# Multiple-Use Options for Coastal Structures: Unifying Amenity, Coastal Protection and Marine Ecology

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## ABSTRACT

Often coastal protection works are carried out to mitigate the effects of erosion, but do not attempt to address the cause. For example, rock/concrete walls, breakwaters or groynes along the beach act to mitigate the effects or to realign the beach. However, end effects on the shoreline downstream and the environmental imperatives to retain natural character and amenity values often preclude hard structures. Also, coastal re-alignment or retreat may not be possible in built-up areas where natural alignments would sweep though modern shoreline developments that often have capital value far in excess of the cost of protection structures. While there will always be a need for some hard engineering structures on the coast (e.g. Port and Marina walls), in many cases softer options would have far better outcomes both in terms of environmental impacts and multiple-use options. One such option is the offshore, submerged reef. Since coastal protection measures can be moved offshore and underwater, opportunities arise for the incorporation of amenity (e.g. high-quality surfing breaks) and ecological enhancement (e.g. the provision for species specific habitat), while the natural character of the beach is maintained and the amenity value is enhanced (e.g. wider beach). The information and technology is available to design and construct environmentally-sensitive coastal erosion solutions, and examples of this technology are present in Australia. The challenge is to increase the awareness and understanding of the function and advantages that multi-purpose reefs may provide as a coastal solution.

**Additional Keywords:** coastal protection, multi-purpose, amenity enhancement, submerged reefs, marine ecology, numerical modelling

This paper is presented in two sections. The first considers the value of our beaches and of the additional value that can be incorporated through the intelligent design of coastal structures. The second section describes the advances in multi-purpose reef design that make the amalgamation of multiple use options a reality.

# ADDING VALUE TO THE COAST WITH MULTI-PURPOSE REEFS

## INTRODUCTION

Enjoying the coast and the nation's many beaches is very much entrenched in Australian and New Zealand culture, as it is in many other Western societies. It is clear that society loves and values the coast for a wide array of aspects (recreational, commercial, environmental and sporting), and usage has been steadily increasing due to the rising numbers of people choosing to live on the coast (the 'coastal drift') and the increase in water-based sport and recreation (e.g. the huge increase in people participating in surfing over the past two decades). However, while the coast is often referred to as an important resource, in many cases where development occurs it is the land adjacent to the coast that is considered to have the most value, not the foreshore and beach.

If we consider a sport and recreation such as surfing (something that I am personally involved in), which is very respected and strong in Australasia, it relies on the natural configuration of the coast to provide suitable surfing breaks. While increased coastal development is putting more pressure on the coast, increases in numbers and skill levels of surfers is putting pressure on the existing surfing breaks. For example, in New Zealand more people surf that play either of the national sports of rugby and netball (Table 1). There are thousands of kilometres of coastline around the world that receive enough swell needed for surfing. However, there are only a limited number, a relative handful, of high-quality surfing breaks on these coast, even less that are easily accessible to the majority of the world's surfing population. Taking the West Australian coast as an example, even though it boasts an incredible number of high-quality surfing breaks in comparison to many coastlines around the world, in total these breaks represent only a tiny fraction of the entire coast. For over a decade surfing has been, and still is, one of the fastest growing sports and recreations on the planet. Millions of surfers now regularly spend time on the coast in search of waves all over the world. This has created an ever-increasing pressure on existing surfing breaks. Adding momentum to this pressure is a huge and ever expanding $Billion surfing industry. The industry is promoting the sport and constantly increasing the number of participants, but very little is being done to increase the necessary resources required for the sport to continue to expand – accessible high-quality surfing breaks. Furthermore, advances in surfing equipment have led to advances in the skill levels of surfers. Average surfers are now able to perform manoeuvres and ride intense breaking waves that were the domain of professional surfers just a couple of decades ago. This has resulted in increased pressure on many of the best surfing breaks. Surfers need access to more high-quality facilities. Similar situations exist for many other coastal sports and recreations (e.g. fishing, beach volleyball, surf lifesaving, etc.), as well as just relaxing by the coast – development is reducing the number of opportunities to enjoy this natural asset.

This paper first considers the value of our beaches and of the additional value that can be incorporated through the intelligent design of coastal structures that amalgamate multiple-use options. We then go on to describe the advances in multi-purpose reef design that make the amalgamation of multiple use options a reality and describe some of the projects that we are involved with that are achieving outcomes that result in advantages to the coastal environment and the people that value it the most.

## SUSTAINABLE DEVELOPMENT

Travelling to distant locations in search of perfect waves will always be the aim and dream of surfers. However, the reality is that most of the population live and work in the cities, on the developed coastlines, where sports fields, basketball courts and golf courses are many, but surfing facilities are rare – in New Zealand it is uncommon to even have showers at city beaches. Indeed, in the past, beaches and surfing breaks have often been lost due to development; there are several examples of this on the Australian coast. It is also true that in some cases, while aesthetic values and some kinds of beach usage have been lost, some coastal developments have created surfing breaks (e.g. where sand trapped by groynes has produced more consistent longer peeling breaks), demonstrating that coastal structures can also have positive benefits in terms of creating more surfing facilities. We now have the information and technology that enables the design of multi-purpose reefs that incorporate coastal protection, ecological enhancement and world-class surfing breaks and thereby create new, high-quality surfing facilities. Factors that have led to this current position include state-of-the-art numerical modelling, the application of a huge amount of knowledge of coastal processes that has previously been the domain of the scientists and rarely applied to coastal engineering, new science into the function of surfing breaks and the increasing number of experts in the relevant disciplines with coastal backgrounds. This technology is now being used not only to enhance the surfing conditions of exposed coasts, but for a range of coastal engineering applications and amenity and environmental enhancements.

Sustainable management means managing the use, development, and protection of natural and physical resources in a way, or at a rate, with enables people and communities to provide for their social, economic and cultural well-being while sustaining and safeguarding the environment to meet the foreseeable needs of future generations (NEW ZEALAND RESOURCE MANAGEMENT ACT, 1991). The greatest pressure on resources, such as our beaches, occurs where the population density is highest, and hence it is these areas that concepts of sustainable development currently most urgently need to be applied. There are many types of environmental impacts of population density that affects our coast including water quality issues, accessibility, the need for coastal protection, loss of amenity, loss of natural habitat, etc. Here we consider the integration of coastal protection, amenity and habitat as a method of avoiding, mitigating and remedying environmental impacts on the coast. Indeed, the Artificial Reefs Program (ARP), which formed the foundation of this current work, was a response to the need for positive development and environmentally sensitive solutions to coastal protection and to the continued growth in recreational usage of our beaches.

Table 1. Number of people (over the age of 18 years) participating in sport and leisure activities over a 12 month period in New Zealand (HILLARY COMMISSION, 1998).

| **RANK** | **ACTIVITY** | **ADULTS (18+)** | *RANK* | **ACTIVITY** | **ADULTS (18+)** |
|---|---|---|---|---|---|
| 1 | Any walking | 1891700 | 22 | Basketball | 139800 |
| 2 | Gardening | 1535100 | 23 | Skiing-downhill/cross country | 128200 |
| 3 | Swimming | 954800 | 24 | Horse | 127500 |

| | | | | | |
|---|---|---|---|---|---|
| | | | | riding/Equestrian | |
| 4 | Exercising at home | 860500 | 25 | Squash | 121000 |
| 5 | Fishing | 651200 | 26 | Aquarobics | 113400 |
| 6 | Any cycling | 628900 | 27 | Volleyball | 103100 |
| 7 | Golf | 507400 | 28 | Bowls-indoor | 102300 |
| 8 | Exercise classes/Gym | 497800 | 29 | Bowls-lawn/outdoor | 90000 |
| 9 | Running/Jogging/Marathons | 392900 | 30 | Badminton | 87700 |
| 10 | Tramping | 322300 | 31 | Cricket-indoors | 69700 |
| 11 | Tennis | 309400 | 32 | Rugby League | 58800 |
| 12 | Aerobics | 261500 | 33 | Athletics (track and field) | 51200 |
| 13 | Touch football | 249600 | 34 | Rowing | 50300 |
| 14 | Surfing/body boarding | 219600 | 35 | Kapa Haka | 35500 |
| 15 | Cricket | 201100 | 36 | Hockey | 32700 |
| 16 | Shooting (rifle and pistol) | 171000 | 37 | Softball | 32200 |
| 17 | Soccer | 159700 | 38 | Triathlon | 25700 |
| 18 | Netball | 157700 | 39 | Surf life saving | 12800 |
| 19 | Motor sports (motorcycling) | 154400 | 40 | Waka | 9900 |
| 20 | Yachting/sailing/dinghy sailing | 151500 | 41 | Taiaha | 7700 |
| 21 | Rugby Union | 144700 | | | |

Unfortunately (or fortunately?) we can't go back to living in caves, but neither can we stop progress and development, no matter how many bulldozers are laid in front of, nor indeed will any of the coastal developments that are already in place be removed – property on the coast is invariably worth many times more than the cost to protect it. However, you can use the principles of sustainable development together with sound knowledge and principles of coastal processes to ensure that development has the least possible effect on the coastal environment and its users. The incorporation of surfing breaks and habitat enhancement into offshore submerged breakwaters for coastal protection, is a further step towards this; providing amenity for people who use the coast. If you are going to build a structure to protect the coast, why not build it offshore and underwater where it creates habitat for marine biota and provides a good surfing break? Unlike shore-based solutions (e.g. seawalls, rock rip rap, etc.) the beach is not lost, it is widened creating more space for beach users.

## VALUE OF THE BEACH

The value of our coast is now starting to be realised in a far broader sense than it has been in the past. There is no doubt that it is difficult to put a value on some things and that people value different possessions, objects, experiences and environments in different ways (HICKMAN, 2002). Recent developments by environmental economists aim to ensure that all aspects of the value held towards environmental goods and services are taken into account through a holistic valuation concept referred to as 'total economic value' (TEV) (Fig. 1). A range of valuation techniques has been developed to assist with imputing the monetary value attached to environmental goods and services in an effort to estimate the TEV (HICKMAN, 2002). While it is beyond the scope of this paper to consider these techniques in detail, the important point is that many of the beach values that were previously ignored, mostly due to inability to measure them, are now starting to be taken into account. With the high, and increasing, numbers of surfers now using the coast, TEV is likely to have positive impacts in the future. Indeed, the few socio-economic studies that have been directed towards the coast and surfing in particular have invariably shown the high value of natural assets such as surfing breaks.

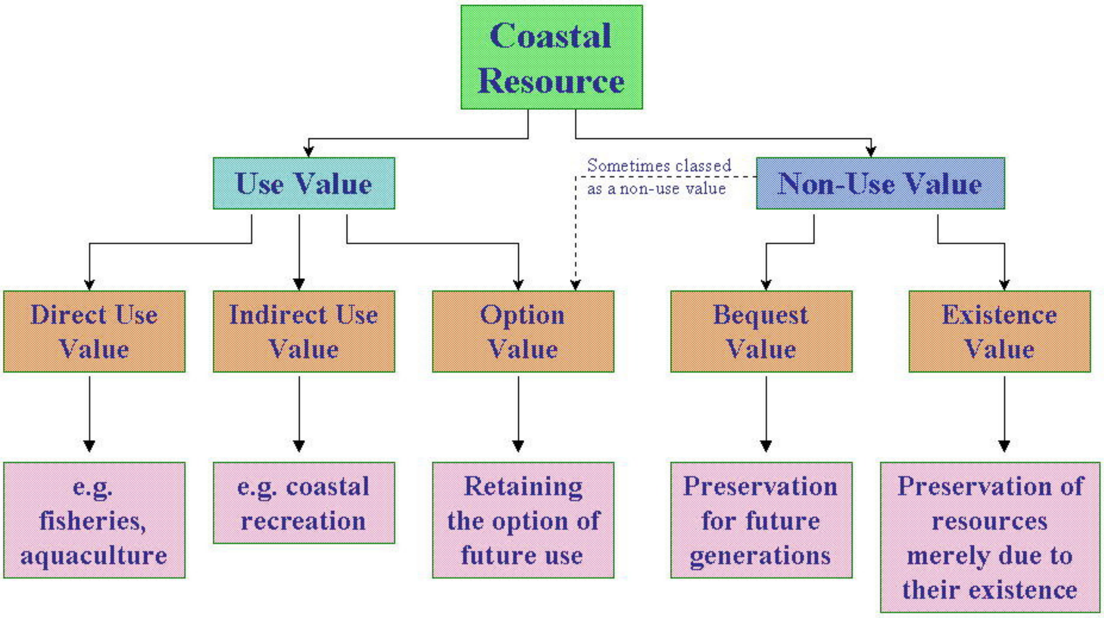

Figure 1. Use and non-values of the coastal resource used for total economic value (TEV) assessment (source: HICKMAN, 2002).

Several studies have been undertaken to assess the economic value of surfing. These studies have shown that the economic benefits of recognised good beaches and surfing conditions can be large. Events associated with the beach and surf can be of considerable economic importance. For example, a recent festival at Noosa in Australia to celebrate the restoration of the beach attracted an estimated 20-30,000 visitors over the weekend and therefore at least AU$2M into the economy if visitor spending was only AU$100/ visitor. Surfing competitions are now heavily promoted and publicised - for instance, a single international level surfing (short board or longboard or bodyboard etc) can bring hundreds of thousands of dollars into the local economy. On the Gold Coast, it is estimated that a single high profile surfing event is worth AU$2.2M (RAYBOULD and MULES, 1998).

In Bournemouth, UK, despite the present mostly poor surf and a short summer, there are 11 specialist surf shops in town that service the surfers, and a large group of non- or irregular surfers who purchase clothing and surfing paraphernalia from the shops. The shop statistics show that surfing attracts the attention of people touring the district who will simply come to watch or participate in the "surfing environment". The shops presently have an estimated annual turnover of at least £2.5M. Given the lack of "formal focus" on the sport at present in Bournemouth, this figure indicates the economic importance of ocean recreation, particularly felt in associated retailing. The other indirect benefits are felt in the hospitality and food industries. It would be expected that a similar situation would apply to most other coastal towns and cities. Indeed, a recent study of the economic importance of coastal activities on the Cornwall coast in the UK found that the direct spend of surfers alone contributes £21M to the local economy (OVE ARUP AND PARTNERS INTERNATIONAL, 2001).

In New Zealand, GOUGH (1999) assessed the economic effects of a small (50 m length of ride) artificial surfing reef at Mount Mauganui beach. This study was directed at surfers, took into account the number of surfers the reef would be able to support at any one time and considered how surfers spent money on food, petrol, surf gear, accommodation, etc. It was found that surfers using the reef would spend about $1.6M annually, which was reduced to $500,000 to account for good surfing conditions occurring approximately one third of the time.

Studies of benefits associated with the construction of surfing reefs at various locations around the world have all shown significant benefit/cost ratios. The lowest estimate is 20:1 for a small reef in Bournemouth, in the UK (BLACK *et al.*, 2000), while over 60:1 has been indicated for Narrowneck reef on the Gold Coast, Australia (RAYBOULD and MULES, 1998). On the Gold Coast, the most significant factor that resulted from the coastal protection provided by the multi-purpose reef was the increase in beach width (Fig. 2). The Gold Coast, or more specifically, Surfer's Paradise, depends largely on tourists and eroded beaches have been well correlated to down turns in visitors and consequently revenue (RAYBOULD and MULES, 1998). Hence, the creation of a large stable beach, compared to the earlier proposal for a groyne, has provided even more benefit than the creation of a surfing break and marine habitat associated with the reef.

Figure 2. Narrowneck Beach on the Gold Coast prior to the construction of the multipurpose reef in 1999 (left), and in 2002 (right), 3 years after construction began.

A recent presentation of the economic value of beaches in the USA (HOUSTON, 2002) focussed on tourism and highlighted some important points relevant to the application of multi-purpose reefs in California. Beaches are the leading tourist destination in the US, receiving 85% of all tourist related revenue, over $260 billion annually (HOUSTON, 2002). Over 500,000,000 tourists visit the Californian beaches, with Californian State beaches receiving 72% of the visitors, even though they represent only 2.7% of the State parks (HOUSTON, 2002). Similar to the Gold Coast in Australia, erosion is the number one concern that people have about beaches, but very little has been spent on addressing erosion problems in California. In comparison, Miami's beach restoration experience has shown that the presence of wide sandy beaches is valued at a benefit/cost ratio of 500:1 (HOUSTON, 2002). HOUSTON (2002) advocates the need for "… a paradigm shift in attitudes toward the economic significance of travel and tourism and necessary infrastructure investment to maintain and restore beaches …" in the US. Along with the Engineer Research and Development Center's current thrust to develop novel erosion control methodologies with low negative environmental impacts, it is likely that opportunities to enhance surfing conditions along the developed coastal areas in California are becoming available. Similar situations, in terns of both value and changes in attitude, are likely to exist in West Australia.

In New Zealand, coastal erosion is now being addressed with coastal management plans, coastal care groups, buffer zones (which have been artificially created with sand fences, planting, etc.), etc., working within the natural coastal system to preserve what's still intact and enhance what's been degraded. Multi-purpose reefs are becoming a part of this process, working within the existing coastal processes to provide outcomes with more than one benefit.

## BIOLOGICAL ENHANCEMENT

In ecological terms the principles are simple and well known; hard stable substrate, such as reefs, result in greater biodiversity and species abundance than mobile sandy substrates (Pratt, 1994). Comparatively few species (mostly worms and bivalves) inhabit the abrasive, mobile seabed provided by sandy sediment than stable complex reef habitat. The first known use of artificial reef structures for habitat enhancement dates back to Egyptians in 500BC. More recently there has been a large amount of work on ecological enhancement using artificial reefs throughout the world (e.g. BULLETIN OF MARINE SCIENCE, 1994). From these studies it is evident that, as a general rule, species abundance and diversity are greater when the habitat is more stable (in comparison to mobile substrates – e.g. MEAD *et al*., 1998), topographically more complex (a higher number of different niches are available) and when the reef is larger (PRATT, 1994). Construction of artificial reefs also provides the opportunity to create specific habitat and 'seed' specific species that may be of commercial or cultural value (e.g. SAITO, 1992). Therefore, the biological enhancement due to the construction of a multi-purpose reef may include increased environmental value (increases in bio-diversity and abundance), increased amenity in the form of a diving and snorkelling venue and enhanced fisheries by the incorporation of specific habitat.

Like surfing reefs, where only occasionally do the factors all come together to make a high-quality surfing break, the same is true of habitat for specific species. Indeed, it seems that the majority of species in the oceans are not limited by their number of offspring, but by the availability of habitat for them to colonise and inhabit (PICKERING and WHITMARSH, 1996). Creating reefs presents the opportunity to incorporate specific topography for specific species, which opens opportunities of fisheries management, reserves, recreational amenity, etc. Marine organisms are far more capable of responding and adapting to physical change than the flora and fauna that inhabit the land. The Gold Coast reef is a good example of this, with the fast colonisation since construction quickly resulting in a diverse reef ecosystem that is now a very popular fishing spot, boasts a dive trail and a snorkelling site for tourists (Fig. 3).

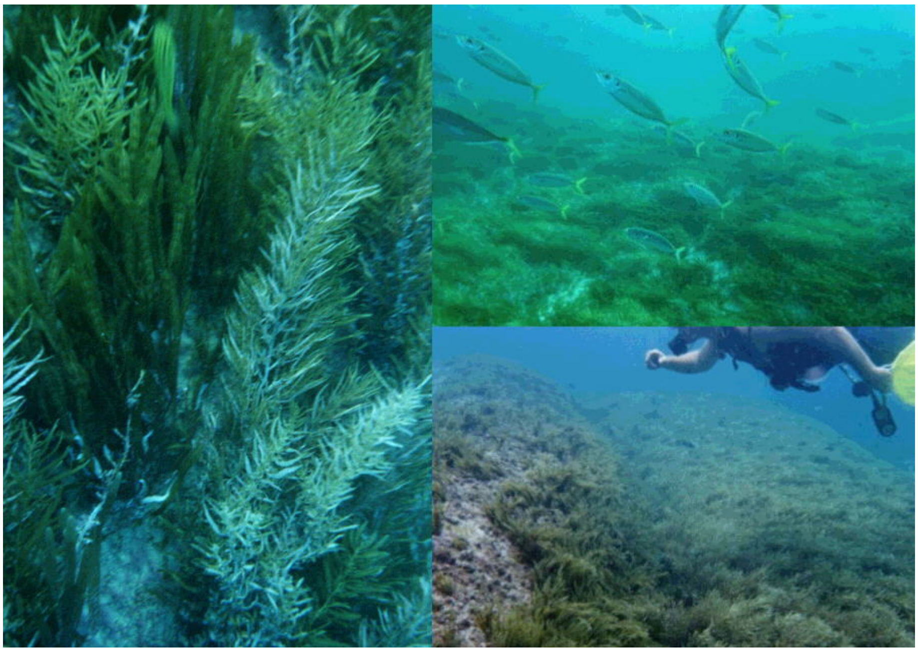

Figure 3. Colonisation by seaweeds began the moment the Gold Coast multi-purpose reef was under construction. Over 2 years later a large variety of marine life inhabit the reef.

## DESIGNING HIGH-QUALITY SURFING BREAKS

In 1995, the Artificial Reefs Program (ARP) was initiated by Prof. Kerry Black at the Centre of Excellence in Coastal Oceanography and Marine Geology, a joint graduate school in the University of Waikato and the National Institute of Water and Atmospheric Research (NIWA), in Hamilton, New Zealand. By unifying senior scientists and experienced industrial partners, the ARP aimed to:

- enhance the coastal amenity value of developed shorelines by evaluating multiple use options (surfing, diving, recreational and commercial fishing, navigation and swimming safety) for incorporation into coastal constructions

A team of scientists were involved including biologists, physicists and environmental managers, so that both the environmental aspects and the coastal dynamics could be fully investigated to enable the complete development of multi-purpose artificial reefs. A series of related-studies provided the input into the broader program so that engineers who build offshore protection works are aware of and able to incorporate the proposed concepts into their designs to fulfill the demands and requirements of the marine environment, coastal users and developers. Many of these studies are directed towards the design of high-quality surfing breaks, since other than the work of Dr. Walker in the 1970's (WALKER, 1971, 1974a, b; WALKER *et al.*, 1972), very little research in this area had previously been undertaken.

Eight years on, ASR Ltd represents the commercial offshoot of the ARP, and although selected graduate students are still involved in the ARP (with joint supervision from ASR Ltd and the University of Waikato) the primary aim of the Program has been achieved. Indeed, Special Issue No. 29 of the Journal of Coastal Research (WINTER, 2001), "Natural and Artificial Reefs for Surfing and Coastal Protection" includes over a dozen scientific papers on the design, impacts and construction of multi-purpose reefs and more than 8 Doctoral and Masters theses have resulted from the ARP. The first reef designed by ASR Ltd at Narrowneck on the Gold Coast in Queensland, Australia, won the a State Environmental Award and has demonstrated the effectiveness of multi-purpose reef technology, with significant widening of the beach without downstream impacts (the Narrowneck area of the Gold Coast has a net northerly sediment transport of ~500,000 $m^3$/yr), enhanced marine life and quality surfing waves (Figs. 2, 3 & 4). Design for a similar project has recently been completed for Noosa (Australia) and, at present, ASR Ltd are at various stages with multi-purpose reef projects in New Zealand (7), Australia (2), US (1), India (1), Bahrain (1) and the UK (4). While there is still ongoing research into aspects of multi-purpose reef design (e.g. Master's students are currently undertaking field studies and numerical modelling to assess the down coast impacts of offshore reefs under differing metocean conditions), we already have the data and the tools to design high-quality surfing breaks that optimise surfing conditions for any given set of variables (swell height, direction, existing bathymetry, etc.).

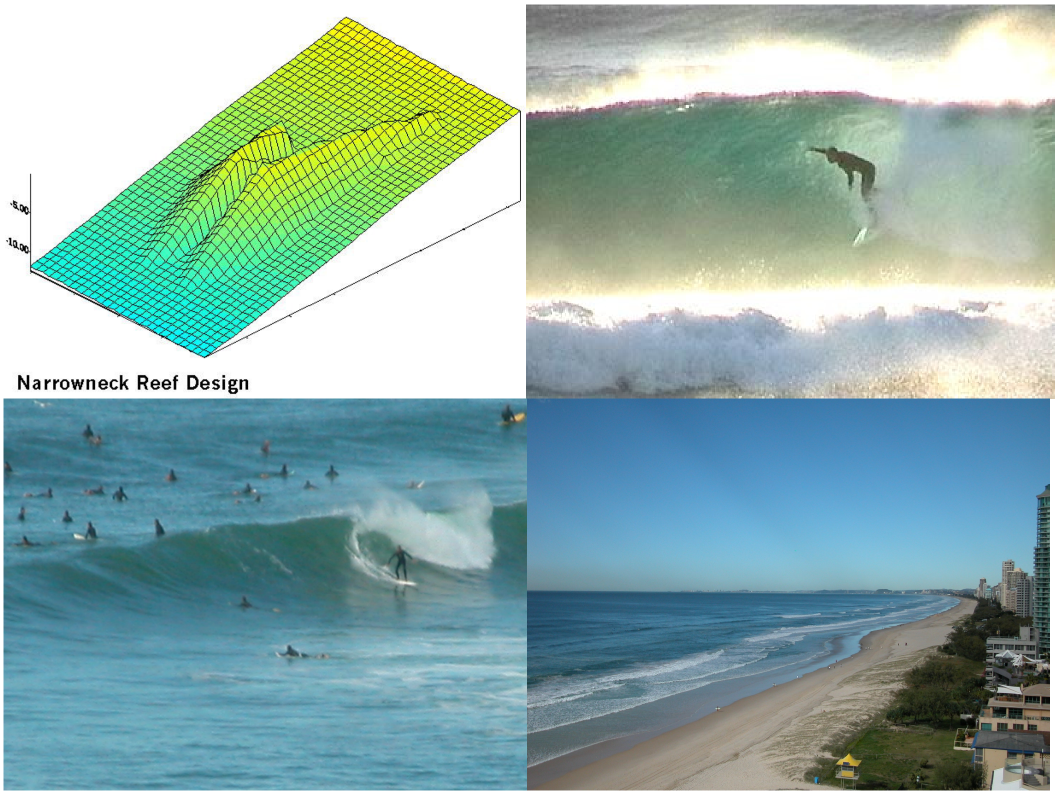

Figure 4. The Gold Coast multi-purpose reef (Clockwise from top left), topographical representation of the design, surfing on the reef in 1999 and 2003, the view of the salient looking south (June, 2003).

## CURRENT PROJECTS

Previously tax/rate-payer funds were not allocated to public facilities for surfers, even though surfers make up a significant component of the population, while public sports fields, tennis courts, skateboard parks, etc., continue to be provided and maintained. Of multi-purpose reef projects presently underway, all but one is receiving the majority of its funding from local Government, even though most are being driven by the local communities. This is partly due to coastal protection being the responsibility of local and regional Government, and partly due to the recognition of surfing as a serious sport and recreation and the economic value of our beaches. However, it is the amalgamation of multiple-uses into the ASR's and the socio-economic benefits not necessarily directly connected with surfing that have made this transition possible i.e. the move towards environmentally-sensitive coastal development. Of the 16 projects presently underway, over half (11) incorporate coastal protection, while the remainder are primarily for surfing. Of the 11 projects that incorporate coastal protection, over half (6) have coastal protection as the primary aim of the structure, where as it is seen as an added benefit to the other 5 projects (i.e. those that are primarily for surfing). All incorporate ecological enhancement of some kind or scale. The majority of these projects are in locations that derive income from the tourism industry and are driven by the social and economic benefits that multi-purpose reefs provide. All of the reef projects are in areas that already have coastal development to some degree. Some of these projects are described in more detail in the second section of this paper.

## CONCLUSIONS

Surfing is now perceived as a valid sport and recreation, no longer the domain of anti-social dropouts. This is now beginning to be reflected in Australia, New Zealand, the USA and the United Kingdom, where local government funded Artificial Surfing Reef (ASR) projects are currently underway. In addition, the economic value of wide sandy beaches and high-quality surfing breaks is now being recognised, and with the amalgamation with coastal protection and environmental enhancement, multi-purpose offshore reefs can provide coastal development solutions with a wide range of benefits.

The development of multi-purpose reefs has become increasingly feasible, and is now proceeding, due to the relatively new developments in surfing reef design, coastal process and response assessment through state-of-the-art numerical modelling and biological enhancement research.

Recognition of the real value of the coast, and not just the land that is adjacent to it, will lead to the creation of more surfing facilities in the future. Similar holistic management approaches that are well developed on land are needed to make the physical, biological and social connections between the land and the sea.

With information dissemination rapidly increasing due to the continued advances in information technology, the growing recognition of the coasts real value, and a general increase in the level of understanding of coastal processes, it's more than likely that multi-purpose reefs will become common place in the future.

# WAVE ROTATION FOR COASTAL PROTECTION – WORKING WITH THE NATURAL SYSTEM

## INTRODUCTION

There are many devices that have been or are presently being used to protect the coast. These include seawalls, groynes and artificial headlands, detached breakwaters and submerged reefs, beach nourishment and dune rehabilitation, as well as training walls to stabilise river entrances (NIELSEN, 2001). In broad terms, these have often been described as hard or soft, but there are several intermediate options also. Another relevant categorisation relates to the positioning, i.e. on the sandy beach or offshore (both above and underwater). There has been a negative public reaction to large structures on the beach in many parts of the world (BLACK, 2001). Indeed, the shoreline structures more correctly provide “land” protection rather than “beach” protection, because often the beach is severely degraded by the presence of a seawall, groyne or hard rock/concrete protection device.

The various forms of civil engineering works can be classified into different categories, depending on whether they are working with nature, against nature or have the objective of modifying nature (NIELSEN, 2001). For example, beach nourishment is an option that works with nature. It feeds a natural demand of the sand transporting processes, albeit artificially, and thereby prevents further erosion of the shore. In contrast, seawalls fight nature by repelling wave action, which may have adverse consequences on other parts of the beach. Submerged reefs work with nature by modifying the natural nearshore wave transformation processes to alter nearshore currents and obviate coastal erosion processes.

Many of these measures just deal with the effect, not the cause of the erosion problem. On beaches, erosion occurs when inputs of sand are less than outputs from a region, and this arises at a series of time scales. The most serious and unsustainable are long-term loss trends, assuming that the beach is still reasonably intact and able to accommodate the shorter and neutral erosion/accretion events. The cause of long-term trends will often relate to changes to sediment supply (e.g. altered river or coastal cliff supply, upstream construction) or changes to beach orientation due to construction. The latter is prevalent in modern cities that have sculpted the shoreline with retaining walls or coastal development. The fundamental problem relates to an imbalanced alignment of the coast in relation to the average wave orientation, which leads to wave-driven longshore currents. These currents transport sand away from the site and local erosion results.

We have been involved in several of these cases in recent applied investigations. Examples are Noosa Beach (Australia), Westshore Beach (New Zealand), New Plymouth City Beach (New Zealand) and Bournemouth Beach (Southern England). In each case, the coastal orientation is out of alignment with the wave orientation, and input supply is not able to sustain the sediment losses that occur with the currents. Moreover, commercial and residential developments have precluded the option of allowing the coast to naturally re-align. Re-nourishment with construction of groynes or rock walls has been undertaken to overcome the sediment losses, but the costs have been high, and the mitigation has not been sustainable in the long term. The responsible agencies (mostly local councils) have questioned their own willingness to re-nourish and maintain the structures due to the accumulating costs.

The follow sections describe offshore underwater reefs that act to dissipate or rotate the waves. On a “dissipator”, the reef acts to reduce the reduce wave energy at the shoreline by wave breaking. The “rotator” reduces the longshore currents to stabilise the coast. The reefs also have the important benefit of creating opportunity for incorporation of surfing and other water sports as artificial surfing reefs (ASR’s).

## WAVE DISSIPATION AND WAVE ROTATION

Natural offshore reefs have a beneficial impact on coastal stability. Black (2001) described offshore protection as nature’s way and cites examples of coral-fringed islands, where the reef dissipates wave energy to protect the coast, and the many nearshore reefs found on beaches worldwide. Salient or tombolo growth in the lee of the reef leads to enhanced shoreline stability and protection. Nearshore submerged reefs also provide a shoreline protection solution with low environmental impact. Visual amenity is not impaired and there is often no requirement for hard structures along the shoreline. Moreover recreational and public amenity can be incorporated through surfing, diving, sheltered swimming and water games.

The effects on the shoreline of wave breaking on an offshore reef are becoming better known. There are many examples on the Australian New South Wales coast where salients have formed in the lee of offshore reefs and islands (Fig. 5). Moreover, recent studies of natural offshore reefs and islands have provided empirical relationships governing the geometry and size of natural salients or tombolos (BLACK and ANDREWS, 2001a,b).

The use of wave rotation as a method of coastal protection is less advanced but the principal of neutral alignment leading to sandy beach formation has been considered by BLACK and ROSENBERG (1992a) and many authors have confirmed the importance of wave orientation at the breakpoint driving littoral drift (e.g. KOMAR, 1998; U.S. ARMY COASTAL ENGINEERING RESEARCH CENTRE, 1975). Now, with modern computer modelling and larger wave climate datasets the neutral alignment of the waves (in relation to existing beach orientation) can be more accurately determined. The same computer models are then used to design a structure to be placed offshore to achieve the required wave re-alignment in order to change the longshore wave-driven sediment fluxes.

The “rotator” is a soft option, as all construction is underwater offshore. The method is particularly beneficial in regions of high tidal range, where wave dissipation at high tide may be minimal, but it remains important to consider wave realignment in all offshore structures in relation to longshore drift. The main force that drives the currents is wave-induced radiation stress in the surf zone. The radiation stress is responsible for the well-known phenomenon of “rip currents” which transport sand offshore. The longshore currents arise when the wave crests are aligned at an angle to the beach. That is, for a given wave height, the strongest currents occur as the angle of the waves to the shoreline increases (sediment transport also increases with wave height). This results in a net movement of sand along the beach and, when the upstream supply of input sand is inadequate, the beach erodes.

In the past, there have been attempts to overcome this mismatch by realigning the beach. However, in heavily populated sites, such beach realignments are not possible because it involves destroying coastal properties and cutting a new shoreline shape. Thus, a rotation of the wave crests to deflect or stretch the waves crests will act to reduce the wave energy or spread it over a greater area, thereby reducing local wave height and coastal erosion. The rotator system is focused on a single principle, i.e. the submerged reef rotates the wave angles as they approach the beach in order to: (i) deflect and stretch the waves or (ii) to align the waves to be more shore-parallel so that the wave-driven currents along the shore are reduced. In both cases, this leads to reduction or elimination of the sediment movement responsible for beach erosion.

Figure 5. Natural coastal protection due to salient formation in the lee of offshore reefs in New South Wales, Australia. Clockwise from top left a) Sapphire Gardens to Emerald Beach, b) Toukey and Budgewoi, c) Conjola Beach and Ulladunlla, d) Woolgoola to Red Rock. (Source: Readers Digest, 1986)

## CASE STUDIES

To optimise the coastal protection in relation to construction cost and environmental goals, while also amalgamating the coastal protection with water activities like surfing, a careful design optimisation is needed. This is further necessitated because the reefs are designed to put the system closer in balance, leaving the natural erosion/accretion cycles to continue, rather than simply barricading the shoreline like a rock wall. We examine 3 case studies here, which show the basis for and benefits of the numerically determined solutions.

### *Noosa*

Noosa Beach in southern Queensland is greatly valued for its natural character with sweeping white sandy beaches, adjacent National Park and wooded streets. The surfing headlands in the National Park have been the mecca for surfers since the early 60’s and the region remains a natural wonderland for swimmers, walkers and beach lovers. However, with coastal development, the Main Beach at Noosa is subject to bouts of severe erosion. While the expensive real estate is protected by a boulder wall and downstream rock groyne, the loss of the sandy beach leads to a major downturn in tourist numbers and a loss of natural character. With the company’s unique expertise in sustainable, environmentally-sensitive solutions to coastal erosion problems, ASR Ltd, in association with International Coastal Management Ltd, were asked by Noosa Council to overcome the erosion problem.

The purpose of the Noosa study was to design a “structure” to provide coastal protection and public amenity at Noosa Main Beach. The structure had to:

- best suit the local physical system, and;
- meet strict environmental, visual and public usage requirements.

The Noosa Beach field site was investigated through historical data, aerial photographs, current and wave meters and the full suite of numerical models were adapted to the site. The analysis unravelled the complexity of the regional and Main Beach dynamics. The primary cause of the erosion was found to be misalignment of the waves and the present-day shoreline leading to dominant current patterns to the northwest. This led to an unstable beach with net erosion and depletion of sand. With the beach tucked in behind a major headland, sand arrivals in slugs coming down the headland were out of phase with the local erosion on Main Beach, which led to periods of severe depletion along the shoreline. With the rock wall in place and no buffering sand dune system, the beach was unable to recover rapidly and so nearly 1 million $m^3$ of nourishment had to be pumped from the estuary over two decades to artificially sustain the beach.

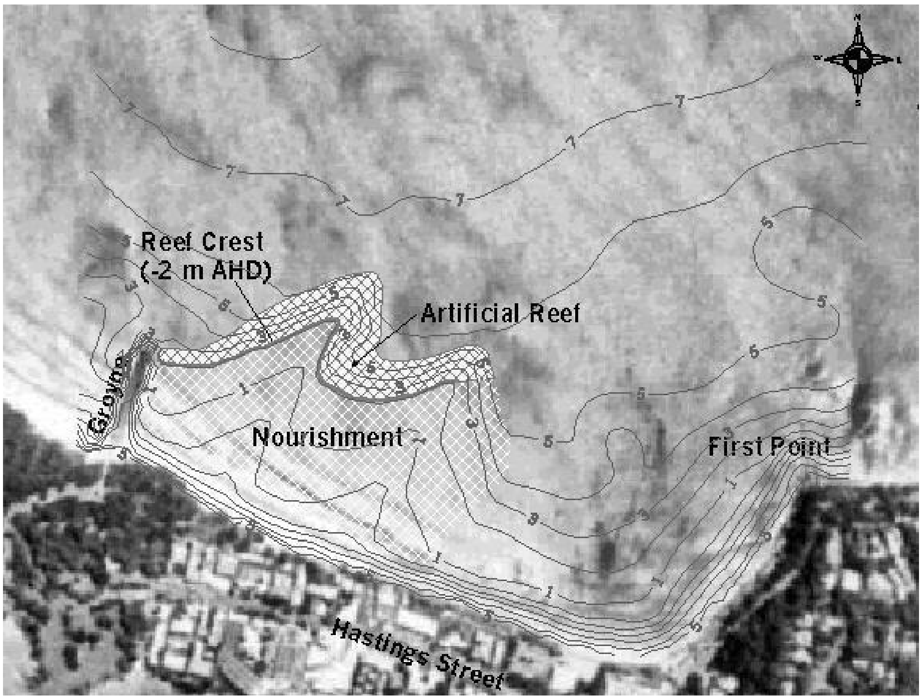

Figure 6. Plan of the wave rotation reef designed for Main Beach, Noosa.

After considering a range of alternatives (extension of the groyne field, nourishment on an offshore bar to protect the shoreline, continued shoreline nourishment, an offshore ("surfing") reef, etc.), the most cost-effective and environmentally sound solution was an underwater "berm" that rotates the waves and changes the longshore current patterns along the shoreline responsible for the erosion was found to provide exceptional protection for the beach. Council requested inclusion of board and body surfing areas to further improve the benefit/cost ratios of the structure.

The detailed shape and position of the berm (Fig 6.) was determined using the 3DD suite of models (BLACK and ROSENBERG, 1992b; BLACK, 1995) in predictive mode (approximately 3500 model simulations), after successfully calibrating against measured movement of a large slug of nourishment placed as an interim measure on the beach and offshore bar. The offshore berm rotates the waves and reduces the current flows along the beach while also breaking the large storm waves to dissipate their energy. With the sophistication of the numerical models to optimise changes in beach set-up and radiation stress gradients, the berm will be highly efficient at the site. Nourishment will be added to initiate the new beach and eliminate short-term impacts downstream. In future, new sand will pass across the new beach profile and spill over the berm, like water spilling out of a submerged bathtub, thereby eliminating any impacts downstream.

### *New Plymouth City Beach*

At New Plymouth, we established a time-lapse video system on a tall city building overlooking the site. The rectified images showed that the wave orientation was 20° out of alignment with the modern rock wall shoreline (BLACK *et al.,* 1999). Thus, while adjacent beaches with more neutral alignments were sandy (e.g. Fitzroy Beach), the main city beach had been lost and a large rock wall was required to protect the city foreshore. Interestingly, the wall eliminates the potential for fully "connecting the city to the sea", as requested by local ratepayers, and significantly reduces the various public uses of the region, leading to a negative socio-economic impact.

To create a new public beach, onshore facilities were merged with a multi-purpose structure offshore. The sedimentary impact on downstream beaches was assessed in conjunction with a large field and modelling study being undertaken on behalf of the local port (McCOMB and BLACK, 2000). Numerical modelling of the natural sedimentation within the structure was predicted to be slow, requiring beach creation by initial nourishment and a design that retains this sand. A curving rock wall, constructed of local rock, was adopted with an attached submerged surfing reef. The reef dissipates wave energy, allowing wall height to be reduced while providing recreational amenity. Interstitial rock structure was chosen to enhance shellfish habitat. Even though the main method of coastal protection in this case is a dissipator, this study demonstrated that a misaligned shoreline was the cause of erosion. In this location, a rotator device would be effective for erosion protection, but could not provide the same level of public amenity.

### *Bournemouth*

Bournemouth Borough's ocean frontage is 12 miles of arcuate coastline linking Poole to Christchurch Bay in southern England. The Bournemouth beaches are artificially created in front of a boardwalk and stabilised cliffs (Fig. 7). The beach is presently protected by sand renourishment placed in 1975 and 1989 between a succession of wooden groynes that have a significant negative visual and amenity impact on the shoreline.

The wave approach directions relative to the shoreline orientation in Poole Bay cause the wave heights to increase from Poole to Southbourne because of the protection afforded by the headlands to the west (Handfast Point, Peveril Point and Durlston Head). Consequently, the bay has developed a spiral shape and it is believed that the net longshore transport is to the east and increases towards Southbourne (HARLOW, 2000).

Cross-shore beach profiles show that the beach volumes tend to gradually and systematically diminish at decadal time scales out to the limit of the surveys at 450 m offshore of the sea wall (HARLOW, 2000). The dropping beach levels in the context of the net longshore transport means that sand leaked from between the groynes is lost from the beach system, with loss rates that vary from about 80,000 $m^3yr^{-1}$ at the west end of the borough to about 110,000 $m^3yr^{\ 1}$ at the east. As such, renourishment is still required approximately every 15-20 years, which leads to a substantial cost from council revenue and MAFF grant aid.

Figure 7. An aerial view of the successive groynes in Poole Bay.

The project at Bournemouth was not undertaken for coastal protection because the primary goal was to create high quality surfing reefs along the foreshore. However, the numerical modelling undertaken for the study confirmed that the shoreline was out of alignment with the prevailing wave climate, which led to the recorded losses of sand (HARLOW, 2000). Reef construction costings and numerical studies indicated that a single reef could replace two groynes, and that the construction costs would be similar. By orienting the reefs to rotate the waves to the west, the net transport could be locally neutralised, thereby acting to help stabilise the beach. A series of reefs along the foreshore would be needed to make the full adjustment, and it was proposed that construction would occur each time a groyne needed replacing. The groynes have a typical lifespan of 20-25 years and so the full replacement could be achieved in that time scale.

Similar projects that utilise wave rotation for coastal protection are currently underway in California, Wales and Orewa (NZ).

## DISCUSSION

The wave rotation concept is particularly useful in situations where long-term erosion leads to expensive or unsustainable maintenance measures. Neither the rotator nor submerged dissipator reefs attempt to stop the short-term erosion/.accretion cycles that naturally occur on beaches in response to storms and swell. Instead, these devices aim to overcome the underlying long-term trends that lead to maintenance requirements. Thus, the solutions allow the beach to retain natural character, while the natural cycles occur on a buffered, wider beach after the formation of the salient enhances beach width. A major additional benefit of the offshore solution is the capacity to incorporate water sport amenity, particularly surfing, sailboarding and diving reefs. In order to rotate the waves, the reef needs to be aligned at an angle to the shoreline (Fig. 8), and this is in synchrony with the requirements for ASR's (BLACK and MEAD, 2001; MEAD and BLACK, 2001a, b).

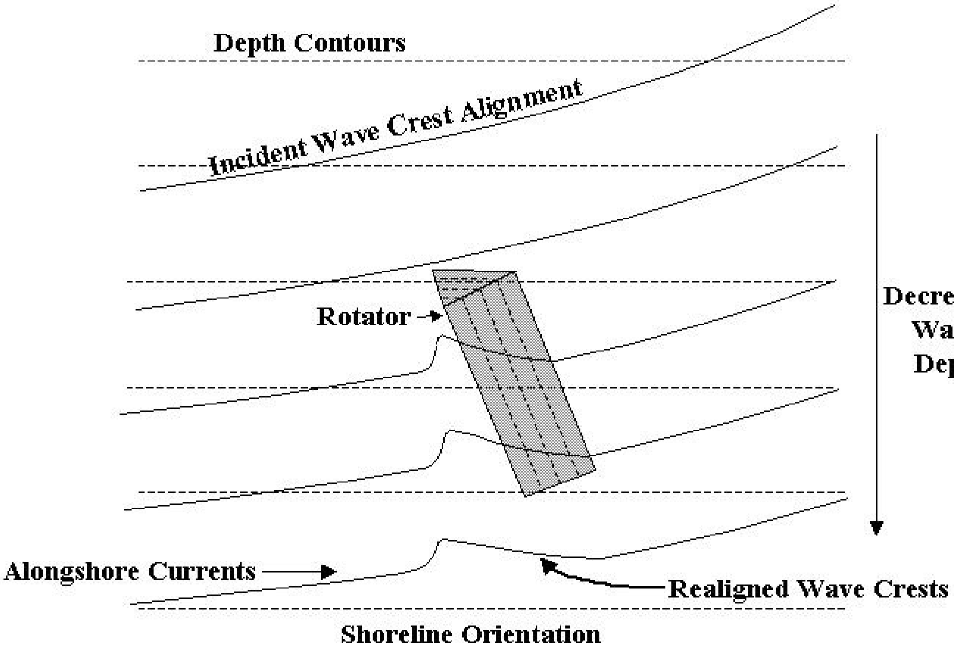

Figure 8. Idealised schematic of a rotator reef.

Offshore solutions also offer benefits through the incorporation of marine habitat, sometimes specifically for target species. Construction of a submerged reef can provide a more complex and stable habitat (than mobile sandy substrate) and will therefore increase the biodiversity and species abundance. There has been a large amount of work on ecological enhancement using artificial reefs throughout the world (e.g. BULLETIN OF MARINE SCIENCE, 1994). From these studies it is evident that, as a general rule, species abundance and diversity are greater when the habitat is more stable (in comparison to mobile substrates – e.g. MEAD *et al.*, 1998), the topographically more complex (a higher number of different niches are available) and when the reef is larger (PRATT, 1994). The reef itself provides a substrate for larval organisms in the water column to settle on and become established. Once primary producers become established, these organisms, and the reef itself, provide shelter and a food source for fish and other marine life and act as a fish-aggregating device (FAD) (BOHNSACK and SUTHERLAND, 1985). Construction of artificial reefs also provides the opportunity to create specific habitat and 'seed' specific species that may be of commercial or cultural value (e.g. SAITO, 1992). In addition, a reef may also subtly alter the local hydrodynamics in a way that could increase settlement in the lee of the reef (e.g. BLACK and GAY, 1987). Therefore, the biological enhancement due to the construction of a multi-purpose offshore reef may include; increased environmental value (increases in bio-diversity and abundance), increased amenity in the form of a diving and snorkeling venue and enhanced fisheries by the incorporation of specific habitat.

In combination with the economic benefits of offshore coastal protection (e.g. RAYBOULD and MULES, 1998; GOUGH, 1999; BLACK *et al.,* 2000), wave rotators provide an environmentally-sensitive solution to coastal erosion problems with potential to locally enhance ecological and amenity values.

## CONCLUSIONS

In many practical cases, the shoreline is out of alignment with the wave climate due to coastal construction or changed sediment supply, which leads to longshore currents and sediment losses. However, an engineered re-alignment of the shoreline cannot always be achieved because of existing land structures or public use. Sometimes, shore-attached structures are implemented but these same structures can induce end effects (e.g. rock walls) or downstream effects (e.g. groynes).

As a substitute for shore-based construction, we consider wave rotation to be a useful "soft" alternative which provides a long-term reduction in net sediment losses, and thereby a more sustainable solution. The wave rotation concept is particularly useful in regions with larger tidal ranges and when net littoral drift is causing beach sediment losses. A common application of the technology is adjacent to a headland or artificial structure or along a beach requiring hard engineering or re-nourishment for its protection.

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