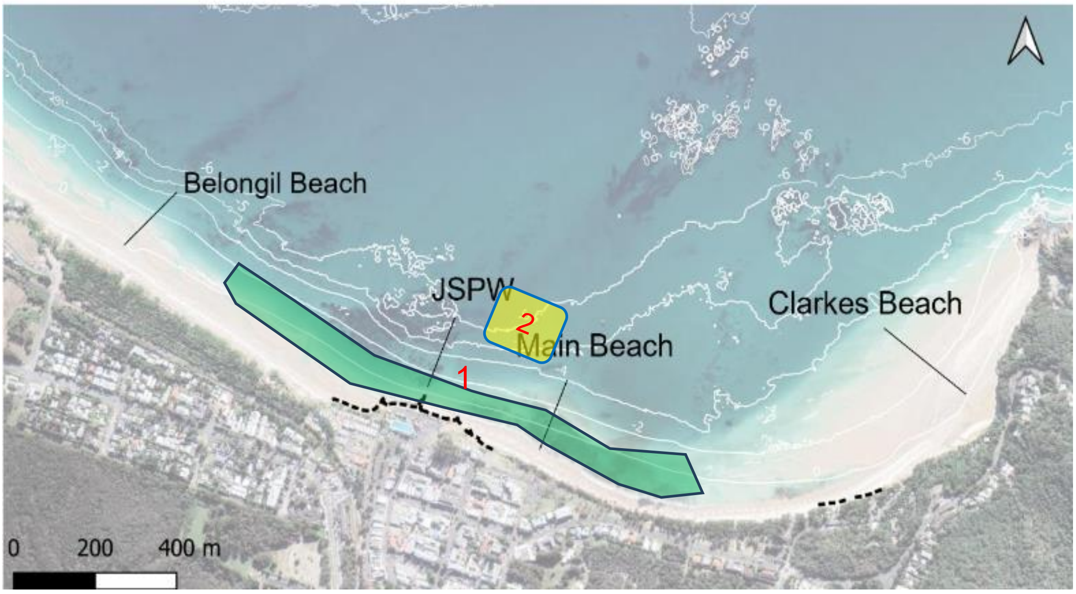

Fig 8. Conceptual design of living shorelines (1. Seagrass Restoration; 2. ARs)

In terms of its construction methods, the successful example in Ramblers Road Foreshore (details seen in 5 Performance and validation by a similar project) is applied, including: 1) the reef will be constructed from modular cages containing rock and shell. The cages will corrode over time, leaving a primarily natural reef. 2) The reef should be seeded with native mussel species, and is being monitored to examine results for colonization of shallow and intertidal marine communities. [10]

5. Performance and validation by a similar project

As the constraints of the author's proficiency in SWASH simulation model, we only justify ARs effectiveness by a similar case project in AUS. The artificial reef project acts as a semi-submersible breakwater in Ramblers Road Foreshore,[10] involving the construction of an artificial reef 100m out, parallel with the shore, with 130m long and 8m wide (in Fig 9).

Fig 9. ARs project in Ramblers Road Foreshore.

By comparing the shoreline changes before and after project implementation in Fig 10 and Fig 11, it shows that the shoreline is pushed seaward, and the sediment deposits like a natural beach nourishment process. Because ARs work as a buffer in the foreshore, to slow and attenuate waves before they hit the shorelines.

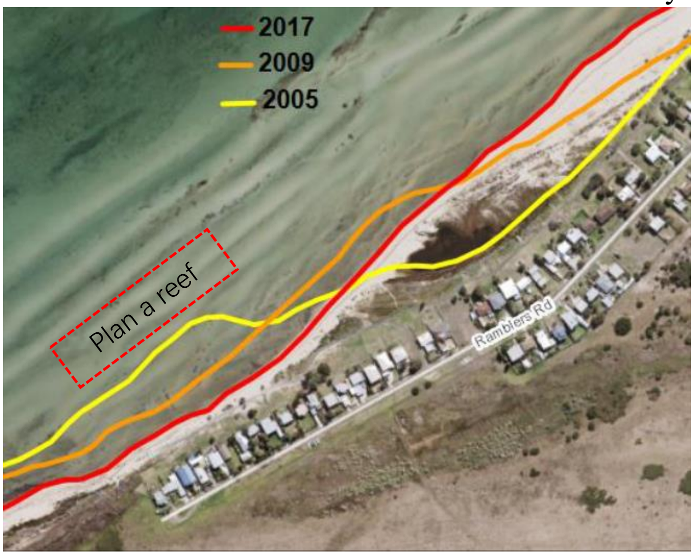

Fig 10. Before implementation (2005~2017)

Fig 11. After implementation (Map in 2024)

6. Conclusion

We design a living shoreline measure for MBSP in Byron Bay according to criterion in living shoreline guideline, involving: 1) Seagrass Vegetation Restoration, and 2) an artificial reef in foreshore zone. As many constraints living shorelines impose on the habitat and shore environment, in this study, the high wave and tide conditions limit the constructability and effectiveness of ARs.

In generally, ARs cannot be applied in high erosion and high wave scenarios, as it will reduce their performance in wave attenuation and sediment deposition. Besides, the shore slope is critical to provide a stable platform for ARs.

As the coral reef grows generally toward the low water line, shallow offshore depth is one of the primary factors that create the low-medium energy conditions required for living reefs to thrive, and limit wave exposure. That largely affect the selection of ARs layout. In terms of the selection of ARs' structures considering the current patterns, the ratio of parallel distance between ARs and shorelines and their design length define the patterns. Suitable selection can optimize the performance in longshore sediment control and residual wave attenuation.

Not only hydrodynamic and terrestrial elements, but the ecological parameters as special considerations should be undertaken into design, especially the water quality and sunlight exposure duration.

By comparison to verify ARs performance in shoreline restoration, it shows a significant seaward growth trend in shorelines after ARs implementation, like a natural beach nourishment.

In summary, living shorelines are living, natural structures that support rather than degrade the surrounding ecosystem, by not only stabilizing the shoreline, but also providing many other ecological functions enhancing the ecosystem. Living shoreline projects often involve the restoration of naturally occurring habitats or the planting of these biogenic habitats which have many ecological benefits. However, they need more considerations in the design phase to develop their effectiveness and constructability.

7. References:

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[2] R. L. Morris *et al.*, “Current extent and future opportunities for living shorelines in Australia”.

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[4] M. W. Beck, I. J. Losada, P. Menéndez, B. G. Reguero, P. Díaz-Simal, and F. Fernández, “The global flood protection savings provided by coral reefs,” *Nat. Commun.*, vol. 9, no. 1, p. 2186, Jun. 2018, doi: 10.1038/s41467-018-04568-z.

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8. Appendix

8.1. Appendix I: Wave properties and baseline in MBSP

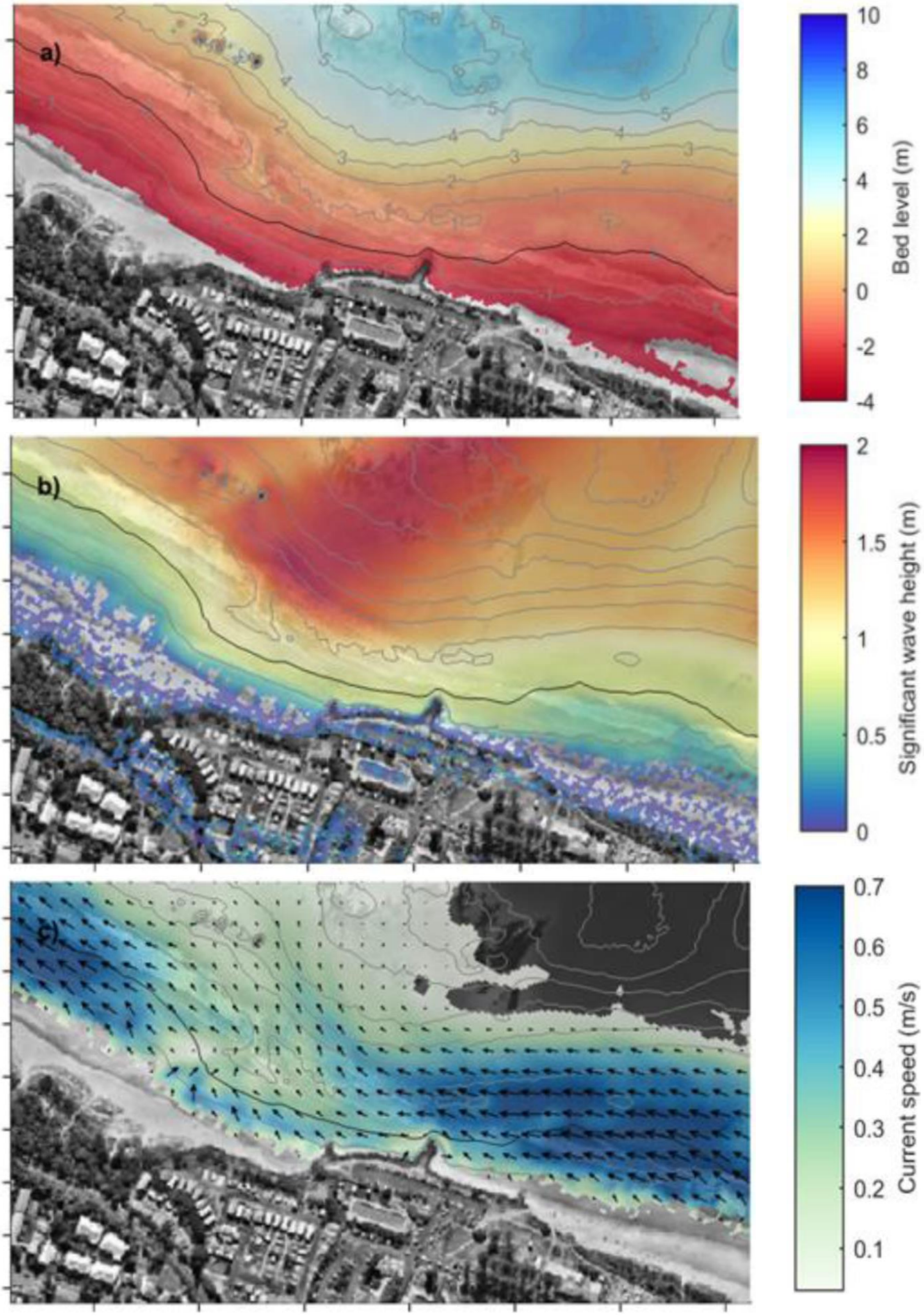

Fig 12. SWASH modelling results for basecase for 90th percentile wave scenario

8.2. Appendix II: Critical ranges of different NbS structures in guideline

From the Living Shorelines Engineering Guidelines by New Jersey Department of Environmental Protection (SIT-DL-14-9-2942) [6], in Table 3 an attempt has been made to put quantitative bounds on the somewhat subjective limits imposed. Guidance on specific limiting values for many of the relevant parameters used in the design of living shoreline projects is limited. The ranges defined in Table 2 were established by combining limits found in the literature, with engineering experience.

Table 2. Appropriate Conditions for Various Living Shoreline Approaches

	Marsh Sill	Breakwater	Revetment	Living Reef	Reef Balls
System Parameters					
Erosion History	***Low-Med***	***Med-High***	***Med-High***	***Low-Med***	***Low-Med***
Relative Sea Level	Low-Mod	Low-High	***Low-High***	Low-Mod	Low-Mod
Tidal Range	***Low-Mod***	Low-High	Low-High	***Low-Mod***	Low-Mod
Hydrodynamic Parameters					
Wind Waves	***Low-Mod***	***High***	***Mod-High***	***Low-Mod***	***Low-Mod***
Wakes	***Low-Mod***	***High***	***Mod-High***	***Low-Mod***	***Low-Mod***
Currents	Low-Mod	Low-Mod	Low-High	Low-Mod	Low-Mod
Ice	***Low***	***Low-Mod***	***Low-High***	***Low***	Low-Mod
Storm Surge	Low-High	***Low-High***	***Low-High***	Low-High	Low-High
Terrestrial Parameters					
Upland Slope	Mild-Steep	Mild-Steep	***Mild-Steep***	Mild-Steep	Mild-Steep
Shoreline Slope	***Mild-Mod***	***Mild-Steep***	**Mild-Steep**	***Mild-Mod***	Mild-Steep
Width	***Mod-High***	***Mod-High***	Low-High	***Mod-High***	***Mod-High***
Nearshore Slope	***Mild-Mod***	***Mild-Mod***	Mild-Steep	***Mild-Mod***	***Mild-Mod***
Offshore Depth	Shallow-Mod	Mod-Deep	Shallow-Deep	Shallow-Mod	Shallow-Mod
Soil Bearing	Mod-High	***High***	***Mod-High***	Mod-High	***Mod-High***
Ecological Parameters					
Water Quality	Poor-Good	Poor-Good	Poor-Good	***Good***	***Poor-Good***
Soil Type	***Any***	Any	Any	Any	Any
Sunlight Exposure	***Mod-High***	Low-High	Low-High	Mod-High	Low-High

Table 3. Criteria ranges for Various Living Shoreline Approaches

	Criterion		
Parameter	Low/Mild	Moderate	High/Steep
System Parameters			
Erosion History	<2 ft/yr	2 ft/yr to 4 ft/yr	>4 ft/yr
Sea Level Rise	<0.2 in/yr	0.2 in/yr to 0.4 in/yr	>0.4 in/yr
Tidal Range	< 1.5 ft	1.5 ft to 4 ft	> 4 ft
Hydrodynamic Parameters			
Waves	< 1 ft	1 ft to 3 ft	> 3 ft
Wakes	< 1 ft	1 ft to 3 ft	> 3 ft
Currents	< 1.25 kts	1.25 kts to 4.75 kts	>4.75 kts
Ice	< 2 in	2 in to 6 in	> 6 in
Storm Surge	<1 ft	1 ft to 3 ft	>3 ft
Terrestrial Parameters			
Upland Slope	<1 on 30	1 on 30 to 1 on 10	>1 on 10
Shoreline Slope	<1 on 15	1 on 15 to 1 on 5	> 1 on 5
Width	<30 ft	30 ft to 60 ft	>60 ft
Nearshore Slope	<1 on 30	1 on 30 to 1 on 10	>1 on 10
Offshore Depth	< 2 ft	2 ft to 5 ft	> 5 ft
Soil Bearing Capacity	< 500 psf	500 psf - 1500 psf	> 1500 psf
Ecological Parameters			
Water Quality	-	-	-
Soil Type	-	-	-
Sunlight Exposure	<2 hrs/day	2 to 10 hrs/day	>10 hrs/day