A review of multi-use and eco-engineering features for trained river entrances, armoured harbours and groynes

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Cover image: Montage of multi-use and eco-engineering features used in NSW coastal infrastructure
Cover photo sources: P Dwyer, L Mamo, Google Earth, Ron Main and Adrian Toovey

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Executive Summary

This report reviews large protective coastal infrastructure in intertidal and nearshore zones, including trained river entrances, armoured harbours, and groynes. Along the New South Wales (NSW) coastline, there are at least 43 trained—or partially trained—estuary entrances, 39 armoured harbours and 13 sites with a groyne or groyne field.

Estuary entrance modification was identified as the second highest threat to the environmental assets in the NSW marine estate by the Marine Estate Management Authority's Threat and Risk Assessment (TARA). The main source of modification—trained entrances and breakwaters—can contribute to changes in coastal processes that also increase the risk of degradation to natural, private and government assets. Yet, this infrastructure is integral to the protection of the same types of assets in other areas.

Initially, the primary goal of the majority of coastal protection infrastructure in NSW was to ensure safer navigation and asset protection. As a result, most existing developments have been reactive rather than proactive, costly, and sometimes ineffective. They have even been the cause for more erosion. Structures have generally been neither eco-friendly nor attractive to the public. Although hard coastal protection can be an effective response for one or two decades in some areas, alternative measures might be more cost-efficient and beneficial in the long-term.

This review finds support for a sustainable, more holistic concept of coastal management, where interdisciplinary groups (e.g. asset owners, engineers, scientists, stakeholders, and community groups) work together to ensure that coastal areas are safe for communities, without compromising social, cultural and environmental values. This is an approach that embraces the NSW Government's vision for the marine estate. Early planning is essential, as is site-specific assessment, use of decision-making frameworks such as the mitigation hierarchy including direct, tangible costs from construction and damage-prevention, but also from ecosystem services, recreation and tourism.

In NSW, most of the large coastal infrastructure is owned by the NSW Government. Much of this infrastructure was built more than a century ago. It is now vulnerable to damage from an increasing intensity and frequency of storms and sea level rise associated with climate change. It is also vulnerable to structural decline associated with ageing. As a result:

- Some existing training walls, armoured harbours and groynes will need to be upgraded.
- New coastal protection infrastructure may need to be built in some areas.
- The footprint of existing infrastructure might need to be reduced.
- A managed senescence or active removal of other infrastructure might be required.

The implementation of hard protection should be the last resort after retreat and soft approaches have been ruled out as viable options. It should include eco-engineered as well as multi-use features. Existing infrastructure might be removed, abandoned if deemed uneconomic, or retrofitted with eco-engineered and multi-use features if it is the present best option.

A key finding of this review is a decision-making pathway to enhance science-informed, evidence based policy to help achieve a healthy coast and sea managed for the greatest wellbeing of the community now and into the future.

The review fulfils the delivery of Action 2.1.2 outlined in the Marine Estate Management Strategy and informs two key management action outputs:

- an audit of NSW's trained river entrances, armoured harbours and groynes and their multi-use and eco-engineering features
- guidance notes for designers and project managers on incorporating multi-use and eco-features into breakwater maintenance and upgrade works.

Case studies from NSW and around the world give examples of where coastal protection infrastructure has either been modified with ecological engineering techniques or adopted approaches to facilitate multiple uses and add social, cultural and economic value to maximise sustainable outcomes.

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Introduction

Coastal zones are associated with large and growing concentrations of human populations, development, and socio-economic activities in many of the world's biggest cities (Small and Nicholls 2003). In Australia, more than 85% of the population lives within 50 kilometres of the coast (Clark and Johnston 2017; ABS 2018) and the population is increasing by 1–2% a year (ABS 2016). As a result, many areas in the NSW marine estate are facing multiple pressures (Figure 1).

Natural processes such as erosion (van Rijn 2011), flooding (Jackson and McIlvenny 2011), storm surges and sea level rise as a result of climate change can have a deleterious effect on urban settlements and the associated coastal infrastructure such as trained river entrances, armoured harbours, and groynes (Rahmstorf 2007; DCC 2009).

The Intergovernmental Panel on Climate Change projects a total sea level rise of 0.26–0.83 metres for 2100, with a high-end scenario estimate of 1.1 metres (Church et al. 2013). Under this high-end scenario, the estimated cost of replacing affected infrastructure in Australia is more than $226 billion, of which an estimated $63 billion includes buildings at risk of inundation from sea level rise alone (Department of Climate Change and Energy Efficiency 2011).

The 43 trained—or partially trained—estuary entrances, 39 armoured harbours and 13 sites with groyne or groyne fields along the NSW coastline are vulnerable to these pressures. The large coastal infrastructure in the intertidal and nearshore zone is especially vulnerable, as are the many assets that rely on this infrastructure to reduce exposure to environmental hazards. However, training or armouring of coastal areas can also exacerbate erosion or inundation in adjacent areas. Sea level rise adaptation strategies for such infrastructure must consider the consequences for both these situations.

Management options could include modification, upgrade or retirement and removal. Life-cycle analysis that takes into account the current and likely future purpose can be a useful tool to inform decision makers of suitable adaptation strategy pathways (to retreat, accommodate or protect) and their consequences.

Figure 1. Coastal areas such as Coffs Harbour are social, economic and ecological hotspots
Source: P. Dwyer

Study objectives

This report has the following objectives

- to review the national and international literature to provide an overview of how hard coastal protection infrastructure, in particular trained river entrances, armoured harbours and groynes, are used
- to identify and consider the socio-economic and environmental benefits and costs of these structures
- to examine mitigation strategies employed to minimise unintended socio-economic and environmental impacts

This review has already been used to inform an audit of breakwaters, harbours and groynes in NSW. It has also been used to inform the development of guidance notes for multi-use and eco-friendly features for breakwater maintenance and upgrade works. Together, these activities provide the foundation for a science-to-policy-to-practice approach for the management of hard coastal protection infrastructure in NSW that aligns with the NSW Government's vision for the marine estate:

'a healthy coast and sea, managed for the greatest wellbeing of the community, now and in the future'

This review has several limitations. First, much of the information is in grey literature (particularly for multi-use options) or potentially ephemeral documentation, such as plans and contracts. Second, there is a lack of previous research on certain topics and in certain regions. Finally, the design and management of hard coastal protection infrastructure spans multiple disciplines. Examples are provided in guidelines for breakwater designers and project managers (Dwyer and Dengate 2021a) (Appendix 1), which were developed through close consultation with practitioners during this review.

Management of the marine estate in NSW

The marine estate in NSW includes tidal rivers and estuaries (including wetlands), the shoreline (including beaches, dunes, headlands and rock platforms), submerged lands, offshore islands, and the waters of the NSW coast to three nautical miles offshore. To manage the often competing interests of sharing the NSW marine estate, the Marine Estate Management Authority developed a five-step decision-making process (NSW Government 2018):

1. Find out how the community derives economic, social and environmental benefits from the marine estate.
2. Identify the threats and risks to those benefits based on expert advice and community views.
3. Assess current management arrangements to see where action is needed to reduce priority threats and to enhance community benefits.
4. Develop management options that will reduce the priority threats and risks and that are cost-effective.
5. Be accountable. Monitor, evaluate and report on the effectiveness of the management options to ensure they are working.

The first two steps inform an evidence based, statewide assessment of the key threats and risks to the marine estate in NSW (Fletcher and Fisk 2017).

This assessment identified estuary entrance modification associated with trained entrances and breakwaters as the second highest threat to the environmental assets in the marine estate. Yet, the evidence gathered for consideration of social, cultural and economic matters found that lack of access to the marine estate was a widely held concern. Trained river entrances and armoured harbours generally incorporate breakwater structures that address this need and facilitate greater access to the marine estate.

Trained river entrances are a feature of many of the large estuaries on the north coast. These estuaries are characterised by broad coastal floodplains that have been extensively cleared and drained for agriculture. The Sydney basin is highly urbanised; in the past 50 years, several groyne fields have been established to try and protect infrastructure from coastal erosion. In the Sydney region, the main estuaries are drowned river valleys with generally good shipping access and little need for modification. In contrast, the NSW south coast is less urbanised and is characterised by fewer rivers and larger numbers of coastal lakes and lagoons (Environment Protection Authority 2015). Armoured walls were constructed throughout the 19th Century to enhance some natural harbours for shipping.

There are about 184 estuaries in NSW. They can be classified into five main types (Hughes et al. 2019) (Figure 2):

- bays—broad, deep entrances with large water surface area compared to intertidal area, tidal ranges similar to the ocean (there are nine bays in NSW)
- drowned valley estuaries—broad, deep entrances, rocky foreshores in the lower estuary, tidal ranges similar to the ocean (there are eight such estuaries in NSW)
- riverine estuaries—channels with narrow, shallow entrances, tidal ranges existent, low-lying floodplains in lower estuary (21 in NSW)
- barrier estuaries (open)—lake-like with narrow, shallow entrances, little tidal range (36 in NSW)
- intermittently closed and open lakes and lagoons (ICOLLs)—lake-like with narrow, shallow entrances, often closed off, non-tidal for extended periods (110 in NSW).

Figure 2. Examples of estuary types found along the NSW coast: Bays (A, Botany Bay), drowned valley estuaries (B, Hawksbury River), riverine estuaries (C, Richmond River), barrier estuaries (open) (D, Lake Illawarra) and ICOLLs (E, Smith Lake). The white bars represent 1 kilometre.
Source: Google Earth©.

Trained river entrances, armoured harbours and groynes

Trained river entrances, armoured harbours and groynes are types of hard engineered infrastructure that are common in NSW. These structures include elements such as breakwaters (which are often attached to training walls), dikes and seawalls. This infrastructure usually has a primary purpose of improving waterway access by controlling where and how rivers meet the sea, creating safer anchorage, or protecting coastal and estuarine areas from inundation or erosion (Schoonees et al. 2019).

Terminology

The terminology used in the literature for coastal protection infrastructure is diverse and can include:

- ‘coastal engineering’ (a broad term that encompasses design of infrastructure in the coastal zone and a consideration and manipulation of how it interacts with coastal processes)
- ‘coastal defence infrastructure’
- ‘coastal armour’
- ‘port infrastructure’
- ‘artificial reefs’.

The terminology appears to be growing richer. This is, perhaps, due to the range of infrastructure and settings, the increasingly multidisciplinary nature of the field, or the colloquial language of infrastructure uses and bias for terms that reflect their interests.

This is particularly apparent when secondary or opportunistic benefits provided by the infrastructure become as, or more important than, the initial primary engineered purpose. For example, if the primary purpose of a placed rock or geotextile bag structures located slightly offshore from the beach is to serve as coastal protection, it might be termed ‘submerged breakwater’. If the purpose changes over time, stakeholders such as surfers, fishers or divers could describe the same structure using a terminology that fits their interests, such as ‘artificial reefs’. This can lead to an interchangeable use of terminologies for the same structure (e.g. Pondella and Stephens 1994; Harris 2009), which creates a lack of clarity in some situations.

An overview of the main types of hard coastal protection infrastructure and some other insights into terminology is in Table 1.

Table 1. Overview of main hard coastal protection structure types found along the Australian coast, with examples

Protection structure	Details	Primary purpose	Example
Offshore structures			
Detached breakwater	Shore-parallel, sloping, single or multiple with gaps	Dissipate wave energy, prevent erosion and flooding, improve recreational conditions Does not occur in NSW	 Adelaide, South Australia
Submerged breakwater These structures are often called ‘artificial reef’.	Offshore, artificial (geotextile sandbags) or nature based (rock-based reef seeded with oysters)	Dissipate wave energy, prevent erosion and flooding, improve recreational conditions; outcomes are uncertain Does not occur in NSW	 Narrowneck Artificial Reef Queensland OR Palm Beach Artificial Reef, Queensland

Protection structure	Details	Primary purpose	Example
Beach front structures			
Connected/attached breakwater	Extending outwards from shore, sloping, often associated with armoured harbours and marinas	Dissipate wave energy, prevent erosion and flooding, improve recreational conditions	 Coffs Harbour, NSW
Groynes	Perpendicular to shore, often multiple along a single shoreline	Trap longshore sediments, stabilise coasts	 Botany Bay Sydney, NSW

Protection structure	Details	Primary purpose	Example
Estuarine structures			
Jetty or training wall These structures are colloquially called ‘breakwaters’ in NSW and Queensland. They fix the estuary bank into one position further landward.	Perpendicular to shore, extending to deeper waters, often associated with river entrances	Control previously migrating river entrances and protect part of the river entrance from cross waves, promote tidal and flooding scour to limit sediment accumulations, and protect navigation channels from waves and sediment accumulation	 Forster, NSW
Seawall These structures are sometimes called ‘training walls’ in NSW and Queensland.	Shore-parallel, vertical to sloping, often associated with built-up areas (can also include the estuarine component of the entrance training walls)	Installed to establish a new and fixed shoreline Often associated with land claim and prevention of flooding, fix shoreline position	 Sydney Harbour, NSW

Protection structure	Details	Primary purpose	Example
Rock revetment	Shore-parallel, sloping, often associated with low-energy waterways. Often built in an *ad hoc* manner in response to erosion. The piece meal nature of these structures can be exacerbated when foreshore lands have multiple landowners	Generally installed onto the natural shoreline when erosion impacts occur to prevent erosion impacting on assets	 Melbourne, Victoria
Dike This includes embarkments, levees, and road embankments.	Shore-parallel, gently sloping on both sides, often compliments drainage ditches and floodgates (one-way valves) in rural areas	Used to exclude tidal inundation, truncate the intertidal zone or facilitate drainage of coastal floodplains for land reclamation.	 Northern NSW

Source: Information compiled from Schoonees et al. (2019) and photos from Google Earth©

A timeline

The utilisation of hard coastal protection infrastructure dates back several millennia. The oldest known breakwater and port structure, located at the Egyptian Red Sea port of Wadi al-Jarf, has been dated to over 4,500 years old (Tallet and Marouard 2016). The main drivers for construction of coastal protection structures include land reclamation for agricultural use, protection of property (Charlier et al. 2005), construction and protection of beaches (Bruun 1972), navigability of ships (Wyllie et al. 1999, Nielsen and Gordon 2016), and land-based access to ships.

Coastal protection design has primarily been based on natural phenomena: seawalls mimic rocky shores; breakwaters mimic headlands; dikes mimic dunes; and submerged breakwaters mimic subtidal reefs (Bruun 1972). However, coastal management and implementation of protection infrastructure was rarely an interdisciplinary process: it was usually the sole responsibility of coastal engineers. As such, community consultation or environmental impact assessments were often lacking from the development process (Antunes do Carmo 2019).

The past

Construction of the first European built ocean breakwater in Australia, the Macquarie Breakwater, started in Newcastle in 1818 (Coltheart 1997). The breakwater's construction was a directive of Governor Macquarie, who used convict labour to constrict the estuary entrance of the Hunter River by linking Signal Hill (now known as Fort Scratchley) and Nobbys Island (Fig. 3).

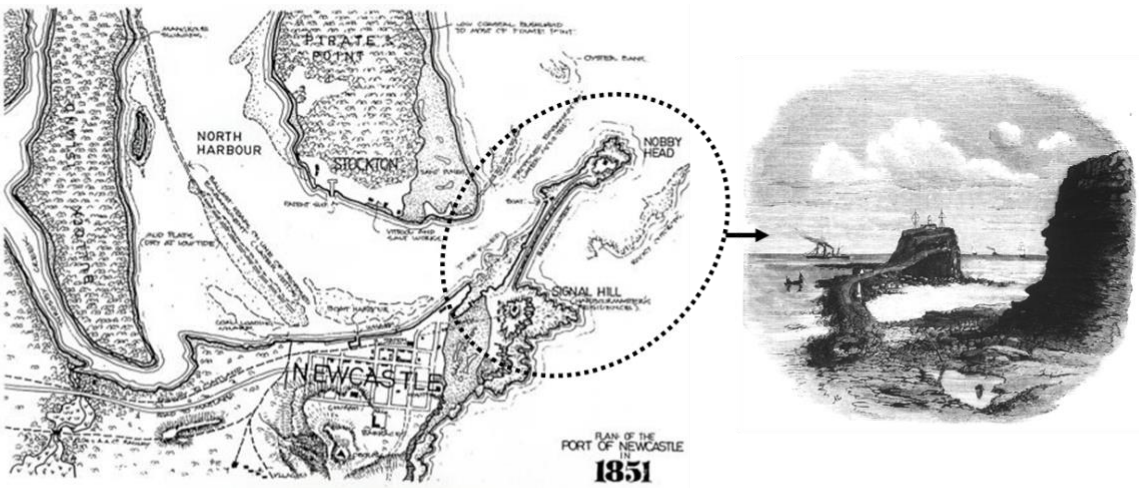

Figure 3. Map showing Port of Newcastle in 1851 and a historical illustration of the Macquarie Breakwater Sources: Newcastle and Hunter District Historical Society Gallery and Sydney News (25/11/1871)

From European settlement in the late 1700s to the early 1900s, shipping was the dominant form of transport and the only opportunity to export goods, especially coal and cedar. In many NSW estuaries, small-scale river training works were constructed from the coordinated deployment of shipping ballast rock. On the NSW south coast, armouring works increased the protection afforded by already sheltered bays and inlets.

1890 to 1910 was a significant period for the construction of large coastal infrastructure works, as entrance works at most of the large river entrances on the NSW coast were built during this period (Tables 2, 3 and 4). These works sometimes involved breaking up indurated sandstone rocky shelves at estuary entrances and training extensive sections of lower estuarine reaches. Deeper narrow channels increased tidal penetrations into estuaries; extensive areas of intertidal foreshore were progressively reclaimed during the next 60 years.

While large-scale dredging and breakwater maintenance works were constructed during the first half of the 20th Century, the extensive rail network, which had also been developed through the late 1800s and early 1900s, provided another transport option. It progressively reduced the volume of materials being shipped to very minimal amounts after the 1940s. A resurgent interest in improving the safety for shipping across coastal bars occurred during the 1960s and 1970s to support developing trawl fisheries, emerging tourism industries, and recreational boating. Trained entrance and breakwater works at the mouths of the Brunswick, Evans, Wooli and Bermagui rivers and the Wagonga Inlet were completed during this period along with auxiliary harbour works. Additional harbour works were constructed at Coffs Harbour and a new harbour was created at Crowdy Head. Breakwater extensions to trained entrances were also constructed at the Tweed, Richmond, and Clarence rivers. Additional entrance walls were built at the Hastings River and Wallis Lake.

The majority of coastal infrastructure in NSW has been installed by the state government. Since the 1960s, several privately commissioned or local council managed structures have been built. Most of these structures are groynes installed to manage coastal erosion.

Table 2. List of trained entrances, armoured harbours and groynes in NSW (north to south) in Marine Estate Management Strategy North Region (NSW–Queensland border to Stockton)

River/inlet/site	Structure	Date constructed
Tweed River	Twin training walls	1890–1902 1962–66 extended 380 metres
Tweed River Jack Evans Harbour	Estuary harbour breakwater	1890s
Tweed Estuary Marina	Estuary harbour	1960s
Cudgen Creek	Twin training walls	1967
Mooball Creek	Twin training walls	1968
New Brighton Kendalls Groyne	Groyne	1970s
Brunswick River	Twin training walls	1960–62
Brunswick River Boat Harbour	Estuary harbour breakwater	1960–62
Byron Bay Main Beach	Groyne field (3 structures)	Mid-1970s
Richmond River	Twin training walls	1889–1910
Martin Street Boat Harbour	Estuary harbour breakwater	1900s
Ballina Boat Harbour	Estuary harbour breakwater	1966–67
Evans River	Twin training walls	1963
Evans River Boat Harbour	Estuary harbour breakwater	1963
Clarence River	Twin training walls	1874–1903, 1959–69 extended northern wall 1,000 metres 1862–1903, 1960–71 extended southern wall 600 metres
Iluka Boat Harbour	Estuary harbour breakwater	1970s
Yamba Boat Harbour	Estuary harbour breakwater	1900s
Wooli River	Twin training walls	1973
Coffs Creek	Single training wall (north)	1977, upgraded 1987

River/inlet/site	Structure	Date constructed
Coffs Harbour	Ocean harbour multiple breakwaters	1915–24 northern wall 1917–46 eastern walls 1972–80 Inner wall harbour works
Bellinger-Kalang River	Twin training walls	1892–1906
Nambucca River	Single training wall (north)	1890–1903
Macleay River	Twin training walls	1896–1906
South West Rocks Creek	Twin training walls	1935, extended 1960s and upgraded 1979–82
Laggers Point	Ocean harbour single breakwater	1889–1903
Killick Creek	Single training wall (south)	1957–59
Hastings River	Twin training walls	1901, 1978–79 extended northern wall 500 metres 1890–1902 southern wall
Camden Haven River	Twin training walls	1909–11, 1970s extension northern 1898–1907, 1970s extension southern
North Haven Boat Harbour	Estuary harbour breakwater	1960s
Crowdy Head	Ocean harbour twin breakwaters	1964
Manning River	Single training wall (north) Estuary training wall (south)	1895–1918 northern wall 1902–04 southern wall
Racecourse Creek, Old Bar	Buried gabion baskets and geotextile bags	1992
Wallis Lake	Twin training walls	1965–66 northern 1898–1903 southern
Foster Harbour	Estuary harbour breakwater	1900s, 1960s port facilities added
Port Stephens Hawks Nest	Estuary training wall	1900s
Port Stephens Carrington	Estuary harbour breakwater	1840s
Port Stephens, Tahlee	Estuary harbour inlet	1820s
Port Stephens Soldiers Point	Estuary harbour breakwater	2000s
Port Stephens Corlette Point	Estuary harbour breakwater	1980s–90s
Port Stephens Nelson Bay	Estuary harbour breakwater	1973–86

Sources: NSW Crown Lands Annual Reports; Coltheart (1997); Short (2020); Dwyer and Dengate (2021b).

Table 3. List of trained entrances, armoured harbours and groynes in NSW (north to south) in Marine Estate Management Strategy Central Region (Stockton to Shellharbour)

River/inlet/site	Structure	Date constructed
Hunter River	Twin training walls	1818–94
Hunter River North Channel Hereford St Harbour	Estuary harbour breakwater	1890s
Hunter River North Channel Griffith Ave Harbour	Estuary harbour breakwater	1890s
Hunter River Koorangang Island	Estuary training wall	1960s
Lake Macquarie	Twin training walls	1877–1910
Lake Macquarie Salts Bay Mats Point	Groyne field (4 structures)	1990s
Lake Macquarie Swan Bay	Groyne field (6 structures)	2006
Lake Macquarie Myuna Bay Eraring Power Station Outlet	Single training wall for outlet	1977
Mannering Point Inlet and Vales Point Power Station Breakwater	Training wall	1960s
Caves Beach–Spoon Rocks 'Mawsons Breakwater'	Ocean harbour single breakwater	1968
Budgewoi Lake Power Station Constructed Outlet at San Remo	Single training wall for outlet	1965
The Entrance Roberts Beach	Groyne	2017
Avoca Lake	Boulder training wall	1990s
Cockrone Lake	Boulder training wall	1970s
Ettalong Beach	Groynes (5 structures)	1972
Gosford Harbour	Estuary harbour breakwater	1880s, 1950s
Woy Woy Railway Wharf	Breakwater	1890s
Woy Woy Bay	Breakwater	1920s
Parsley Bay, Brooklyn Harbour	Estuary harbour breakwater	1965–66
Narrabeen Lagoon	Single concrete training wall	1950–60s?
Dee Why Lagoon	Boulder training walls	1979
Manly Lagoon	Training concrete race	1940s, 1999 low flow extension
Frenchmans Bay / Yarra Bay	Groynes (2 structures)	1940s and 1970s
Botany Bay Molineux Point	Estuary harbour breakwater	1977–78
Botany Bay Foreshore Beach	Groyne field (3 structures)	1990s
Cooks River	Twin training walls	1950s
Botany Bay Lady Robinsons Beach	Groyne field (11 structures)	1997–2005
Botany Bay Silver Beach	Groyne field (14 structures)	1969–70
Bellambi Point	Ocean harbour single breakwater	1979
Towradgi Creek	Twin training walls	1990s

River/inlet/site	Structure	Date constructed
Wollongong Harbour	Ocean harbour twin breakwaters	1837–44, 1978 northern wall
MM Metal Manufactures Beach	Groyne	1974
Port Kembla	Ocean harbour twin breakwaters	1901–25 1962 extensions
Lake Illawarra	Twin training walls	2000–07
Berkeley Harbour	Estuary harbour breakwater	1950s
Yallah Bay, Tallawarra Power Station Constructed Outlet	Single training wall for outlet	1950s
Elliott Lake, Barrack Point	Single training wall (north)	1966–68 2006–08 extension
Shell Harbour	Ocean harbour twin breakwaters	1830–82

Sources: NSW Crown Lands Annual Reports; Coltheart (1997); Short (2020); Dwyer and Dengate (2021b).

Table 4. List of trained entrances, armoured harbours and groynes in NSW (north to south) in Marine Estate Management Strategy South Regions (Shellharbour to NSW–Victorian border)

River/inlet/site	Structure	Date constructed
Shell Cove	Twin training walls	2013–22
Bass Point Jetty	Groyne	1970s
Kiama Harbour	Ocean harbour twin breakwaters	1859–67
Werri Lagoon	Concrete training wall race	1930s Upgraded 1975
Crookhaven River	Single training wall (north)	1910–12
Crookhaven Regional, Boat Ramp	Estuary harbour breakwater	1960s
Crookhaven, Numbaa Point	Single training wall (south)	1908
Crookhaven, Greenwell Point	Groyne	1979–80
Currarong Creek	Single training wall (south)	1940s or 50s
Currambene Creek	Single training wall (south)	1920s
Currambene Creek, Myola	Single training wall	1980s
Jervis Bay, Captains Point	Estuary harbour breakwater	1915
Jervis Bay, Murrays Beach	Estuary harbour breakwater	1982
Blackwater Creek, Mollymook	Twin geotextile training walls	Mid-1990s
Ulladulla Harbour	Ocean harbour twin breakwaters	1863–82 Expansion 1964–65
Batemans Bay Clyde River	Single training wall (south)	1899–1905
Batemans Bay Harbour	Estuary harbour breakwater	1978–80

River/inlet/site	Structure	Date constructed
Tomaga River Mossy Point	Single training wall (south)	1850–59
Moruya River	Twin training walls	1897–1903 Extended 1923–25 and 1946–54
Moruya River	Remnant southern wall	Originally built 1861–62
Wagonga Inlet (Narooma)	Twin training walls	1922 Extension 1976–1978
Bermagui River	Twin training walls	1958–59 Extension 1979–82
Bermagui Harbour	Estuary harbour	1958–59
Twofold Bay, Shipping Terminal	Estuary harbour breakwater	1965, 1987
Twofold Bay, Quarantine Bay	Estuary harbour breakwater	1978–79

Sources: NSW Crown Lands Annual Reports; Coltheart (1997); Short (2020); Dwyer and Dengate (2021b).

The present

The impact of built structures in seascapes worldwide is increasing and estimated to include a cumulative physical footprint of 32,000 square kilometres (km^2) and cause modifications to as much as another 3.4 million km^2 of adjacent area (Bugnot et al. 2020). About half of the Sydney Harbour foreshore is affected by built structures (Chapman and Bulleri 2003). Many of these existing structures were constructed decades ago using approaches that do not conform to modern-day engineering standards. Deteriorating, ineffective or unsafe structures could require upgrading or rebuilding, modification or removal (Blacka et al. 2004).

Decisions about existing coastal protection infrastructure can be constrained when there is strong stakeholder sentiment about its use and the actual and perceived protection or opportunity it provides. Where infrastructure has been in place for generations, there is often very little understanding of the ongoing impacts caused by the infrastructure due to the shifting baselines phenomenon (Pauly 1995).

Environmental concerns about coastal infrastructure have played an increasingly important role in recent decades (Charlier et al. 2005). There is also a developing appreciation of the non-engineering aspects of building coastal protection infrastructure, including aesthetics, sustainability, tourism, fishing industries and other socio-economic factors (Antunes do Carmo 2019).

Current decisions about the use of hard protection infrastructure depend on various factors (e.g. wave climate and cost-efficiency). Finding an adequate solution can often involve years of trial and error. For example, the Leirosa dune system in Portugal has suffered considerable erosion. The response has involved three major mitigation measures. First, the dunes were reconstructed and revegetated. Later, they were stabilised with geotextile bags and tubes filled with local sand. The shore still experienced damage. To protect the sand dune system and enhance local surfing conditions, the efficiency of a multifunctional artificial reef has been tested using numerical modelling, but it has not yet been constructed (Mendonça et al. 2012).

Maximising multiple-use and eco-friendly features into the necessary maintenance works of existing structures is beginning to evolve from being thought of as an occasionally achieved ‘best practice’ into a regularly achieved standard practice. When new structures are proposed in many countries, including Australia, the environmental assessment process is informed by a mitigation hierarchy centred on avoiding, then minimising, impacts and offsetting only those impacts that remain. Proposals for the installation of new structures are closely scrutinised to ensure deleterious impacts are avoided. ‘Greening’ new infrastructure—no matter how well done—remains an uncertain surrogate, while the impacts of new infrastructure on natural systems are often known (Firth et al. 2020).

The future

To cope with the increasing intensity and frequency of storms and rising sea levels (Bindoff et al. 2007, Gordon 2014), some existing training walls, armoured harbours and groynes are likely to need to be upgraded. In other areas, new coastal protection infrastructure may need to be built. In some instances, the best decision could be to substantially modify existing infrastructure, manage the structure's senescence, or actively remove it.

Sea level rise can result in protection structures being overtopped by water and waves, posing serious hazards to people, infrastructure and coastal stability (DCC 2009). Rising sea levels can also elevate the impact point of storm surges, intensifying their severity and posing additional wave loading to coastal protection structures (Arns et al. 2017, Gent 2019). For example, Shanghai's coastal protection structures are currently up to 6 metres high, which is still inadequate for projected sea levels and continuing land subsidence (Wang et al. 2012). Adaptation measures for coastal protection structures include increase in crest height, the addition of a berm to dissipate wave energy (Dengate et al. 2017), strengthening the inner slope, or the construction of additional submerged structures (e.g. breakwaters) (Gent 2019).

To deal with uncertain future scenarios, coastal protection approaches need to be adaptive, cost-effective, robust and safe (Spalding et al. 2014). Decision-making tools such as cost–benefit analysis, which consider investment and maintenance costs, as well as cost avoidance by installing protection structures, can inform viable long-term management strategies (André et al. 2016).

The general premise of this approach is that protection should take place as long as the benefits from avoiding damage exceed the costs of construction efforts while remembering that 'the value of land is only an imperfect indicator of the true welfare loss to consumers' (Fankhauser 1995). The aim of infrastructure upgrades is often to maximise and promote a range of additional uses for coastal infrastructure, as well as serving its primary purpose. Factors that need to be considered for coastal protection infrastructure upgrades (Bouma et al. 2009) are:

- budgetary constraints
- social and recreational considerations (such as visual impact)
- use opportunities and design criteria
- environmental impacts are also major factors.

For example, commercial cities and ports can adopt direct approaches, such as simply raising coastal protection structures. Resort cities such as the Gold Coast have a strong interest to maintain beaches, lagoons and waterways to maintain tourism industries (Cooper and Lemckert 2012).

Case study 1: Mawsons Breakwater at Caves Beach: never finished, never used

In 1968, Arthur Mawson, a Swansea hotel-keeper and businessman, initiated a bold mining venture, partnering with 'Silver Valley Minerals' (Canberra Times, 31/01/1968).

The venture, first proposed in the early 1950s, involved constructing a harbour a kilometre south of Caves Beach to load and ship coal mined in the Lake Macquarie area (Newcastle Morning Herald and Miners' Advocate, 06/11/1953). The private harbour would handle ships up to 40,000 ton capacity and avoid transport costs and fees incurred using the existing Newcastle Harbour (Mawson 1988).

Construction of the southern harbour breakwater commenced in 1968 using sandstone overburden material from the mine site (Canberra Times, 06/07/1968). By the end of the year, the breakwater extended from the coastline to Spoon Rocks, a rocky reef about 300 metres offshore (Figure 4).

Despite the grand ambitions, the project failed, and the so-called 'Mawsons breakwater', the first privately constructed and owned breakwater in NSW, was never completed. It is now an abandoned structure that is gradually being washed away.

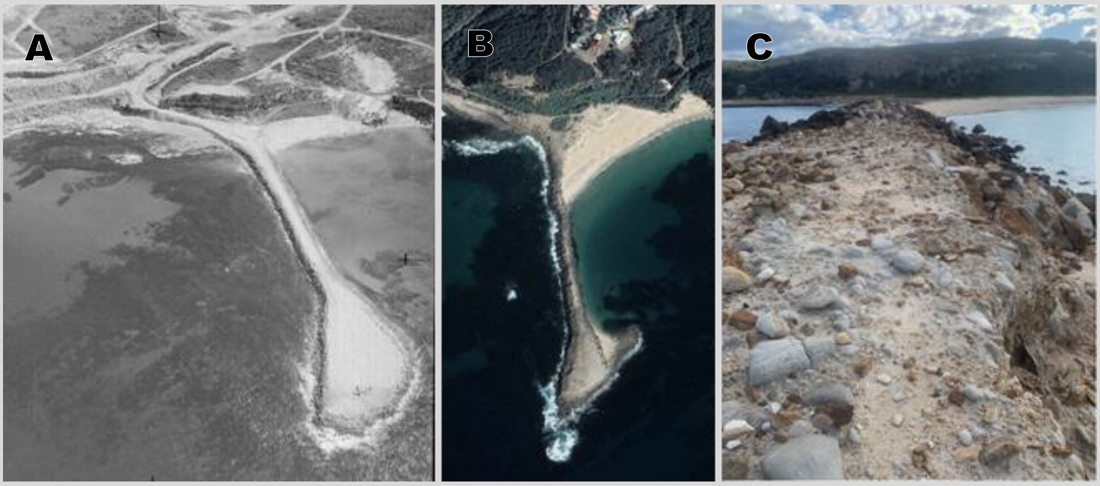

Figure 4. Photos of Mawsons Breakwater after construction in 1970 (A), in 2019 (B) and 2020 (C) Sources: (A) Hilder Collection, Hunter Photobank Newcastle Library; (B) Google Earth; (C) P Dwyer

Environmental considerations

When works started on the breakwater in 1968, the process for considering potential environmental or other impacts was very limited. The mining lease held by Mawson and Silver Valley Minerals extended offshore and included the footprint of the breakwater and the proposed harbour area.

Socio-economic considerations

While there was no process to consider the impact of the proposal on other users of the nearby coastal area, some contemporary records indicate concern among some stakeholders and impacts on other coastal uses. An aerial photo (Figure 5) taken while the breakwater was being constructed appears to show a large sediment plume.

A book on spearfishing published just after the construction started suggests both construction and likely lasting impacts on spearfishing, it notes:

> *'A tiny headland south of Caves Beach called Yondaio is sometimes good [for spearfishing] but unfortunately a breakwater is being constructed from Caves Beach and out to sea over Spoon Rocks and consequently the water is very muddy during construction.' (*Andrewartha and Kemp 1979:23–24*)'*

A compendium of Australian surfing locations notes:

> *'At the far southern end of the beach, if you're very lucky, you'll get to experience the Caves Beach right-hander. Since the construction of the long breakwater this requires a very large swell to get into the area. Once upon a time a shallow bank created consistent barrels breaking left into the southern corner during the winter months. Those days of perfect cylindrical forms are now rare, and often come when they are least expected. Caves Beach needs a giant SE swell and is best in SW to W winds.' (*Warren 1988:91*).'*

Figure 5. Mawsons breakwater during the construction period caused high levels of silt and turbidity in the surrounding waters.
Source: Hilder Collection, Hunter Photobank, Newcastle Library

The abandoned breakwater has been somewhat repurposed as a fishing spot. Occasionally, the sheltered northern side of the breakwater is used for a yearly local ocean swim event. Essentially, a strategy of 'abandonment' is being applied to this orphan structure.

Impacts of large coastal protection infrastructure

Coastal zones contain some of the most ecologically significant ecosystems around the world (Harley et al. 2006) and also provide humans with goods and services that could be worth up to US$27.7 trillion per year (Costanza et al. 2014). These include food provisioning (e.g. seafood), climate regulation, tourism and transport, as well as other recreational and commercial opportunities (Luisetti et al. 2014).Coastal areas and associated landscapes, such as beaches and tidal inlets, are among the most dynamic environments (Hanley et al. 2014). Large coastal protection structures affect ecosystems and natural coastal hydrodynamics and sedimentation processes.

Hydrodynamic and socio-economic impacts

The introduction of hard coastal protection structures can have disrupting influences on ecosystems and on natural coastal hydrodynamics and sedimentation processes, ultimately affecting erosion and deposition rates (Pranzini et al. 2015).

The impact of hard coastal protection structures on socio-economics depends largely on the geomorphology and land use surrounding the area (Haasnoot et al. 2019). Beaches in urban areas, for example, are of immense importance to the tourism industry; protecting them from erosion is a major challenge for coastal management (Alexandrakis et al. 2015). Depending on the characteristics and position of the protection structure, processes such as longshore sediment transport can either starve adjacent beaches of sediment or lead to increased sediment deposition (Hanley et al. 2014; Morad 2014; Nielsen and Gordon 2016; Cooper and Jackson 2019).

Shore-perpendicular breakwaters or jetties for creation of navigable channels, for example, typically enhance sediment accretion on one side and shoreline erosion or retreat on the lee-side of the structure (Noujas et al. 2014) (see case study 2). Similarly, the latter often occurs around seawalls or stabilising rock armour, which fixes the land-water line but concurrently leads to sand scour through increased wave reflection (Cooper and McKenna 2008). As a result, infrastructure that is built to protect coastal assets to favour tourism often leads to the erosion of one of the major tourist attractions. For example, the construction of a number of offshore breakwaters at Norfolk (United Kingdom), has resulted in the favourable formation of salients (slight sediment accretion on the beach sheltered by the breakwater), but secondary management actions to decrease significant erosion between the salients contributed to the formation of tidal tombolos (Figure 6).

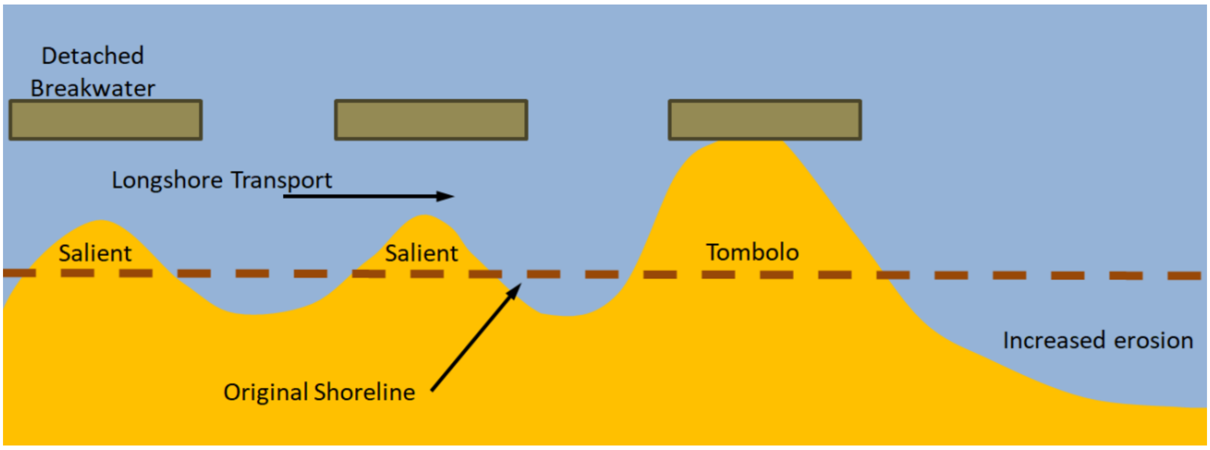

Figure 6. Shoreline change outcomes that can be caused by the installation of offshore/detached breakwaters

In contrast to salients, tidal tombolo formations occur when sediment accumulations connect the beach to the breakwater. This disrupts longshore sediment transport past the breakwaters and exacerbates erosion at beaches down-drift (Thomalla and Vincent 2003).

Several buried terminal boulder walls have been successful in protecting oceanfront buildings on the Gold Coast from erosion. During extreme storm events, parts of this protective structure can become exposed. This results in the temporary loss of beach sand and a decrease in tourism amenity until the beach is re-established. To resolve this, works commenced in 2017 on more than three million cubic metres of beach nourishment along Gold Coast beaches. Approximately 470,000 cubic metres of sand was used to nourish Palm Beach, where an artificial reef was also constructed (Gold Coast City Council 2020). The Palm Beach Artificial Reef, a 60,000-tonne rock reef, was completed in September 2019. It is about 270 metres offshore and is sometimes used by surfers and divers (Gold Coast City Council 2020). The Narrowneck Artificial Reef, built in 1999, was also refurbished during the 2017 and 2018 works. Both these reefs were designed to create salients.

In NSW, a tombolo feature, estimated to cost over $1 million, was proposed as an erosion management tool to limit an erosion front that has advanced upstream into Lake Macquarie since the breakwaters were installed in the 1880s. During the past 50 years, the front has accelerated and is now advancing by more than 5 metres a year (Figure 7) (Walpole and Giles 2007). As a temporary measure, wooden groynes and geotextile bags were installed and these features have reduced the rate of erosion in the channel north of Black Neds Bay. However, erosion caused by entrance channel adjustment remains a threat in several other nearby areas of the lake (S Walpole, pers. comm. 2020). Coastal engineers observe that the need for frequent maintenance to maintain scour protection on the piling foundations of the main road bridge, and the collapse of a foreshore building into the Swansea channel, demonstrate ongoing adjustment. They calculate that it will take hundreds of years for the Lake Macquarie foreshore and channel to stabilise in response to the installation of the training walls in the late 1880s (Nielsen and Gordon 2017).

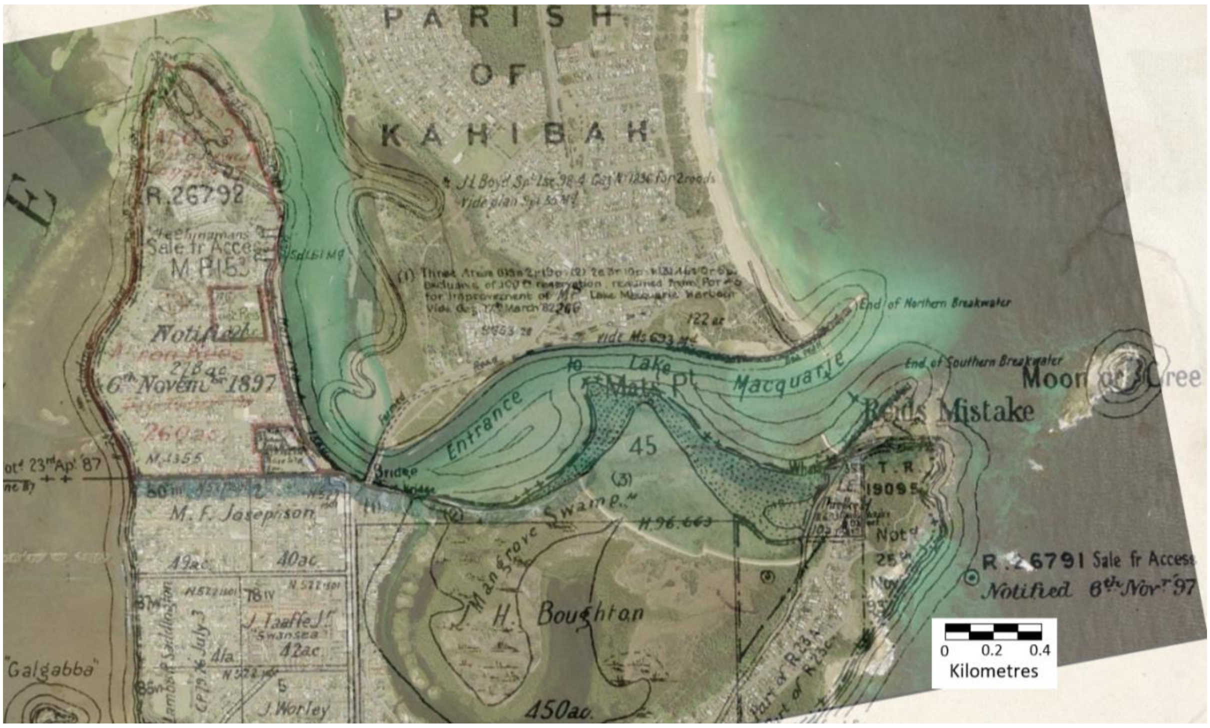

Figure 7. A 2018 satellite photo of the entrance of Lake Macquarie overlain with a 1914 parish map showing upstream movement of an erosion front since installation of the breakwaters

A similar suite of hydrodynamic and socio-economic impacts is also reported by Nielsen and Gordon (2017) at Wallis Lake, where the headstocks of the main bridge were widened to manage scour impacts. The documented impacts in Wagonga Inlet at Narooma, where entrance breakwaters were installed much more recently, appear to be mainly have influenced seagrass, saltmarsh and mangrove vegetation distribution.

Case study 2: Tweed River

The Tweed River is a barrier estuary that is just south of the Queensland–NSW border. In its unmodified condition, natural processes such as northwards longshore drift and the formation of sand bars and islands constrain its value as a navigable port (Hyder Consulting Pty Ltd et al. 1997).

Early European settlers in the Tweed River valley were heavily reliant on coastal shipping for the export of cedar and agricultural goods, as well as the import of goods, such as clothing and hardware supplies (Hyder Consulting Pty Ltd et al. 1997). Construction of training walls and dredging works started in 1891 and were completed in 1904 (Coltheart 1997) (Figures 8A and 8B).

While maintenance dredging continued, an offshore bar developed and navigation problems continued. Two additional training walls were constructed from 1962 to 1965, extending seaward over 300 metres (Coltheart 1997; Hyder Consulting Pty Ltd et al. 1997; Dyson et al. 2001) (Figures 8A and 8C).

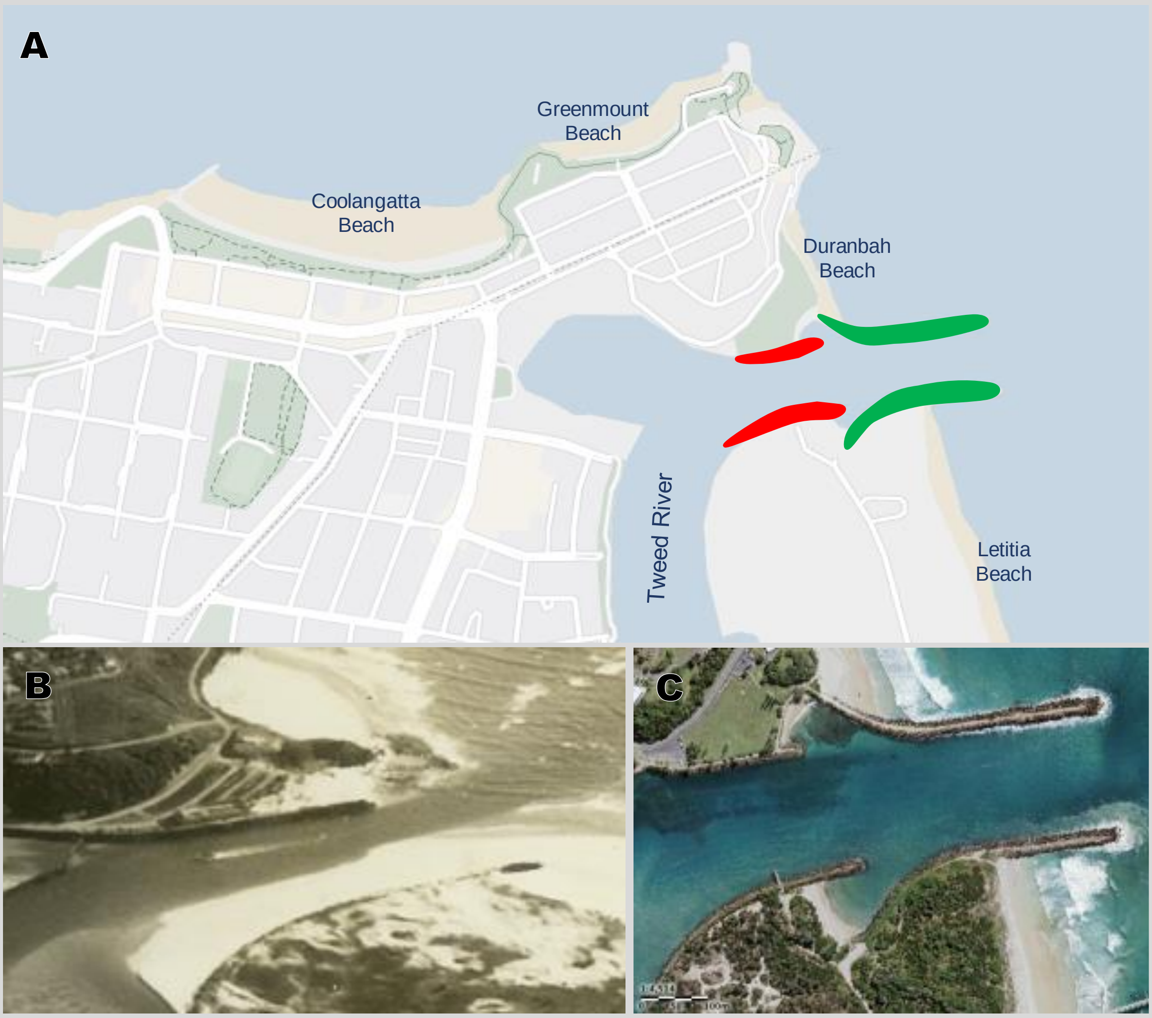

Figure 8. Map of the Tweed River mouth (A), showing the location of training walls constructed between 1890 and 1902 in red (and in B), and the breakwater extension works constructed between 1962 and 1966 in green (and in C)
Sources: (A) Tweed Sand Bypassing Scheme; (B) NSW Crown Lands photo collection; (C) SixMaps

After an initial improvement to navigability, the offshore bar reformed just beyond the extended training walls. The increased length of the training walls caused greater intrusion into the nearshore longshore northward drift of sand. Erosion on the southern Gold Coast beaches immediately to the north of the training walls was further exacerbated following multiple cyclones and major storms in the 1970s, which resulted in a response that involved the construction of groynes and rock revetments and nourishment of Gold Coast beaches (Hyder Consulting Pty Ltd et al. 1997; Dyson et al. 2001). Accretion of sand to the south of the Tweed River entrance, erosion of beaches to the north and sand build-up in the mouth continued to be major issues. Eventually, a permanent sand bypassing system was proposed to mimic the natural littoral drift (Hyder Consulting Pty Ltd et al. 1997; Acworth and Lawson 2012).

The Tweed River Entrance Sand Bypass Project

The Tweed River sand bypass project spans the Queensland–NSW border, so it was necessary for both states to reach an agreement. The ***Tweed River Entrance Sand Bypassing Act 1998*** enabled a joint project that includes sand dredging in the river mouth, as well as the construction of a permanent sand bypassing system. This was collectively called the ‘Tweed River Entrance Sand Bypass Project (TRESBP)’ (Dyson et al. 2001). The sand bypassing system, which was implemented in 2001, pumps sand from underneath a jetty in NSW to beaches in Queensland, and so ‘bypassed’ the Tweed River entrance (Figure 9), maintained navigability of the river, and reduced erosion risk along northern beaches (Hyder Consulting Pty Ltd et al. 1997). The bypassing system has become more effective over the years. It has greatly reduced the frequency of dredging events (Acworth and Lawson 2012). By 2010, the project has cost more than $100 million.

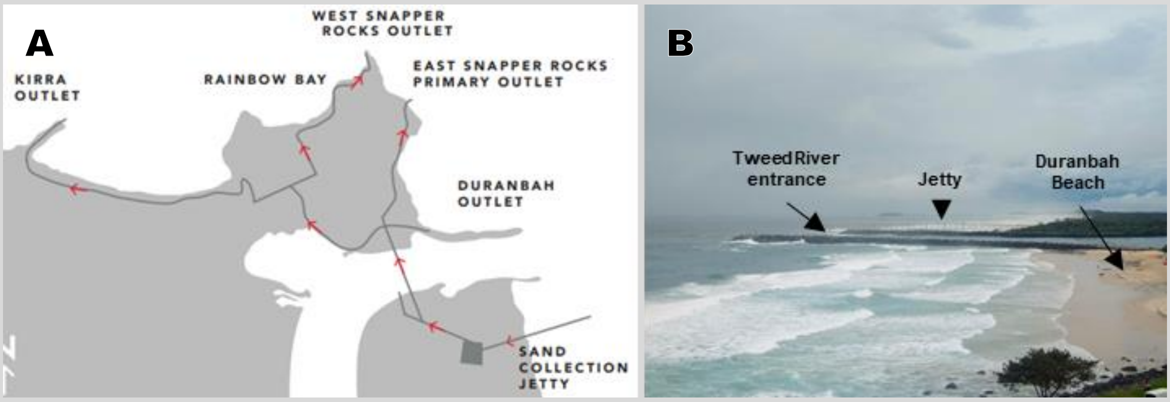

Figure 9. Schematic of the Tweed River entrance sand bypassing system (A). Jet pumps collect sand from a jetty south of the river entrance (B), and the sand–water mixture is then pumped under the Tweed River to multiple outlets
Sources: (A) State of NSW and State of Queensland (2017); (B) L Mamo.

Socio-economic considerations

Community consultation has been important before and during the implementation of TRESBP. The consultation specifically targeted different segments of the community such as businesses, tourists, boat owners, surfers, fishers and divers (Foster et al. 2001). TRESBP has been successful in reproducing the net longshore drift, although the significant widening of beaches has led to a reduced amenity at some beaches, while others improved greatly, especially with respect to surf break quality (Brayshaw and Lemckert 2012). As noted, the project was about ‘creating better beaches, saving foreshore infrastructure, and better navigation. Improving surf quality has been a happy accident’ (NSW Department of Industry – Lands and Comms&Co 2017). The associated socio-economic benefits encouraged development of more local businesses and the tourist industry, leading to increased employment and other financial and social benefits (Hyder Consulting Pty Ltd et al. 1997).

Environmental considerations

Environmental impact assessment studies were carried out prior to construction and ongoing environmental monitoring (Dyson et al. 2001 Lawson et al. 2001). These assessments considered both the direct impact of the works and secondary impacts that can occur remote from the works and some time after the works had been completed. The assessment identified the impact of increased sand supply at Kirra and Coolangatta beaches: the offshore Kirra Reef was smothered and buried under sand within a few years of implementation of TRESBP.

As a result, benthic cover was significantly decreased initially, but increased again once sand volumes delivered by TRESBP stabilised to sand volumes that were more consistent with natural rates of longshore drift (Conacher et al. 2017). In contrast, fish richness before and after the implementation of TRESBP were similar (Conacher et al. 2017).

The assessment also predicted small tidal changes—where the increased river entrance depth allows waves to penetrate further into the river mouth—that might be exacerbated with respect to an increase in storm surges due to climate change (Hyder Consulting Pty Ltd et al. 1997; Lawson et al. 2001; Brayshaw and Lemckert 2012). However, monitoring found that tidal ranges were not influenced by TRESBP. This suggests that TRESBP-related changes in estuary water levels are within the natural variability caused by factors such as drought and floods which can cause changes to mangroves, saltmarshes and seagrasses (Pacific Wetlands Environmental Consultants 2012).

Concluding remarks

Overall, the training wall extension work that started in the 1960s has resulted in a cascade of impacts that have required mitigation, leading eventually to very expensive measures to mimic the pre-extension works state. While meeting the needs of various coastal user groups has been challenging, the channel is now more frequently used by recreational and commercial boats.

This level of service relies on regular dredging (NSW Department of Industry – Lands and Comms&Co 2017). It prompts the question of whether the extension of the training walls and subsequent construction of the bypassing system could have been substituted by a less costly and less interventionist solution, such as a bar-to-beach dredging and a beach nourishment program.

Environmental impacts of large coastal protection infrastructure

Coastal zones contain some of the most ecologically significant ecosystems around the world (Harley et al. 2006). Coastal protection infrastructure can replace and fragment these natural ecosystems (Moreira et al. 2006, Cheong et al. 2013), with subsequent (positive or negative) effects to structure and function at both local and regional levels (Airoldi et al. 2005, Aguilera 2018).

The composition of biota on and around hard coastal protection infrastructure has been studied worldwide, including in Latin-America (e.g. Aguilera 2018), Europe (e.g. Bacchiocchi and Airoldi 2003; Martin et al. 2005; Moschella et al. 2005; Becchi et al. 2014; Airoldi et al. 2015; García-Gómez et al. 2015), North America (e.g. Davis et al. 2002), Asia (e.g. Lam et al. 2009; Dong et al. 2016), and Australia (e.g. Chapman 2003; Chapman and Bulleri 2003; Moreira et al. 2006; Glasby et al. 2007; Jackson et al. 2008; Klein et al. 2011; Green et al. 2012; Mayer-Pinto et al. 2018). This work has focused on benthic taxa (e.g. Chapman 2006; Aguilera et al. 2014), fish (e.g. Burt et al. 2013; Fowler and Booth 2013), infauna (e.g. Martin et al. 2005), and invasive species (e.g. Glasby et al. 2007).

Generally, hard protection infrastructure supports species compositions (e.g. Chapman and Bulleri 2003; Bulleri and Chapman 2004; Lam et al. 2009) or abundances (e.g. Fowler and Booth 2013) that are similar to those of natural structures, but there can be a lower overall species richness (e.g. Martins et al. 2016) or species diversity (e.g. Chapman 2006; Aguilera et al. 2014; Mayer-Pinto et al. 2018).

The heterogeneity in research outcomes suggests that local changes to biodiversity associated with protection infrastructure cannot necessarily be generalised for the following reasons:

- Differences vary according to the type of protection structure sampled (Bulleri and Chapman 2004).
- Biodiversity can vary substantially in time and space (Green et al. 2012).
- Site-specific factors—such as local topography, the age of the structure, hydrodynamic regimes and life-history traits of dominant species—can also influence results (Bulleri 2005).
- The proposed impacts of coastal protection structures can often be species specific (Chapman 2003; Green et al. 2012; Aguilera et al. 2014; Aguilera 2018).

Construction and maintenance

The introduction of new hard habitat into the ocean where it otherwise does not exist can have profound effects on organisms. These include the loss of sandy habitat and, concurrently, the loss of soft-bottom species (Airoldi et al. 2005). In contrast, the introduction of new substrata can also provide additional habitat for reef species that are naturally found on or around rocky habitats. For instance, fish communities around breakwaters in Dubai have similar fish abundances and richness to that of a natural coral reef, although fish community structure differed between natural and artificial structures, which indicates that artificial structures are not surrogates for natural reefs (Burt et al. 2013).

Changed connectivity

Coastal protection structures can influence connectivity by acting as either corridors or barriers (Fauvelot et al. 2009; Dong et al. 2016). Corridors are areas through which genes, individuals or populations flow; barriers are areas that disrupt such flow (Panzacchi et al. 2016). Barriers can obstruct the passage of fishes and bottom-dwelling organisms (Elsharnouby et al. 2012).

The creation of corridors by breakwater infrastructure can disrupt important natural barriers. This can enhance intraspecific gene flow (Fauvelot et al. 2009; Dong et al. 2016), potentially reducing local adaptation and thus decreasing fitness levels. However, such infrastructure might also act as stepping stones for organisms, facilitating the migration of rocky shore species (Dong et al. 2016). A downside is that it could also create novel dispersal routes for invasive species (Airoldi et al. 2015). Factors making artificial habitats unsuitable for native species might also enhance proliferation of opportunistic or exotic species (Megina et al. 2013; Airoldi et al. 2015).

Protection infrastructure can alter the connectivity between aquatic and terrestrial realms by obstructing animal movements between land and sea and by impeding the accumulation of beach wrack (Heerhartz et al. 2014; Dethier et al. 2016). Beach wrack, which is mostly made of macroalgae and seagrasses, has important ecosystem functions, including nutrient cycling, dune formation and source of particulate carbon. Beach wrack supports a complex food web including detritivores, offshore and onshore consumers (Kirkman and Kendrick 1997).

Differing physical attributes

Hard protection infrastructure can act as new habitat, but its physical attributes usually differ from nearby natural reefs. This can impact biotic communities. In general, artificial structures tend to have steeper slopes than the intertidal habitats that are available on natural shores and are often vertically positioned (Chapman 2006). This can result in different species assemblages (Lam et al. 2009), as well as an abnormal increase of species density, or a forced interaction of species that usually do not occupy the same area (Jackson and McIlvenny 2011). This can lead to stronger interactions among species that can have negative effects on physiological properties (Bulleri and Chapman 2010), such as growth and reproductive output (Moreira et al. 2006). Moreover, the steep slopes of artificial structures might decrease water contact-time and enhance flow density. This reduces feeding times compared to natural slopes, which generates smaller individuals (Martins et al. 2016).

Most artificial materials lack microhabitats that can serve as shelter for a diverse range of organisms (Chapman 2003; Edwards and Smith 2005; Aguilera et al. 2014; Aguilera 2018; Bolton et al. 2018). As a result of fewer microhabitats, the abundance of small mobile species and functional diversity on protection infrastructure is lower than on natural reefs (Aguilera 2018). In contrast, hard protection structures can have high levels of spatial complexity at larger scales than natural reef, which might provide shelter for larger species (Aguilera 2018) and favour accumulation of anthropogenic litter in high use areas, such as ports.

Altered hydrological conditions

Open coast

The alteration of hydrological conditions around protection structures can impact species assemblages. Changes affect sediment characteristics such as grain size (Becchi et al. 2014) and water circulation (Frihy 2001). For example, fish numbers can be increased indirectly around structures, which is likely due to improved larval retention caused by decreased water movement (McNeill et al. 1992; Cenci et al. 2011). Similarly, species assemblages can vary significantly between landward (low-energy) and seaward (high-energy) sides of protection structures (Clynick 2006). Alteration of hydrological and sedimentation processes around hard coastal protection structures often necessitates mitigation strategies, such as dredging or nourishing, which can destroy and modify soft-sediment habitats and increase the risk of resuspension of any contaminants present in the seabed.

Estuaries

Hard coastal protection structures can affect estuaries through a cascade of impacts from the changes caused to the entrance condition. Larger estuaries, which are often used for recreational boating and commercial fishing, tend to pose navigability issues because bars and channels are constantly changing. There can also be an increased flood risk to low-lying land when water flow is disrupted by a build-up of sand (Nielsen and Gordon 2017). One response is to stabilise entrances using training walls, whose primary purpose is to constrict or direct tidal water flow to maintain channel depth. Similar to jetties and groynes, training walls can disrupt longshore drift and cause sand to accumulate on one side of the structure and erode further along the coast.

In the estuaries, changes to tidal amplitude, sedimentation patterns, water velocity and salinity can have substantial impacts on adjacent wetlands, including seagrass, saltmarsh, mangrove habitats and freshwater tidal wetlands (Barendregt et al. 2009; Duchatel et al. 2014; Nielsen and Gordon 2016) (see case study 3). For example, changes in tidal dynamics due to entrance training works and maintenance dredging resulted in the upstream movement of brackish water in the Elbe River in Hamburg from 1950 to 2000 (Barendregt et al. 2009).

In Australia, the permanently trained entrance of the Macleay River increased tidal connection throughout the estuary by both creating an unobstructed trained tidal channel and by relocating the estuary entrance to South West Rocks, 13 kilometres upstream from the main natural entrance at Stuarts Point (Figures 10A and B). The associated training wall network also separated some tidal wetlands from most of the tidal flows. This substantially changed the hydrological regime and created backwaters that severely limited sediment inputs to some mangrove habitats (Figure 10C). In other areas, the greater tidal penetration and tidal amplitude caused daily water flows through the estuary and past riverbanks. These factors have contributed to estuary bank erosion. The management response throughout the 20th Century was for the lower reaches of the Macleay River to be heavily armoured with rock in an attempt to stop riverbank erosion.

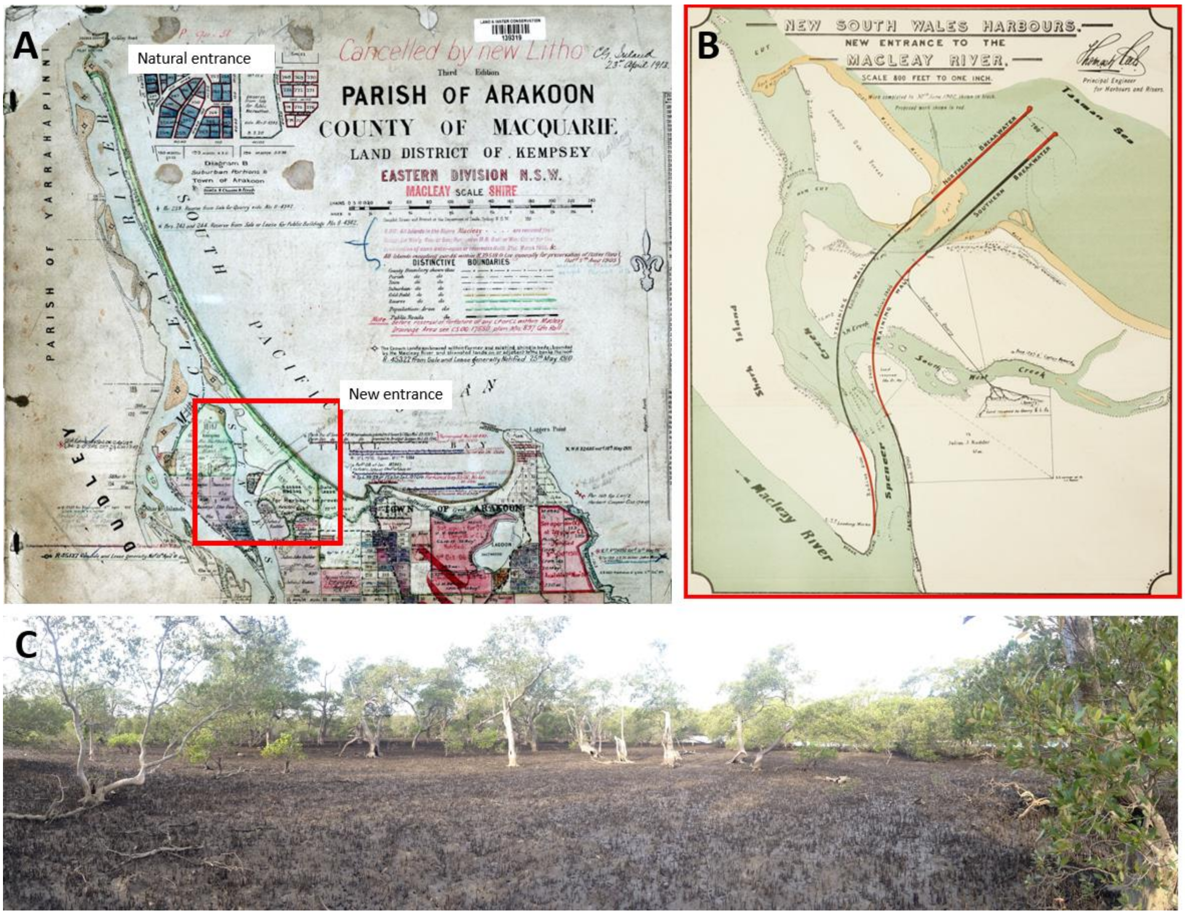

Figure 10. Annotated parish map circa 1900 showing the natural and planned constructed trained entrance of the Macleay River (A). The plan for a trained entrance at South West Rocks is shown in greater detail in a chart (B) from the 1902 NSW Crown Lands Annual Report. C shows erosion at the adjacent mangrove system, which is likely due to secondary impacts from the training walls redirecting away flows and important sediment inputs
Sources: (A) NSW Crown Land Historic Parish Maps; (B) NSW Public Works Annual Report 1902; (C) P Dwyer

Nielsen and Gordon (2008; 2017) note that it will take hundreds of years for some of the trained estuaries in NSW to re-establish hydraulic stability. The changes to estuary bed, banks and habitats can have cascading effects on taxa such as fish as many recreationally and commercially significant fish species in Australia depend on estuarine habitats at some stage in their life cycle.

Grey Mangroves (*Avicennia marina*) appear to benefit from training of estuary entrances in some settings such as ICOLLs. The open entrance provides an opportunity for propagules to enter the lake while the tidal amplitude change increases the intertidal extent and potential habitat throughout an estuary. Some previously submerged areas become exposed with daily low tides creating space that can be colonised by Grey Mangroves. In the former, narrower intertidal zone—a remnant from before the estuary entrance was changed—antagonistic effects can arise where wetland species with greater adaptive capacities, such as the Grey Mangrove, can outcompete species with lower adaptive capacities, such as saltmarsh. Saltmarsh may adapt by upland retreat, but in areas with coastal foreshore development, these migration pathways are generally constrained by landward coastal protection and other infrastructure (Rogers et al. 2016). This so-called ‘coastal squeeze’ is exacerbated with rising sea levels, which reduce the extent of saltmarsh and other wetland species, and the ecosystem services they provide, along modified coasts and estuaries (Giuliani and Bellucci 2019).

Seagrasses in Lake Illawarra have also suffered declines after training wall construction created a permanently open entrance. The increased tidal amplitude causes lower low tides. Seagrasses spend proportionally more time in shallower water or are increasingly exposed where they could desiccate or suffer other stress. Seagrasses, bare substrate and waterway banks have been impacted by increased scour due to increased tidal amplitude (i.e. causing either erosion or increased burial risk due to mobilised sediments). Seagrasses also became more vulnerable to increased turbidity from eroded banks and from wind waves that cause erosion over muddy banks during the lower tides, which reduces light penetration in deeper waters due to the mobilised sediment (Wiecek et al. 2016) (see case study 3).

Case study 3: Lake Illawarra entrance

Lake Illawarra is a coastal lagoon located south of Sydney, which includes a main water body of 36 square metres and a 2 kilometre long entrance channel that forms a connection to the ocean (Water Research Laboratory 2018) (Figure 11A). Historically, entrance condition in the estuary varied between open and closed regimes in response to coastal processes such as sedimentation patterns and scouring (Fig 11B) (Water Research Laboratory 2018), which has resulted in restricted lake–ocean water exchange (Chenhall et al. 1995).

Figure 11. Satellite images of Lake Illawarra (A) and its entrance condition before (B) and after (C) installation of the entrance training walls in 2007
Source: Google Earth©

European settlement around Lake Illawarra has had a significant influence on water quality, sedimentation rates and contamination signatures. Increased sedimentation rates since European settlement were probably due to extensive land clearing and increased rates of erosion and transportation of sediment as a consequence of rural, industrial and urban expansion (Chenhall et al. 1995). Higher sedimentation rates affect navigability, turbidity and nutrient supply, which can affect seagrass beds and sometimes lead to the proliferation of harmful algal blooms (Chenhall et al. 1995). Such blooms occurred frequently in the 1970s (Campbell 2004). Industrial and urban development around the lake also led to metal contamination (Schneider et al. 2015), as well as degradation of water quality through run-off and pollution (Hodgkinson and Valadkhani 2009). These factors, among others, reduced the amenity of the lake area, with the consequence that it became primarily a location for low-income households and public housing (Hodgkinson and Valadkhani 2009).

Lake Illawarra Authority and entrance training

To improve the environment of Lake Illawarra and its surroundings, the NSW Government established the Lake Illawarra Authority in 1988 with the mission 'to achieve a healthy, attractive, well-managed amenity for the benefit of the community' (Lake Illawarra Authority 2013). Many groups in the community believed that constructing a permanently opened entrance to the Lake would enable flushing of the lake, improve navigability and achieve desirable water quality outcomes.

Major works at the lake entrance were constructed in the 1960s, and a southern training wall was completed in 2001 (Lake Illawarra Authority 2013). The entrance began to shoal quickly after construction and dredging works during 2001, which led to the formation of a community action group ('Save Lake Illawarra Action Group [SLIAG]'), voicing the concerns about entrance shoaling and possible impacts on water quality, odour and aesthetics (Lake Illawarra Authority 2013; Eco Logical Australia 2019). After investigating several options, the existing southern breakwater was extended, a northern breakwater was constructed, and dredging works were undertaken to facilitate an initial channel opening (Lake Illawarra Authority 2013) (Figure 11). The permanent opening of the channel has resulted in significant geomorphic, hydrodynamic, and ecological changes (Wiecek et al. 2016).

Socio-economic considerations

Installation of training walls at the lake entrance (Figure 11C) were mainly driven by the community, which values the following aspects of the lake (Lake Illawarra Authority 2013):

- Water quality
- Views/aesthetics
- Native wildlife
- Access to foreshore
- Recreational facilities
- Healthy vegetation

The permanent opening of the channel has increased the ability and consistency with which the lake delivers some of these values in some parts of the lake. However, the outcomes across the lake and over time have not been consistent.

Environmental considerations

The tidal regime in the entrance and lake has changed since the permanent opening of the channel: tidal ranges have increased in all areas (Wiecek et al. 2016). The increased tidal amplitude causes substantially greater water velocities in the lake, and water levels in the lake drain to about 20 centimetres below the water levels that the lake typically experienced before the entrance was modified (Regena 2016; Wiecek et al. 2016). The change in tidal regime and water levels is causing secondary impacts, such as bank erosion, with changes to the distribution of ecological communities, including seagrasses, saltmarsh, and mangroves (Wiecek et al. 2016). ICOLLs usually do not usually support widespread areas of mangroves as these need constant tidal exchange (Wiecek et al. 2016; Williams and Wiecek 2017).

Since the permanent opening of the lake entrance, the total area of mangroves has increased dramatically (Regena 2016; Williams and Wiecek 2017). In contrast, saltmarsh communities have generally declined and will probably continue to do so because (a) increasing tidal ranges will force the landward transition of these communities, which is constrained by human development, and (b) saltmarsh will likely be outcompeted by more adaptable Grey Mangroves (Wiecek et al. 2016).

Seagrass cover has also decreased since the permanent opening of the lake entrance, probably due to a drop in water levels and an associated increased exposure and desiccation at upper distributional limits, as well as increased scour and associated burial of plants in the channel (Wiecek et al. 2016). The effects were not identical across all seagrass species: some species are more and others less susceptible to these changes (Wiecek et al. 2016). This suggests that there might be a long-term regime shift.

The increase in the tidal prism and velocities have changed the lake–ocean water exchange rates, which directly influences water quality. However, water quality can be enhanced only when pollutants and run-offs enter the lake at a lower rate than the water exchange rates. This is a likely reason for water quality having not improved significantly since 2007. This emphasises the need for ongoing improvement to management of stormwater and other pollutants entering the lake (Wiecek et al. 2016), which should improve water quality to a standard closer to that desired by the community. Increased tidal velocities can also influence bed scour, foreshore erosion and sediment transport, which, in turn, can impact foreshore infrastructure, estuarine vegetation, navigability, and recreational activities (Wiecek et al. 2016). In some places, scouring and foreshore erosion have resulted in the loss of sections of foreshore and public assets, including footpaths, jetties and other infrastructure. There has also been a need to reinforce the piles and abutments of the road bridge crossing of Lake Illawarra. As a result of these issues, multiple groynes and seawalls were constructed, although erosion is an ongoing problem (Wiecek et al. 2016).

Figure 12. Satellite images of Lake Illawarra northern bank in 2011 (A) and 2017 (B) showing an area where rapid erosion has taken place since the lake's entrance was trained causing loss of seagrass beds and foreshore amenity and necessitating installation of groynes and armouring to manage erosion impacts
Source: Nearmap

Fauna populations have also changed. The foreshore erosion due to scour has resulted in the loss of nesting areas for threatened bird species such as the endangered Little Tern (*Sterna albifrons* subspecies *sinensi*). In the waterway, commercially prawn fisheries have decreased since the permanent opening of the lake, probably as a result of habitat loss (e.g. seagrasses) and increased flow velocities. Furthermore, it is predicted that more marine fish species will inhabit the lake, which will affect the composition of species and influence commercial fisheries.

Interestingly, sharks and seals have also been observed in the estuary and lake (Baxter and Daly 2010), raising the question of whether the new presence of large predators might influence biodiversity patterns and usage by the community. The lake features a shark exclusion area for swimming. Additionally, the ease of access to the lake might also increase the risk of invasive species and the associated impacts.

Figure 13. Impacts of the Lake Illawarra entrance modifications including loss of Little Turn habitat (A) and modifications required to retain functionality of existing infrastructure such as groynes (B), boat ramps (C), and bridge abutments and piers (D)
Source: P Dwyer.

Towards sustainable large coastal protection infrastructure

The case studies and reviewed literature have demonstrated that the implementation and maintenance of coastal protection infrastructure such as training walls, armoured harbours and groynes can have pervasive effects on the surrounding environment and the associated socio-economic values. In NSW and most other places, the overarching aim of coastal management is to address key threats to the community while maintaining social, economic and environmental benefits (NSW Government 2018) (Figure 14).

Since the 1970s, rising awareness and concerns about anthropogenic interventions in ecosystems has fuelled the need for natural resource management that is more sustainable (Sneddon 2000) . 'Sustainability, at its base, always concerns temporality, and in particular, longevity', essentially meaning that 'anything that reduces a system's natural longevity also reduces its sustainability' (Costanza and Patten 1995). Projected onto a larger time scale, sustainability creates a future setting for humans with benefits similar to the present setting, without major social, environmental and economic compromises (Sneddon 2000). The following section presents sustainable approaches for coastal protection. Some approaches focus more on environmental benefits, and others more on social, cultural and economic benefits.

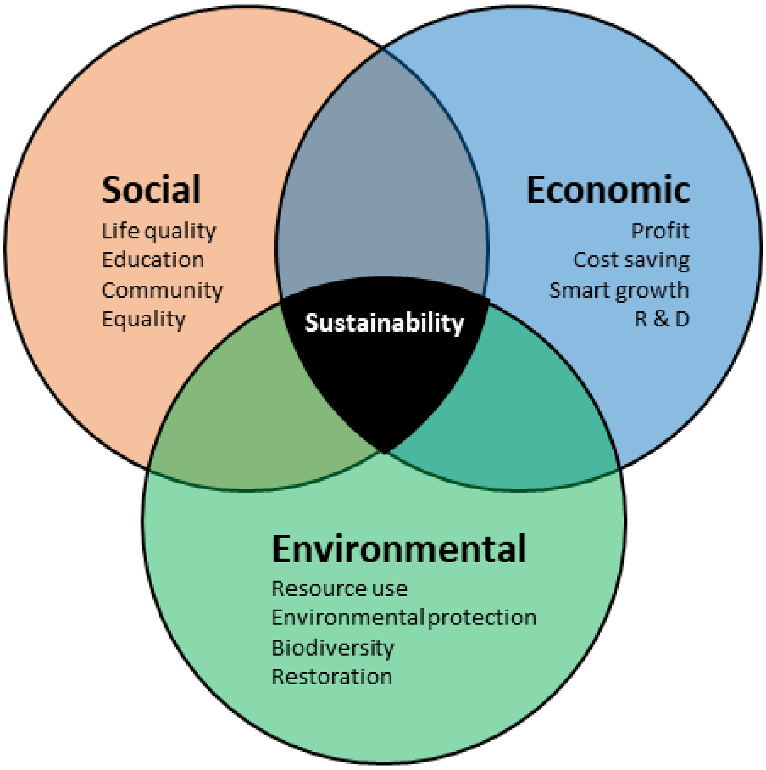

Figure 14. The interplay of factors in sustainable approaches to coastal protection management

Enhancing environmental outcomes

Environmental changes caused by the introduction of hard protection structures affect functional aspects of urbanised coastal systems. These changes have consequences for the provision of ecosystem services on which humans depend (Mayer-Pinto et al. 2018). Negative impacts to ecosystems should be avoided or minimised, and mitigating or restorative measures should be created only where necessary and possible. To maximise environmental outcomes associated with coastal protection, three scenarios must be assessed separately:

- protective infrastructure is not in place
- protective infrastructure is not in place, but planned
- protective infrastructure is in place.

Scenario 1: Coasts without large coastal protection infrastructure

Before installing hard coastal protection infrastructure, a decision framework needs to be used to assess whether coastal protection is the best option and, if it is, whether alternatives to hard infrastructure might be sufficient. Hard coastal protection is associated with a high initial cost and then ongoing and sometimes unanticipated maintenance that must be considered in determining the best management approach (Wiecek et al. 2016).

The Lake Illawarra entrance training project, for example, demonstrated that primary, secondary and tertiary consequences of training works can create scenarios with spiralling and costly mitigation measures, where solutions to problems create new issues that need more solutions, and so forth (Wiecek et al. 2016). Before designing hard coastal protection infrastructure, other, less intrusive options should be considered, such as the adjustment of assets and habitats (i.e. accommodating measures) or the use of 'soft' protective features instead, such as:

- beach nourishment (Hanley et al. 2014; Parkinson and Ogurcak 2018; Stronkhorst et al. 2018)
- dune creation (Hanley et al. 2014) (dune creation approaches are 'nature based' but generally require human interventions)
- the utilisation of ecosystem engineering species (Borsje et al. 2011; Blankespoor et al. 2017; Gracia et al. 2017), including macroalgae, seagrasses, oyster beds, corals, mangroves, and saltmarsh (Piazza et al. 2005; Alongi 2008; Bilkovic and Mitchell 2013; Serrano et al. 2019; Layton et al. 2020) (Table 5).

Soft protective measures rely on their natural ability to attenuate waves, stabilise shorelines and reduce flood surge propagation (Duarte et al. 2013; Bouma et al. 2014; Spalding et al. 2014). While the typical approach is a single habitat solution, multiple-habitat systems have the potential to further enhance flood protection (Guannel et al. 2016).

Advantages of natural protection structures include the ability to self-recover after storm events, the adaptive potential of these natural systems to build elevation in response to sea level rise (e.g. oysters: Rodriguez et al. 2014 or mangroves: Marx et al. 2020), and greater cost-efficiency (Alongi 2008; Narayan et al. 2016). Furthermore, these natural approaches come with a range of co-benefits or ecosystem services that maintain, restore or achieve additional societal, environmental, and economic objectives (Sutton-Grier et al. 2015; Powell et al. 2019).

The NSW Government (2020) investigated the business case for investment into natural infrastructure and its co-benefits and ecosystem services. It found that fostering such an investment shifting would save billions of dollars of public investment and reduce the need for greater government intervention compared with a 'business as usual' scenario.

Natural structures do have limits to their performance as coastal protection. These include a much larger spatial footprint than an engineered structure, slow regeneration after destruction, and their unsuitability for high-energy deep-water environments (Piazza et al. 2005; Spalding et al. 2014; Burt and Bartholomew 2019).

Table 5. Overview of common 'soft' protection techniques applied globally

Approach	Type	Example references
Natural	Combined vegetation	Guannel et al. (2016)
	Mangroves	Duarte et al. (2013), Marois and Mitsch (2015), Blankespoor et al. (2017)
	Saltmarsh	Bilkovic and Mitchell (2013), Duarte et al. (2013)
	Seagrasses	Duarte et al. (2013), Ondiviela et al. (2014)
Nature based	Dune creation	Hanley et al. (2014)
	Beach nourishment	Hanley et al. (2014), Parkinson and Ogurcak (2018), Stronkhorst et al. (2018)
	Oyster shell reef	Piazza et al. (2005)
	Artificial reefs (natural materials, e.g. local rock, metal)	Edwards and Smith (2005), Perkol-Finkel and Benayahu (2005)

Scenario 2: When planning for large coastal protective infrastructure

Where thorough investigations have determined that hard coastal protection is the most effective option, the 'mitigation hierarchy' can be used to limit overall negative impacts to biodiversity (Tallis et al. 2015). It involves four stages:

1. impact avoidance
2. impact minimisation
3. restoration of unavoidable impacts
4. offsetting impacts that cannot be restored.

The mitigation hierarchy prioritises avoidance of impacts to the environment as the most desirable outcome and then minimisation of those impacts that cannot be avoided. Residual impacts should be restored with effective techniques and any remaining impacts should be offset (Figure 15).

All work proposals, structures and actions in work proposals need to be considered in the mitigation hierarchy. Achieving 'avoidance', the first and most effective step in reducing ecosystem impacts might involve reduction or alteration of the infrastructure's footprint, or changing the timing of construction to avoid impacts during certain months (e.g. breeding season of endangered species).

Where impact avoidance is not possible, impact minimisation is implemented in a second step. Here, the duration and intensity of the infrastructure development might be mitigated. For example, noise and pollution reduction could be reduced using well-established mitigation strategies. For species with statutory protection requirements, works could be timed to avoid breeding and other important life stages using an avoidance strategy. For some species, it might be possible to translocate individuals beyond the final development and temporary construction footprints.

Restoration focuses on repairing unavoidable impacts in the temporary construction footprint. Offsetting measures are required for impacts that remain only after the three prior steps have been applied, so offsetting is an option of last resort. Partial or full removal of redundant or orphan items of large coastal infrastructure structure could be an option to consider for offsetting unavoidable negative environmental impacts if a new piece of large coastal infrastructure is required. In all cases for planned infrastructure, early preparation is vital to keep ecosystem impacts to a minimum.

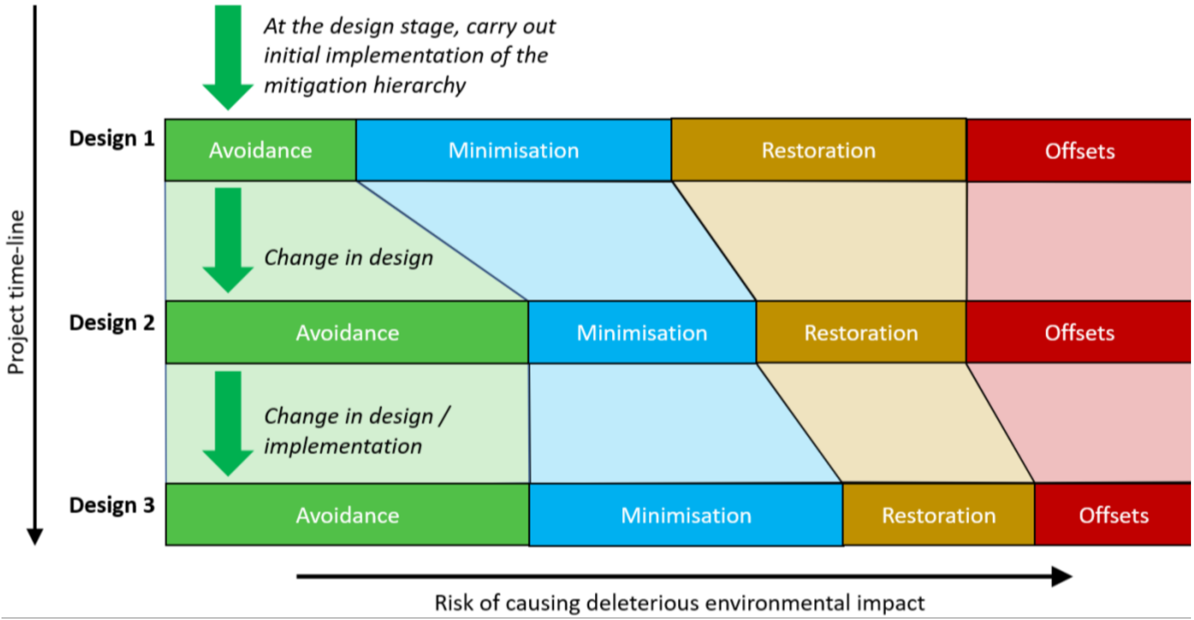

Figure 15. Sequential steps of the mitigation hierarchy used to limit impact to biodiversity from development projects.
Source: Ekstrom et al. (2015)

Ecological engineering: minimise and restore

If impacts on ecosystems cannot be avoided or minimised, then a 'next best' option is to minimise some of the negative impacts on ecosystems and their services (Perkins et al. 2015) by incorporating eco-friendly features into the design phase of newly planned structures. Incorporation of eco-friendly features is commonly known as 'ecological engineering' or 'blue engineering' (e.g. Bugnot et al. 2018), which is defined as 'the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both' (Mitsch 1996). Ecological engineering surpasses traditional engineering-only approaches by incorporating coastal defence, recreation, as well as ecosystem services into one combined method (Cheong et al. 2013).

Decisions about the appropriate type and extent of ecological engineering measures depend on biotic and abiotic characteristics of a particular site (Borsje et al. 2011) as well as on the specific outcome (Davis et al. 2002; Airoldi et al. 2005; Mayer-Pinto et al. 2017).

Eco-engineering for coastal protection can be divided into two general approaches:

1. a hard approach, where hard coastal protection infrastructure is ecologically enhanced through modifications
2. a hybrid approach, which combines hard measures with features of soft protection (Borsje et al. 2011; Moosavi 2017).

Overall, for eco-engineering to be successful, the following factors should be considered:

- enhance habitat availability and diversity
- include different depths (zonation)
- reduce risk of invasive species
- maintain existing water flow, tidal and sediment regimes
- use construction practices that minimise ecological and social disturbance and pollution
- enhance protection measure durability and minimise maintenance (i.e. disturbance)
- reduce shading (e.g. skylights, see Morris et al. 2018b)
- monitor and report outcomes.

Hard approaches

Hard infrastructure options can provide effective habitat structure (complexity, heterogeneity, and scale), which is a critical driver for species diversity and abundance (Beck 2000; Kovalenko et al. 2012).

The complexity of habitats based on hard infrastructure can be enhanced on different scales (Table 6). The macro-scale involves the whole footprint of the structure, the meso-scale the structure's components (e.g. different rock sizes), and the micro-scale structures in those single components (e.g. microhabitats). Microhabitats, such as crevices, pools, and grooves not only increase the surface area but can also facilitate protection against larger predators, as well as against physical forces of water movement in intertidal zones (Coombes et al. 2015; Margiotta et al. 2016; Bolton et al. 2018). Choosing these wave-exposed areas as habitat might appear risky and energetically unwise for a species, yet the benefits, such as organic matter transport (i.e. food resources), seem to outweigh these disadvantages (Tokeshi and Arakaki 2012).

The incorporation of complex and heterogenic biotopes can mitigate the potentially negative impacts of construction works (Iannuzzi et al. 1996) and facilitate the development of rich and diverse marine flora and fauna (e.g. Bulleri and Chapman 2010; Borsje et al. 2011; Toft et al. 2013; Firth et al. 2014b; Ido and Shimrit 2015). For example, water-retaining features, such as artificial rockpools, have been shown to support a higher number of species than the surrounding structure (Browne and Chapman, 2014; Hall et al. 2019). Furthermore, attracting habitat-forming species, such as barnacles, can provide habitat for other species and create a positive feedback-loop (Coombes et al. 2015). Structural modifications might also have unwanted consequences, such as the attraction of non-indigenous species (Bugnot et al. 2018).

Even though these approaches are becoming best management practice, the outcomes are still uncertain. Accordingly, these techniques should generally be considered in the mitigation hierarchy as mitigation actions rather than offset responses.

In addition to habitat complexity, material type can be altered to enhance ecological outcomes. Concrete is one of the most widely used materials in hard coastal protection infrastructure, but it can be unsuitable for marine environments because it has a high surface pH and contains compounds that are toxic to biota. To reduce material costs and enhance eco-friendliness, concrete can be modified by recycling of industrial waste as raw material (Huang et al. 2016) or changing its composition to reduce surface pH and attract more biota (Perkol-Finkel and Sella 2014).

Growth of marine biota on concrete can deteriorate the material's surface, although biogenic build-up can also contribute to the overall weight and bond between structural elements and therefore enhance stability, as well as create a thick layer and protect the concrete from chloride attacks and chipping (Perkol-Finkel and Sella 2014). Concrete can also affect larval settlement, growth and survival (Mos et al. 2019), and it has the potential to mitigate future ocean acidification and temperature effects (Davis et al. 2017). Other materials commonly used in hard coastal protection projects include gabbro, granite, sandstone and wood (Burt et al. 2009). The type of material used can affect the recruitment rates of benthic species such as corals (Burt et al. 2009), ascidians (Chase et al. 2016), and turfing algae (Davis et al. 2017).

Table 6. Overview of common 'hard' ecological engineering techniques applied globally

Type	Example references
Artificial reefs (concrete)	Harris (2009)
Alternative material (e.g. modified concrete)	Huang et al. (2016)
Single surface texture enhancement (e.g. grooves, pits and dimples)	Firth et al. (2014b), Fredette et al. (2014), Liversage et al. (2017), Loke et al. (2017), Strain et al. (2018), MacArthur et al. (2019), Ushiama et al. (2019)
Complex surface texture enhancements (e.g. ECOncrete®)	Ido and Shimrit (2015)
Combination alternative material/surface texture	Perkol-Finkel and Sella (2014)
Shelves (intertidal or subtidal)	Fredette et al. (2014)
Intertidal rock pools (e.g. flowerpots, concrete casts, drill-cored)	Browne and Chapman (2011), Browne and Chapman (2014), Firth et al. (2014a), Firth et al. (2014b), Evans et al. (2015), Firth et al. (2016), Morris et al. (2017a), Morris et al. (2017b), Morris et al. (2018a)
Varying rock size	Firth et al. (2014b)

Hybrid approaches

Ecosystems engineers, such as mangroves, saltmarsh or seagrasses can serve as foreland protection to minimise forces on hard structures (Borsje et al. 2011). This enables reductions in structure bulk and density and simultaneously increases the structure's environmental suitability (Wiecek 2009).

Hybrid approaches often involve designing a structure that permits intertidal plants, such as mangroves and saltmarsh, to establish in a designed sheltered zone where erosion is generally arrested and accretion fosters the establishment of protecting vegetation. For example, in Chesapeake Bay, a combination of planted saltmarsh and slightly offshore placed rock sill (so-called marsh-sill) was used to protect riverbanks from erosion and inundation, as well as preserve intertidal areas and provide hard substrata for epibiota (Bilkovic and Mitchell 2013). A similar approach provided successful results in the Richmond estuary at Ballina, where installation of a rock fillet created suitable conditions along the bank for natural recruitment of Grey Mangroves, River Mangrove and saltmarsh on the riverbank (Figure 16).

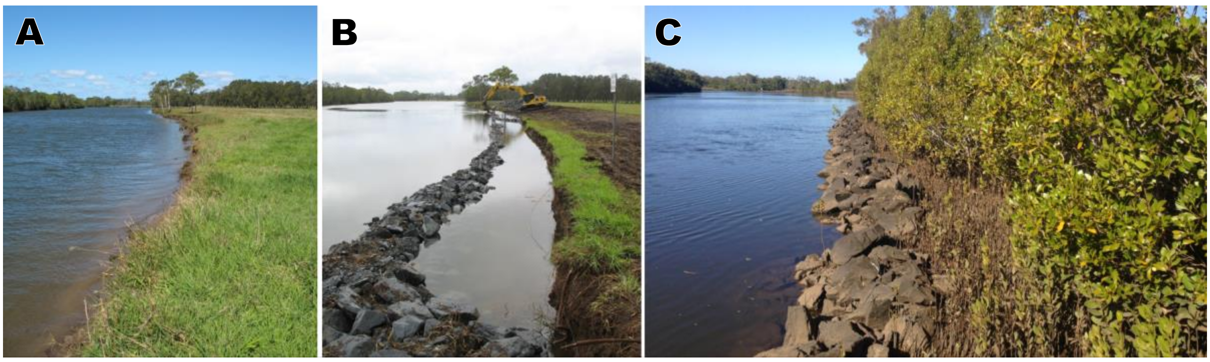

Figure 16. Photos of rock fillet works on the Richmond River estuary using a hybrid approach to the protection of waterway banks from erosion before the rehabilitation project in 2007 (A), during the project in 2008 (B), and in 2018, 10 years after the project had been completed (C)
Source: Charlotte Jenkins

Scenario 3: Where large protective coastal infrastructure is already in place

Infrastructure that fulfils its intended purpose

Similarly, to newly planned protection infrastructure, existing structures can be retrofitted using eco-engineering techniques (see previous section). This is especially of interest as large areas of the coast have already been hardened (Chapman and Bulleri 2003; Aguilera 2018). For example, seeding of existing hard protection infrastructure with native habitat-forming species (e.g. kelp, corals, oysters) could enhance its ecological value (Mayer-Pinto et al. 2019). The infrastructure itself can also be modified to maximise the spaces available for certain species. For instance, a deliberately convoluted breakwater toe and rock scree habitats were incorporated into the Coffs Harbour northern breakwater upgrade to maximise the sand–rock interface area used by the critically endangered marine alga *Nereia lophocladia* (Mamo et al. 2018) (see case study 4).

Where protection infrastructure needs upgrading because it has deteriorated or to withstand climate change-related phenomena such as sea level rise and storms, the simultaneous incorporation of eco-friendly features could significantly reduce costs and enhance sustainable resource management (Fredette et al. 2014; Main et al. 2016). A breakwater in Cleveland, USA, for example was due for repairs. Instead of using standard smooth concrete block only, the surface texture of some of the blocks was modified with grooves and dimples (Fredette et al. 2014).

Case study 4: Coffs Harbour breakwater upgrade

Coffs Harbour in northern NSW has a foreshore that is dominated by two large breakwaters that create a marina and sheltered embayment for a jetty (Figure 17). The Coffs Harbour northern breakwater was originally built in 1924. It is the main protective feature for the marina that hosts Coffs Harbour's commercial fishing fleet, commercial tour operators, and many recreational yachts and boats (GHD 2015).

The breakwater is also the only land access to Muttonbird Island (Figure 17), a nature reserve and an area of Aboriginal cultural significance. The water north of the breakwater is part of the Solitary Islands Marine Park and is subject to special legislative requirements that provide a high level of protection for biological diversity. The breakwater is heavily used by pedestrians as more than 100,000 people using the structure to access Muttonbird Island every year (Dengate et al. 2017). The breakwater has long been subject to regular wave overtopping during storms (Figure 17B) and this can be life-threatening and damaging to infrastructure and vessels (Jayewardene et al. 2010).

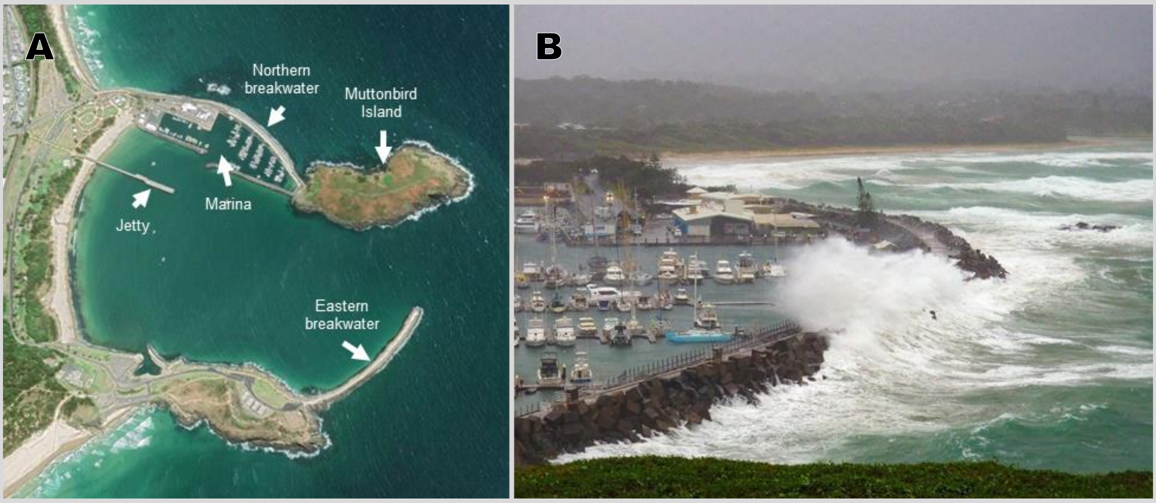

Figure 17. Location of the northern and eastern breakwaters in Coffs Harbour (A) and waves overtopping the northern breakwater during a storm in 2006 (B)
Sources: (A) Google Earth© and (B) H Werner

Breakwater construction and upgrade

To increase the level of protection to people and property, the NSW Government proposed an upgrade of the existing breakwater in 2017 to 2019. Several upgrade options were considered, and technical, engineering and economic factors led to the implementation of an option that widened the toe and increased the crest height of the structure (Main et al. 2016).

Socio-economic considerations

The breakwater is socio-economically unique in NSW in a number of ways, including: highest public visitation rates, regional tourist destination, public access to observe marine fauna such as shearwaters (colloquially called mutton birds), whales, dolphins and turtles, and proximity to diving and fishing sites (Dengate et al. 2017). In response to the numerous social and aesthetic constraints and high levels of public interest, an extensive stakeholder and community consultation took part throughout the design and construction phase and it was found that the community's priorities included (Main et al. 2016):

- maintaining aesthetics and pedestrian views
- providing recreational assets
- improving tourism prospects
- avoiding impacts on the marine environment
- improving community safety
- reducing the likelihood of property damage
- providing emergency access during construction.

Community consultation revealed 'a disconnect between the project's primary objectives and the community's expectations' (Main et al. 2016). The community was in favour of creation of an artificial reef, but cost-benefits were uncertain and led to the implementation of a 100% hard engineered option. The process did, however, begin to highlight how communities have co-opted breakwaters for a wide range of multi-use functions beyond the structure's primary purpose.

Environmental considerations

When the environmental assessment for the upgrade works started, the Coffs Harbour northern breakwater and the immediately adjacent reef was the only known habitat worldwide for a critically endangered species, the marine brown alga *Nereia lophocladia* (Yee et al. 2017), which was listed under the NSW *Fisheries Management Act 1994*. The alga was first discovered in the late 1880s at Port Phillip Heads, Victoria, and had been sporadically recorded at Coffs Harbour, NSW. Historically, the alga's extent was probably reduced by the initial construction of the breakwater in 1924, which has led to altered sand movements and burial of subtidal rocky habitat favoured by the species (Yee and Finley 2015b).

The planned upgrade of the breakwater involved raising and widening the structure—this posed a serious extinction risk to the only known population of *N. lophocladia* at the time. Specific assessments for impacts on the threatened species informed the development of redesigns for a modified upgrade option to minimise impact on *N. lophocladia* (Yee and Finley 2015a,b; Mamo et al. 2018). In addition to a reduced toe width, sections of the breakwater were eco-engineered to make habitat more suitable for *N. lophocladia*, by (a) promoting formation of sand scour holes and (b) creating a complex habitat on the sand-rock interface (Dengate et al. 2017, Mamo et al. 2018).

The mitigation strategy also included offsite (i.e. cultivation) and onsite (i.e. translocations) protection measures, as well as a multi-annual monitoring program for the species (Kelaher 2016; Kelaher 2017; Kelaher and Mamo 2018). In the course of the monitoring program, the alga has been found along the breakwater and adjacent reefs every year since, as well as at new locations (Mamo et al. 2019).

Large coastal infrastructure without a primary purpose

Where coastal protection infrastructure has deteriorated or no longer serves its intended purpose, it could be appropriate to abandon or remove the infrastructure and revert to a natural shore (Chapman and Underwood 2011). There are constraints on removal. There might be a need for the room to flood land or realign or move protection infrastructure (Hughes et al. 2009).

Removing protection infrastructure can resolve long-term erosion problems. Large breakwaters, groynes, seawalls and riprap structures have been successfully shortened, moved or removed to reinstate intertidal and wetland species assemblages and other ecosystem services (e.g. Hughes et al. 2009, Toft et al. 2013, Toft et al. 2014).

Some examples include:

- Southerly Street groyne on Sandringham Beach, Port Phillip Bay: the groyne was shortened in 2018 to improve sand movement in the Bay (Figure 18) (Cardno Victoria Pty Ltd 2016).
- Townsville Breakwater, Queensland: a 100-metre section of breakwater was removed in May 2016.
- Laggers Point Breakwater, South West Rocks: works began on this breakwater in 1889 with the intention of creating a 1500-metre long breakwater extending into Trial Bay to form a harbour. Severe storms washed away hundreds of metres of work, and the project was abandoned in 1903. The breakwater has gradually deteriorated since.
- South Wall at Ballina, NSW: sections of the wall were not maintained. It is approximately 80 metres shorter than it was when construction of the extension finished in the 1960s.
- Breakwater at Flushing Bay, New York: the 600-metre breakwater south-east of the airport was removed in the late 1990s to improve flushing in the bay.
- Port Geographe, Western Australia: the protection structures built as part of the initial marina and canal development in the 1990s caused serious seagrass wrack accumulation and increased coastal erosion on adjacent coastal areas. Apart from removal of the breakwaters and groynes, a new breakwater and seawall were constructed between 2013 and 2014. Additional project outcomes included dredging of the new entrance channel, construction of a coastal lagoon, importation of additional sand to establish new beach profiles, installation of a below ground bypassing pipeline, and extensive landscaping (Pattiaratchi et al. 2015).
- Kirra Main Groyne, Queensland: the groyne was built in 1972 and shortened by 30 metres in 1996 after widening of the beaches due to the commencement of the Tweed Sand Bypass project. It was reinstated to its original 180-metre length in 2013.

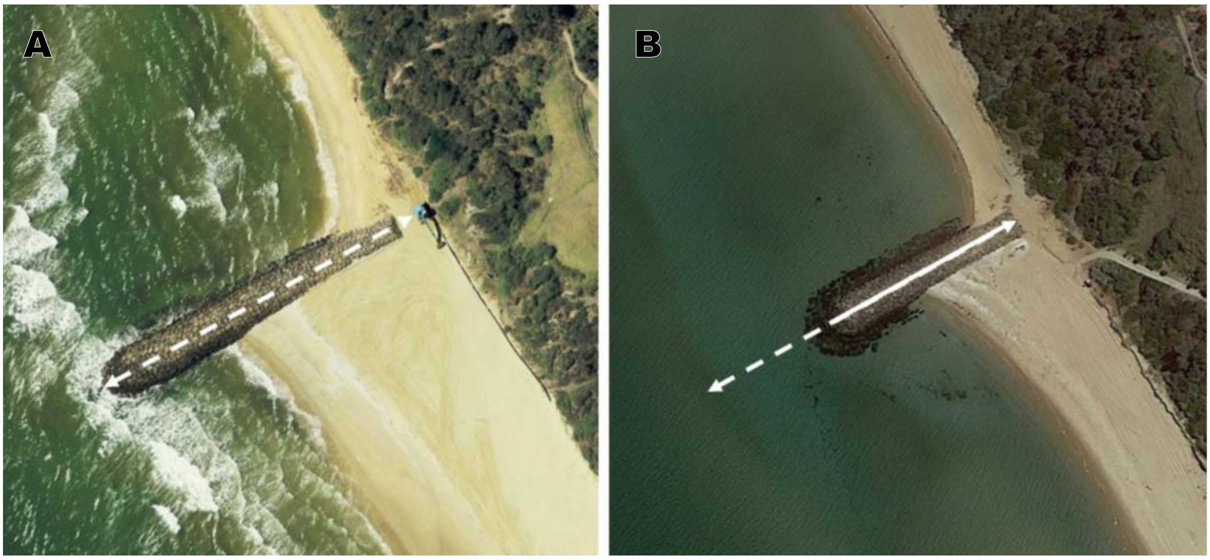

Figure 18. Satellite image showing the Southerly Street groyne in Port Phillip Bay before (A) and after (B) it was shortened in 2018
Source: Google Earth©

Planned removals are proposed at:

- Long Beach offshore Breakwater, California: the East San Pedro Bay Ecosystem Restoration Feasibility Study (US Army Corps of Engineers 2019) is the latest step in a 25-year-old debate investigating the potential removal. It is a 3.5-kilometre long structure built in the 1940s to support construction of navy ships during World War II. Use of the shipyard waned until its closure in 1997. The need for the breakwater has been questioned ever since. It is suggested that removing the offshore breakwater would improve nearshore circulation, improve water quality, and provide surf on the beach. The local surf group is a key stakeholder supporting the removal.
- Chippewa Park Breakwater at Thunder Bay, Canada: proposed removal of a breakwater to improve water circulation and quality in the bay area. Preferred options include the remainder of a thin layer of rock to avoid loss of fish habitat, as well as rock armour and vegetated dunes along the shoreline. Community consultation is currently underway (Schwar and Angus 2020).

Enhancing social outcomes

Multi-use opportunities for breakwaters and other infrastructure

The St Kilda Pier case study demonstrates that eco-features, such as the penguin colony, can be a quadruple bottom line (environmental, social, cultural and economic) reason for incorporating multiple-uses features into a breakwater structure. There are few published reports of recommendations for multiple-use opportunities for breakwaters. As part of this project, an audit of existing NSW breakwaters structures informed the development of multi-use and eco-feature guidelines for breakwaters upgrade works (Appendix 1).

The benefits of including multi-use elements are reported to be as follows.

Increase public safety

Increasing access to the sea can hold some risk, and public safety should always be considered in any design (Yahiro et al. 2008). Maximum safety can be achieved by:

- restricting access to infrastructure under high wind or large swell conditions (Watterson and Driscoll 2011)
- installing of floating devices
- installing of safety signage
- installing of fences and handrails
- installing of lights (Yahiro et al. 2008; Kaftangui et al. 2019)**,** ideally with shields to minimise unwanted impacts on animals
- installing of security cameras, that could also be used for research (e.g. public use of structure, weather, maintenance requirements) or recreation (e.g. surf cam).

Improve public access

Public access can be improved by:

- restricting car access (installation of barricades and gates)
- providing enough parking in adjacent areas
- building clearly marked paths for pedestrians, joggers and bicycles (Kaftangui et al. 2019) (Figure 22A)
- improving disability access using ramps and wide pathways (Byron Shire Council and Bluecoast, 2019, Port Macquarie-Hastings Council 2019) (Figure 22B)
- offering shuttle services (e.g. eco-cars, golf carts) (Kaftangui et al. 2019).

Attract tourists and locals and enhance recreation

Recreational opportunities for tourists and locals can be improved by providing:

- rockpools for swimming
- platforms for ease of water access and egress (Figure 22D)
- emergency access safety stairs
- showers and changing rooms (Byron Shire Council and Bluecoast, 2019, Port Macquarie-Hastings Council 2019) (Figure 22B)
- artificial reefs to enhance fish habitat (Mead 2009)
- artificial reefs to enhance surfing conditions (Mead 2009)
- promotion of local businesses (e.g. marine supplies, boating maintenance, sightseeing tours, sport fishing charters, snorkelling tours, retail) (Biondi 2014)
- business opportunities for rentals of boats, kayaks, surf skis and surfboards
- playgrounds for children
- exercise machines
- photo points at scenic spots and encourage people to use certain hashtags to increase social media presence of nearby towns and cities
- picnic areas
- tables for games (e.g. chess, table tennis).

Increase overall use experience

Overall use experience can be improved by:

- providing benches/smooth rock for seating (Yahiro et al. 2008, Kaftangui et al. 2019) (Figure 22E)
- providing enough restrooms (Biondi 2014)
- providing shading (e.g. canopies, umbrellas) (Kaftangui et al. 2019)
- including landscaping, preferably native plants (also provides shading) (Office of Environment and Heritage 2012; Kaftangui et al. 2019)
- enhancing connectivity to nature through smooth surfaces (‘fluidity’) (Kaftangui et al. 2019).

Maintain sea views

Hard coastal protection infrastructure is often built high to prevent flooding and wash from waves, but it can disrupt desirable views of the sea. Being able to watch the sea is not only important for recreational purposes, but it might be vital for communities that rely on fishing as their main income and need to assess wave conditions (Kimura 2016). Sea views can be maintained by:

- adding viewing platforms or elevating the crest surface (Byron Shire Council and Bluecoast 2019) (Figure 22C)
- adding an extra crest wall made out of glass (Gent 2019)
- installing binoculars.

Enhance fishing experience

Land-based fishing is often the only affordable option for fishers. Protection infrastructure can be modified to include fishing platforms and fish cleaning tables (Derbyshire 2006) (Figure 22F), which should provide suitable access and ease of use, as well as incorporate some or all of the following features (Derbyshire 2006):

- lighting for night-time fishing (this could attract fish, but it might adversely affect biota such as turtles or birds)
- rod holders
- cleaning stations with water supply (Figure 22G)
- signs to promote recreational fishing education (including size and bag limits, and measuring station)
- disabled access
- shade and safety rails for safe fishing
- artificial reefs to provide additional fish habitat.

Recognition of social and cultural values

Social and cultural values give users additional value from use of an area and can be promoted through:

- interpretive information and signs (Figure 22C)
- community activities (e.g. Figure 22H)
- sculptures and other art installations (Kaftangui et al. 2019).

Reduce costs

Infrastructure management can be expensive. Ways of reducing costs include:

- reducing net-energy use (e.g. solar-power, wave-energy-converters, kinetic walkways)
- using recycled raw materials
- using LED for lighting (Shoreham Port Authority 2017)
- providing different bins for different types of waste (e.g. recycling, green waste)
- using biodegradable materials (Shoreham Port Authority 2017).

Figure 19. Examples of multi-use features implemented into existing hard coastal protection infrastructure (Australian unless otherwise stated): (A) Mackay Breakwater—clearly marked and divided paths for cars, bicycles and pedestrians, as well as allocated parking (source: nqbp.com.au); (B) Flynn's Beach seawall—ramp/stairs for inclusive beach access, as well as provisioning of showers (source: Port Macquarie-Hastings Council (2019); (C) Newcastle Breakwater—viewing platform and interpretive signage for shipwreck (source: P Dwyer); (D) Sunabe seawall, Japan—water entry and exit points for swimming, snorkelling, diving and fishing (source: divebuddy.com); (E) Cronulla seawall—innovative seating spaces (source: m.designls.com); (F) Tomaree Head revetment—platforms for fishing and sea views (source: nationalparks.nsw.gov.au); (G) San José del Cabo marina, Mexico—fish cleaning tables with water supply (source: Derbyshire (2006); and (H) Nambucca Heads Breakwater—rocks painted by the public (sources: austracks.com.au)

Integration

Successful coastal management not only considers environmental processes and economic interests, but also the views and involvement of locals, tourists and stakeholders (Saengsupavanich 2013; Antunes do Carmo 2019). Enhanced user satisfaction through the creation of public spaces and offer of services and products has the potential to achieve net positive outcomes from coastal protection infrastructure (Biondi 2014). Properly designed public spaces should be 'plentiful, accessible, unique and well designed' and have the ability to bring communities together (Kaftangui et al. 2019). Satisfying all stakeholders is challenging, but there is evidence that suggests that most people are in favour of multi-use coastal protection infrastructure that incorporates social, economic and environmental considerations (Evans et al. 2017).

Permitting the public to access hard coastal protection structures such as breakwaters comes with safety risks, such as overtopping during large swell (Watterson and Driscoll 2011). However, the potential of such structures to attract tourists and increase the amenity value of a coastal area might outweigh such risks, especially when safety measures can be employed to reduce risks to acceptable levels. For example, the breakwaters at Port Kembla and Coffs Harbour have lockable gates to manage access along the breakwaters in large swell conditions.

Much of the activity around retrofitting multi-use features into existing hard coastal protection structures or designing new structures with these features generally goes unreported in the scientific literature (with some exceptions, e.g. Yahiro et al. 2008; Saengsupavanich 2013; Kaftangui et al. 2019). Several studies have looked at multifunctional marinas. Such options have lessons for hard coastal protection structures, due to their similar setting and layout (often include breakwaters).

Generally, multi-use options tend to be more oriented towards creating socio-economic benefits but might also consider environmental and ecological factors. For example, offshore submerged breakwaters can function as a protective feature while simultaneously enhancing surf conditions. They can also create new habitat for reef species that attracts fishers, divers and snorkellers (Mead 2009). An Australian example that uses geotextile sand containers is Narrowneck Reef on the Gold Coast (Figure 19). It was built in 1999 and reported to have had some success in creating both a surf break and a salient, but it was later found to have a net erosive trend (Blacka et al. 2008). In 2017 an additional 70 geotextile bags were deployed at the site.

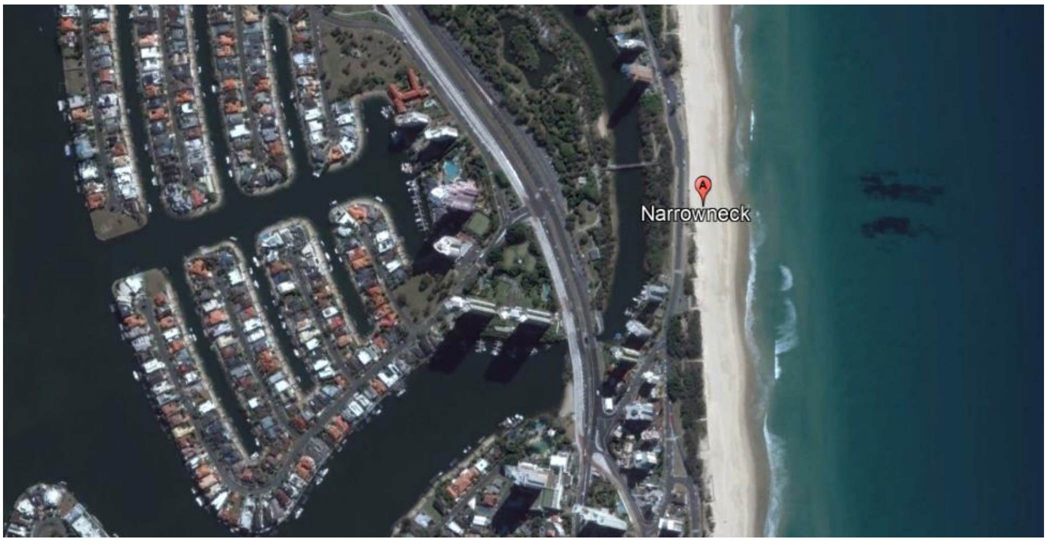

Figure 20. Satellite image showing location of the nearshore artificial Narrowneck Beach, Gold Coast Source: Google Earth©

Another example of incorporation of multi-use features into coastal protection infrastructure is the St Kilda Pier and breakwater in Melbourne, Victoria. This well-known site attracts more than 800,000 visitors each year (Parks Victoria 2020). One of the pier's key attractions is the opportunity to watch Fairy Penguins return to their nest colony each evening (Figure 20).

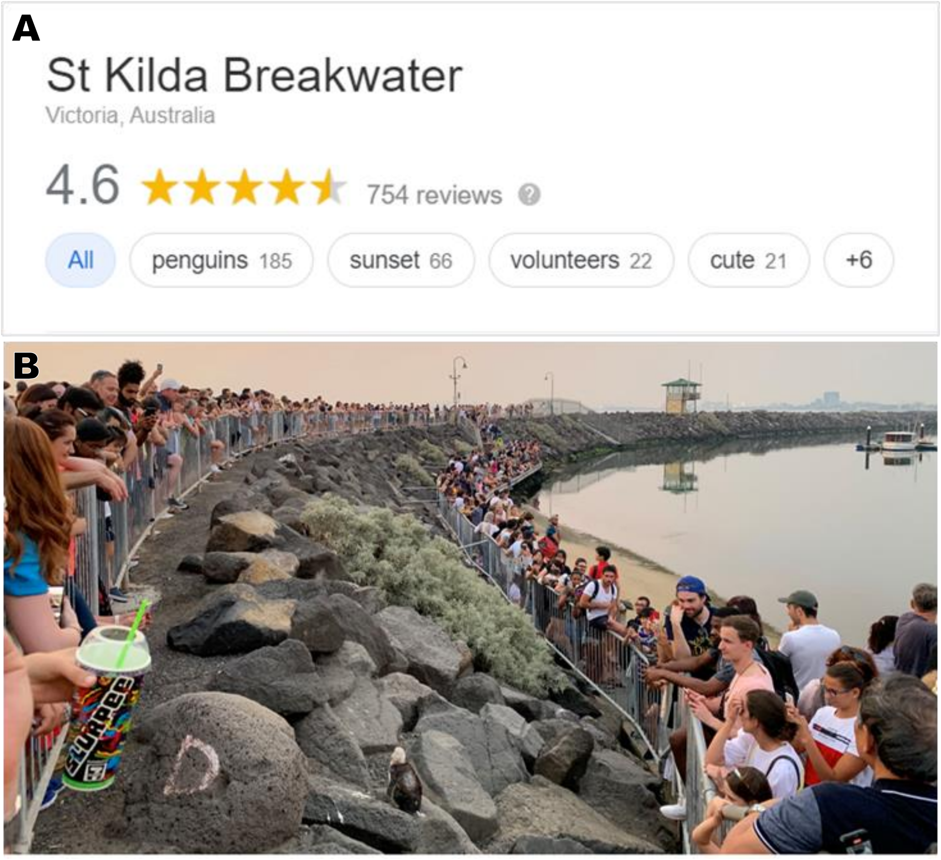

Figure 21. A Google review of St Kilda Breakwater (A) and the large crowds that visit the breakwater to watch the penguins return to their rockery each evening (B)
Sources: (A) Google and (B) Mingye Li

The St Kilda Pier structure is currently being upgraded. It is about 50 years old and reaching the end of its design life. The $50.3 million upgrade followed an extensive public consultation phase and is due to be completed by 2023. The works will provide improved penguin viewing with tiered seating and all access viewing of the penguins. The structure also has a regulated ‘no access’ area to provide habitat opportunities for birds, seals and other wildlife. Additionally, the curved breakwater has been designed to provide a better swimming area for families (Figure 22).

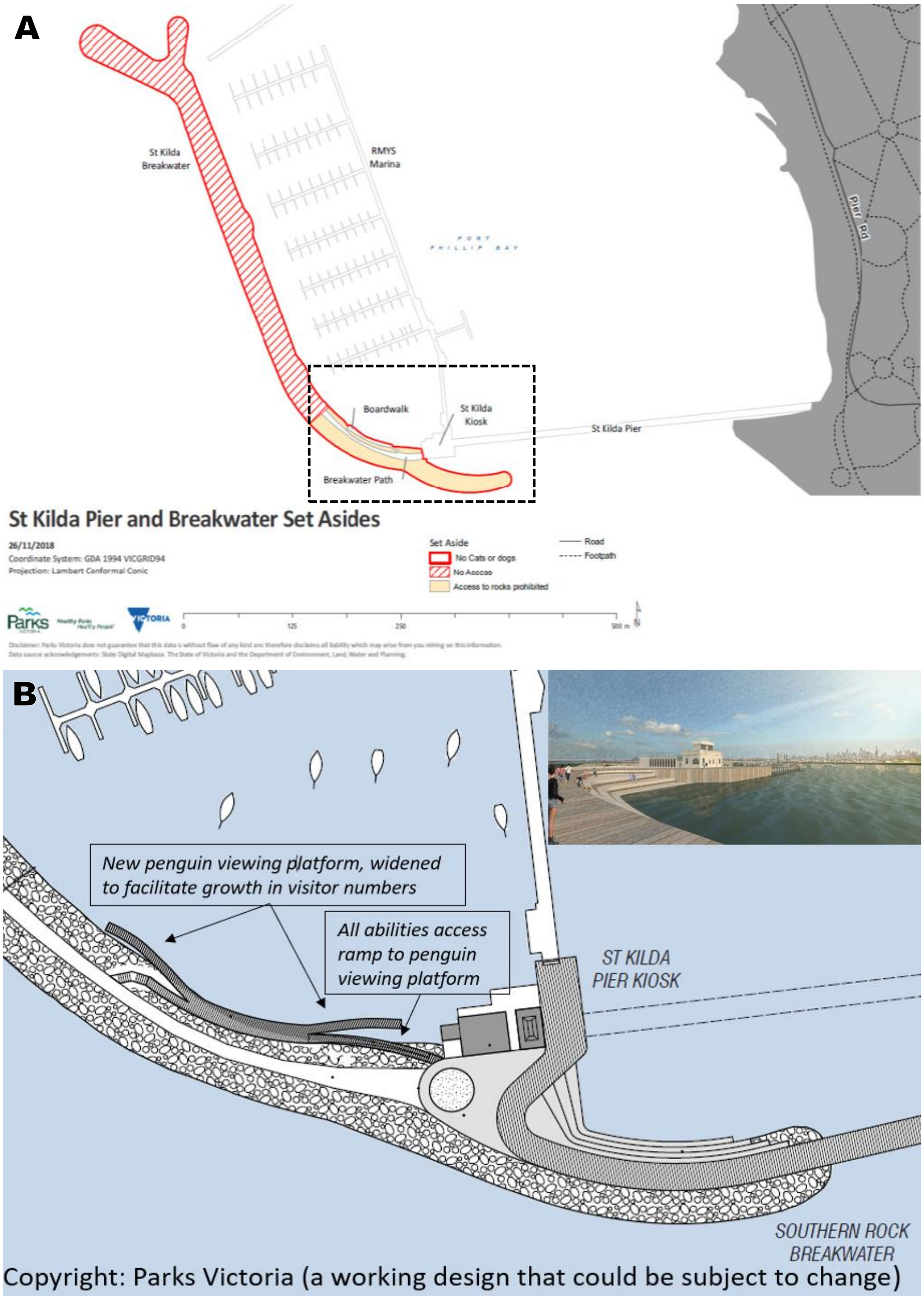

Figure 22. Set aside areas on the St Kilda Pier and breakwater in Melbourne restricted access to certain areas to avoid wildlife disturbance (A) and detail of proposed upgrade works that will improve seating for penguin viewing (B)
Source: Parks Victoria website

Where to from here?

Initially, the primary goal of coastal protection infrastructure was to ensure safety, improved navigation and asset protection (Antunes do Carmo 2019). As a result, most existing developments have been reactive rather than proactive, costly, and sometimes ineffective in preventing erosion. They have even been the cause for more erosion. Structures have generally been neither eco-friendly nor attractive to the public. Although hard coastal protection can be an effective response for one or two decades in some areas, alternative measures might be more cost-efficient and beneficial in the long-term.

This review finds support for a sustainable, more holistic concept of coastal management, where interdisciplinary groups (e.g. engineers, stakeholders, scientists, community groups) work together to ensure that coastal areas are safe for communities, without compromising social, cultural and environmental values. This is an approach that embraces the NSW Government's vision for the marine estate. Early planning is essential, as is site-specific assessment, use of decision-making frameworks such as the mitigation hierarchy including direct, tangible costs from construction and damage-prevention, but also from ecosystem services, recreation and tourism.

The implementation of hard protection should be the last resort after retreat and soft approaches have been ruled out as viable options. It should include eco-engineered as well as multi-use features. Existing infrastructure might be removed, abandoned if deemed uneconomic, or retrofitted with eco-engineered and multi-use features if it is the presently best option. Figure 23 presents a decision-making pathway encompassing the essential elements identified above.

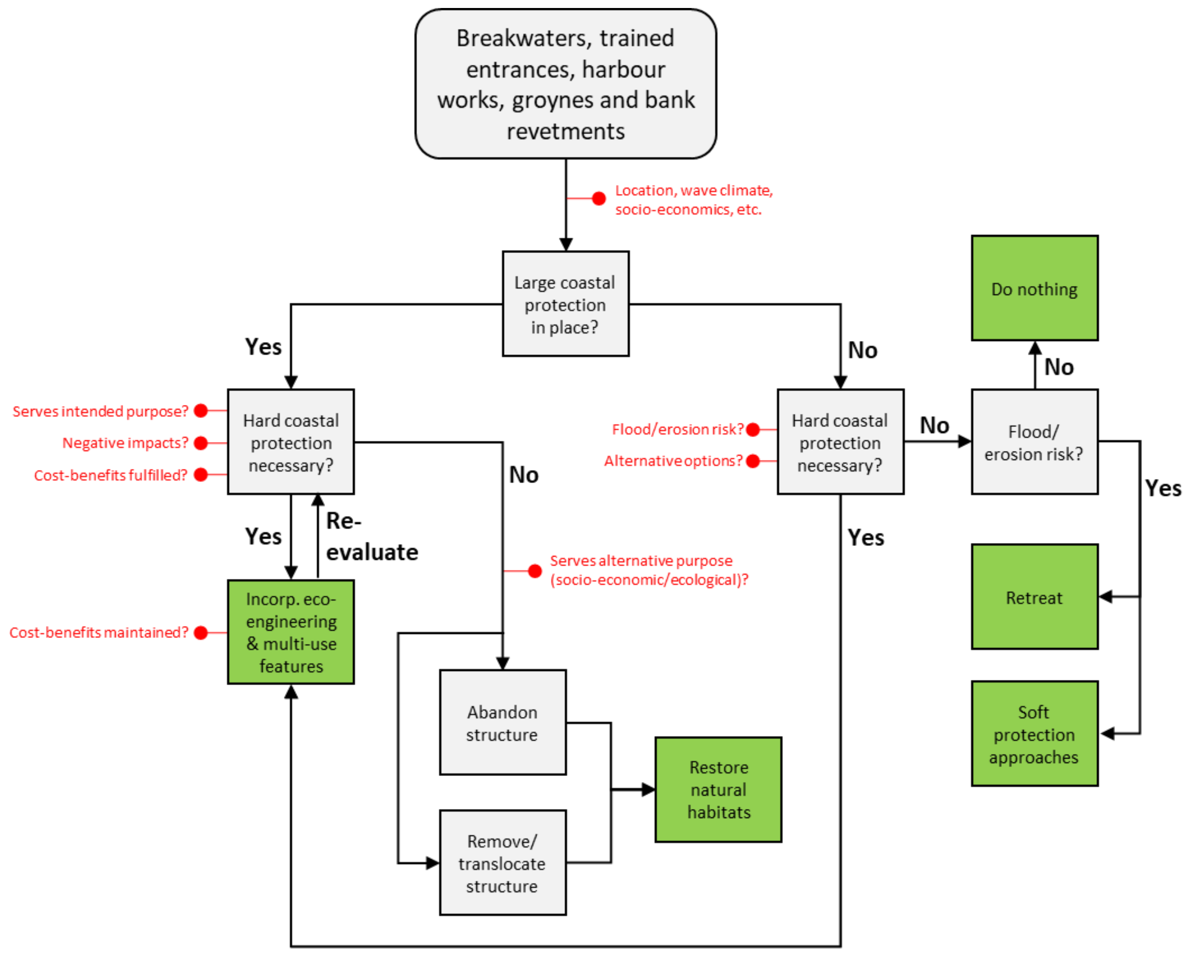

Figure 23. Overview of decision-making pathways in coastal and estuarine flood/erosion management, with eco-friendly approaches shown in green and important considerations for steps identified in red text

Barriers to the implementation of multi-use and eco-engineered features might include:

- initial cost and funding priorities
- lack of scientific evidence that certain measures work
- lack of policy drive and legislative support, and poor communication (Evans et al. 2019).

In NSW and Australia, the legislative framework, multidisciplinary communication and building awareness of stakeholders and environmental considerations support active planning and installation of multi-use and eco-features. Access to specific robust evidence (the academic literature) for the relevant species or specific settings is often lacking (Evans et al. 2017) and takes time to acquire. Perhaps as a result, the outcomes of an audit of large coastal infrastructure in NSW found that eco-friendly and multi-use outcomes have been applied opportunistically rather than strategically, and the outcomes have been reported only on rare occasions.

There are persistent challenges in linking the spheres of science-to-policy-to-practice. The time needed for science to fill knowledge gaps is longer than the rapid response sought by policy makers and the broadly framed positions policy makers want to adopt. This mismatch complicates the step towards more sustainable coastal protection even further (Dale et al. 2019). To create opportunities for multi-use and eco-features with coastal protection infrastructure, it is vital to enhance multidisciplinary collaboration and promote evidence based policy (Dale et al. 2019). Once evidence has been gathered on which options are available and achievable, the next vital step is community inclusion. If public and stakeholder needs are not included in the project design, social sustainability is not likely to be achieved (Biondi 2014). Stakeholder involvement includes the assessments of potential benefits and decisions about which of those are most desirable (Evans et al. 2017). In places where environmental enhancement is not the chief outcome, sustainable coastal protection might need to be promoted as being innovative and therefore attractive to stakeholders and tourists (Evans et al. 2017).

Breakwater and training wall infrastructure in NSW, from its earliest days, has been designed to meet specific site constraints. Accordingly, the mix of suitable multi-use and eco-engineered features—the way these features are designed, installed and operate—differs between sites. At all sites however, it is important to identify key issues early and execute an informed iterative assessment to achieve the delivery of effective solutions that provide for ‘a healthy coast and sea, managed for the greatest wellbeing of the community, now and in the future.’

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Appendix 1

Breakwater maintenance and upgrades: multi-use and eco-features: guidance for asset owners, designers and project managers

Dwyer PG and Dengate C (2021a) Breakwater maintenance and upgrades: multi-use and eco-features: guidance for asset owners, designers and project managers. NSW Government.