Appendix 4: Coastal

This appendix is one of four environment topics covered as part of the NERC funded project report: Naylor, LA., Kippen, H, Coombes, MA., et al. (2017). Greening the Grey: a framework for integrated green grey infrastructure (IGGI). University of Glasgow report. URL: http://eprints.gla.ac.uk/150672/

Business Case for Coastal and Estuarine Integrated Green Grey Infrastructure (IGGI)

This business case assesses the existing evidence of integrated green grey infrastructure (IGGI) measures that can support wider implementation in coastal and estuarine locations. It forms part of the NERC funded IGGI frame project outputs (URL: http://eprints.gla.ac.uk/150672/). Costs, benefits and measures of the engineering and ecological performance (called critical success factors) of a range of IGGI alternatives to traditional 'grey' approaches are drawn from operational and research examples across the UK and beyond.

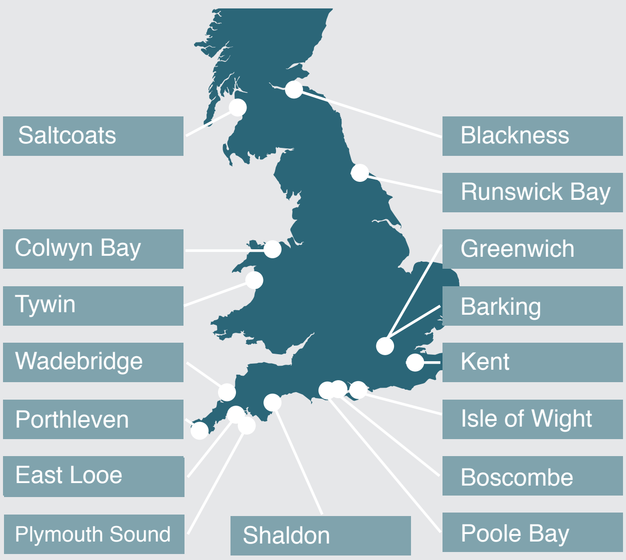
Measures considered include the replacement of existing grey structures with—and creation of new areas of—salt marsh (CS-C1; CS-C2), reed beds (CS-C3) and mudflat (AP-C1), and improving intertidal habitat potential and asset resilience of rock/concrete armouring (CS-C4; AP-C2; AP-C3; AP-C4; AP-C5; AP-C6) and sea walls (CS-C5; CS-C6; CS-C7; AP-C7; AP-C8; AP-C9).

When in the design/life of an asset can this be applied?

Most measures can be applied at any stage in the design life of an asset and have been included in strategic flood risk strategies (green engineering as a key performance indicator), as mitigation requirements, strategic design goals and/or as an alternative to traditional engineering during repairs and maintenance.

The measures described can be used in other settings around the UK to maximize wider application. This document will help identify where these opportunities exist.

Where has this innovation been tested or applied?



Evidence Summary

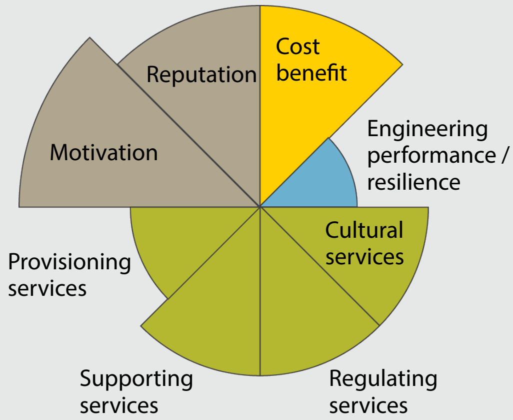
The evidence summary and benefits assessment are a summary of the critical success factors evaluated for all of the coastal case studies and 'Art of the Possible' examples. It is replicated across the four business cases to enable comparison between environmental contexts.

Costs	Ecosystem Services	Engineering	Policy
What do they cost compared to business-as-usual?	What evidence do we have that they deliver ecosystem service benefits?	Are there any risks to design life, inspection or effects on maintenance regimes?	How does it relate to policy and guidance?
Per unit costs for most measures were the same or less, with some research trials costing more. Manufactured versions of trial measures will reduce future costs.	To improve biodiversity through habitat creation that supports intertidal saltmarsh, reed bed and rocky shore species.	No known risk to design life, and for some species (barnacles, seaweeds, reedbeds and fringing saltmarshes) asset resilience may increase. Inspection and maintenance regimes are unlikely to be impacted.	To help meet mitigation requirements such as Environmental Impact Assessment and Habitats Directive.
THE SAME	POSITIVE	NEUTRAL	ACHIEVED

Data Quality	Social	Reputation	Asset Resilience
What is the quality of the data underpinning this bundle?	What are the potential additional social benefits - jobs, cohesion, education etc.?	How have the schemes helped improve public perceptions?	Is asset resilience affected, neutral or improved?
Site specific ecological data for each example was typically high, other data types varied.	Improved amenity value, improved community cohesion (CS-C5) and new skills have been developed with vulnerable populations (e.g. offenders).	Led to improvements in corporate reputation, gained public support for changes in management and won awards (CS-C6, CS-C7, AP-C3).	Some species (barnacles and seaweeds) have been shown to improve asset resilience to weathering-related deterioration (AP-C9).
MODERATE - HIGH	POSITIVE	NEUTRAL	NEUTRAL - POSITIVE

Benefits Assessment

The evidence summary presented above is derived from the examples contained in this bundle, each of which have been assessed using the **Critical Success Factors** guidance developed by this project. The benefits wheels show the benefits of each critical success factor relative to each other. They are a combination of ecosystem services and other important considerations necessary to evaluate IGGI measures compared to business as usual. More detailed breakdown of each element of each can be found below.



Cost

While inclusion of most IGGI measures did increase costs, this was often a small percentage of the overall construction cost. All measures were found to provide (or have the potential to provide) value for money, with additional value gained from increased enhanced ecosystem services, helping meet statutory mitigation requirements, by providing social benefits and additional returns compared to traditional grey engineering.

Engineering value

All of coastal/estuarine IGGI measures reported here have no known adverse impacts on the engineering performance of the hard structures they are on or in front of. Do any IGGI measures have positive engineering benefits? A few coastal/estuarine IGGI measures may have a positive impact on the engineering performance of coastal assets; for example, salt marsh fringes reported here (CS-1 – CS-3) may attenuate wave action as has been proven for larger saltmarshes; mudflats added to a repaired defence helped extend the design life (AP-C1) and; some organisms (e.g. barnacles, seaweeds) have been found to improve the asset resilience of hard coastal structures (AP-C9).

Cultural services

Coastal and estuary areas are attractive to people, and provide a wealth of cultural services from engaging with nature. IGGI measures can be used to generate additional cultural value (CS-C5, AP-C5).

Regulating services

Coastal/estuarine IGGI measures can potentially contribute regulating services such as carbon sequestration, attenuating waves and/or acting as pollutant sinks and reducing deterioration of assets (AP-C9). More research is required to understand and maximise these regulatory benefits.

Supporting services

The primary aim of nearly all coastal/estuarine IGGI measures featured here has been to increase the supporting ecosystem services that hard structures provided through creation of improved habitat for intertidal species.

Provisioning services

Most coastal/estuarine IGGI measures have not been directly designed or tested for their capacity to provide food, energy or raw materials to society. However, their capacity to provide food species or habitat for commercial shellfish and fish species has been shown (CS-C5, CS-C6). They have also been successfully designed to provide food that supports internationally important and protected bird species (CS-C4).

Motivation

IGGI measures can provide significant returns on investment and address the issues that motivated their implementation (e.g. statutory mitigation), by providing useful habitat, engagement and/or aesthetic qualities.

Policy

IGGI measures have been used to provide statutory environmental mitigation (CS-C4, CS-C5, CS-C7, CS-C8).

Reputation

Coastal and estuarine IGGI can help reduce the impact of necessary development that otherwise would reduce habitat and biodiversity. Including IGGI measures in flood risk and development schemes has won several awards, improving the reputation of organisations responsible for the ecological enhancements.

IGGI Measures

Coastal and estuarine IGGI measures (about one third of those included) were derived from the expert knowledge of project partners, information requests and searches, and from the wider academic and practitioner communities. Where required, examples from other countries (that could readily be applied in a UK context) were also included.
The measures are categorised into: (i) evidence-rich and operationally tested case studies, coded CS-C1 to 8, and (ii) 'Art of the Possible' examples that have limited data or which have not yet been applied operationally, coded AP-C1 to 10. Measures are broadly grouped by type (i.e., vegetated, armour, breakwater, sea wall and other) including a range of different structures and incorporating both rock and concrete materials as indicated in the following tables.

Case Studies

Type	Aim of the IGGI	Label	Title
Vegetated	Salt marsh creation on failing defences	CS-C1	Salt marsh on sea defence repairs
Vegetated	Urban re-alignment creating salt marsh habitat	CS-C2	Urban salt marsh creation
Vegetated	Reed beds added in front of sheet piling defence	CS-C3	Intertidal vegetated terraces
Vegetated	Altered mowing on earth embankment defences	CS-M1	Bee Banks
Armour	Use of more ecologically favourable armour	CS-C4	Enhancing armour
Sea walls	Pocket rock pools retrofitted onto vertical sea defences	CS-C5	Seawalls: Vertipools, artificial seashore habitats
Sea walls	Habitat features added under and around a new urban coastal waterfront	CS-C6	Seawalls: habitat enhancement of replacement wall
Sea walls	Niche habitat in stone cladded sea wall repair in a historic conservation area	CS-C7	Seawalls: habitat enhancement of historic wall
Other	Large scale development incorporating enhanced habitat features	CS-C8	Other: Intertidal habitat created around a new development

Art of the Possible

Type	Aim of the IGGI	Label	Title
Vegetated	Repair piling incorporating tidal habitat	AP-C1	Vegetated: Tidal mudflat creation
Armour	Eco-engineered concrete armour units	AP-C2	Armour: Bioblock
Armour	Retrofit habitat added to breakwater rock armour	AP-C3	Armour: drill cored rock
Armour	Retrofit habitat added to rock armour	AP-C4	Armour: Pits and grooves
Armour	Designing habitat into concrete shed units	AP-C5	Armour: Concrete rock pools
Armour	Retrofit habitat added to concrete armour units	AP-C6	Armour: Breakwater
Sea walls	Testing tiles for designing habitat into sea walls and armour	AP-C7	Textured concrete for biodiversity
Sea walls	Testing tiles for designing habitat into sea walls	AP-C8	Textured concrete for sea walls
Sea walls	Using biology to improve asset resilience	AP-C9	Bio protection of sea walls
Other	Retrofit habitat added to outfall cover	AP-C10	Other: eco-enhanced storm water outfalls

IGGI Solutions

IGGI solutions are combinations of one or more measures that can be used together to optimise the ecological potential in a given location. Many of the Case Studies and 'Art of the Possible' reported here have been tested individually rather than as combinations of measures.

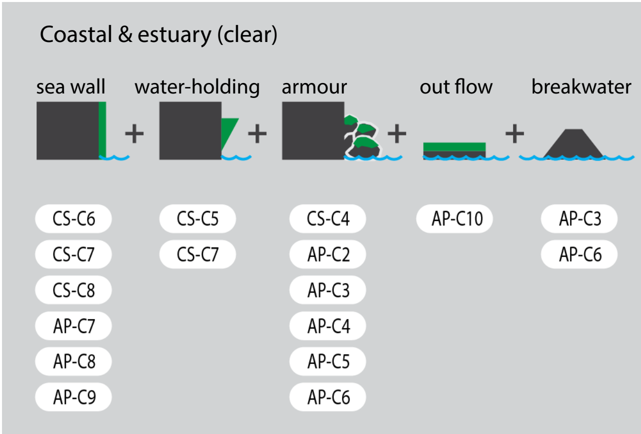
Two case studies from North America illustrate this potential: sea wall enhancement in Seattle (CS-C6) and intertidal habitat mitigation required for Vancouver's Convention Centre (CS-C8). In both examples, a combination of IGGI measures have been successfully adopted to improve both subtidal and intertidal habitats including subtidal habitat creation under the new buildings and piers, and in the intertidal zone by using textured walls, adding water-holding features and designing pedestrian walkways to allow natural light into the marine environment. The Seattle example is also part of a wider initiative to increase use of nature-based solutions; shingle beaches have been re-created to reduce the amount of hard coastal flood alleviation infrastructure in the estuary.

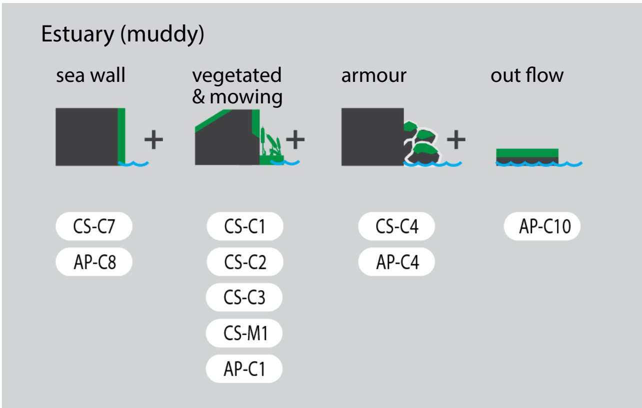
Relevance to other bundles

Coastal examples can often be applied in more than one environment and vice-versa. For example, the Mowing bundle case study Embankment Mowing for Bees (CS-M1) included in this bundle was carried out on a sea defence.

Two coastal examples have been used in historic setting include: CS-C7 is a coastal case study that was successfully applied in a historic conservation area, and AP-C8 was tested on a historic pier; many others could be deployed in this context. All of the coastal examples could potentially be applied in urban areas, where they are appropriate for the local geomorphology, ecology and engineering requirements (see Geomorphology and Engineering suitability section below for details).

We have used expert judgment to identify possible combinations of measures that could be applied to individual coastal and estuarine locations. By using combinations of IGGI measures at one location or strategically positioning them along stretches of estuaries and coasts as part of strategic plans, it would be possible to maximise the ecological potential of hard infrastructure. These measures can also be used alongside softer engineering, nature-based solutions that work with natural processes to improve the ecosystem services provided in urbanised coasts.





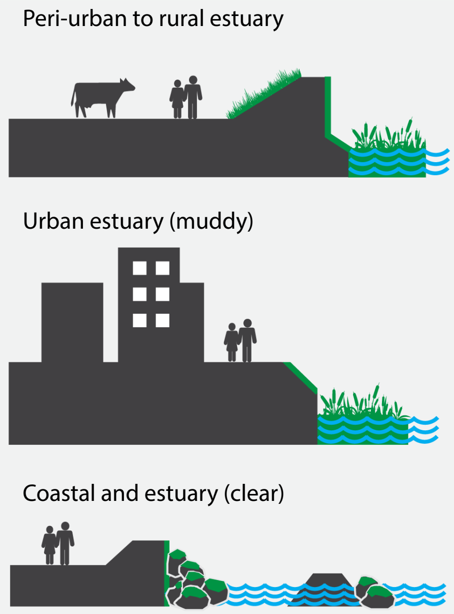
How can you get this type of greening approved for your scheme?

The case studies, art of the possible examples and policy links provided here can be used to demonstrate the economic, environmental and social benefits that can be gained from adding IGGI measures to projects. They also provide clear evidence of the policies that have been used as statutory (CS-C4, CS-C5, CS-C7, CS-C8) or non-statutory (CS-C6, CS-M1) drivers. Where no statutory mitigation is required, how else can you get this type of greening approved? Many of the examples only required a willingness to innovate where testing or applying IGGI measures required minimal change in behaviour or practice. Some examples presented here illustrate how simple changes in operational practice (e.g. CS-C1, CS-C4, CS-M1, AP-C5, AP-C7) can yield improvements in ecological outcomes for less, or minimal extra cost.

Physical, engineering and ecological context

The engineering, geomorphological and ecological feasibility of IGGI measures should be considered on a case-by-case basis. When deciding whether a coastal and estuarine IGGI measure is suitable, there are several key considerations:

What types of physical environments have they worked in?
What types of infrastructure can we apply this to?
What are the ecological factors that need to be considered?



Physical settings where IGGI measures have been applied.

What range of physical setting have these measures been applied?

These IGGI measures have been successfully applied from peri-urban to urban environments in open and sheltered coasts, in clear and muddy waters. Specific geomorphic suitability is detailed below.

What types of infrastructure?

These measures have been tested or applied to a range of coastal and estuarine infrastructure including armour, sea walls, harbour walls, earth embankments, stormwater outfalls, piers and sheet piling. These are grouped into 'vegetated', 'armour', 'sea walls' and 'other' according to what type of enhancement they are or what types of hard assets they have been applied on. A description, physical setting, and number of measures of each type are shown in the following table.

What ecological factors need to be considered?

It is important to consider the ecological suitability of the IGGI measures for a given location, and to consider impacts on habitat connectivity, risk of invasives and timing of installation to optimise colonisation by native species. The ecological suitability of different enhancements needs to be considered across the design life of the structure, taking into consideration predicted changes in sea level. As the design life of hard engineering structures is often 80-100 years, it is possible to create future habitat capacity as sea levels rise to reduce the risk of coastal squeeze. Further details are provided on the risks page of this business case.

Type	Description and infrastructure types	Physical settings*	No. of examples	Labels
Vegetated	Addition or altered maintenance of vegetation to earth embankment, concrete, stone or sheet piling defences	Estuarine	5	CS-C1 to CS-C3 AP-C1 CS-M1
Armour	Enhancing rock or concrete armour through material choice, retrofits or designed units	Open and sheltered coasts	6	CS-C4 AP-C2 to AP-C6
Seawalls	Enhancing sea wall design by adding habitat features in new builds or retrofits and adding textures to the wall fabric	Open and sheltered coasts and estuaries	6	CS-C5 to CS-C7 AP-C7 to AP-C9
Other	Enhancing other coastal assets including storm water outfalls and promenade	Estuary, Open Coast	2	CS-C8 AP-C10

* Summary of all settings, for specific geomorphic suitability see below.

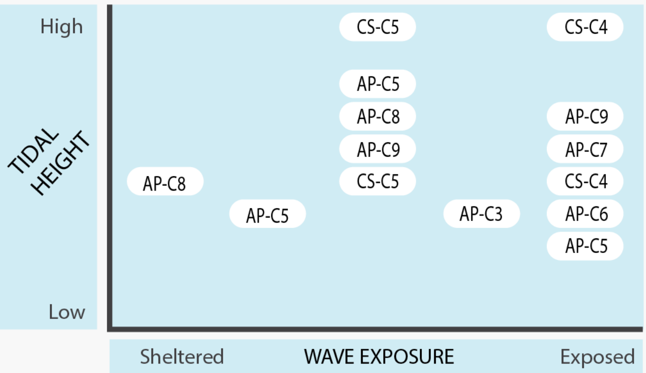
Geomorphic and engineering suitability

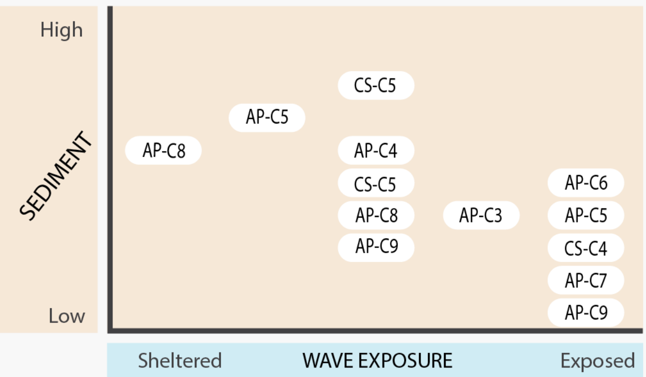
A key question practitioners face when deciding whether to implement an IGGI measure is whether it is feasible in the local geomorphology and engineering context of their project.

The graphs below provide an indication of the tidal heights, wave exposures, sediment loads and (for estuarine examples) water currents that the measures have been applied to date. These have been plotted for open coasts (including harbours within these) and estuaries. Where examples have been tested in more than one place, they are plotted multiple times to show the range of settings they have been tested in. Expert judgment from academics and practicing coastal engineers and geomorphologists has been used to make these graphs. The measures could be applied in a wider range of settings than those shown here; the information only indicates where they have been applied successfully so far.

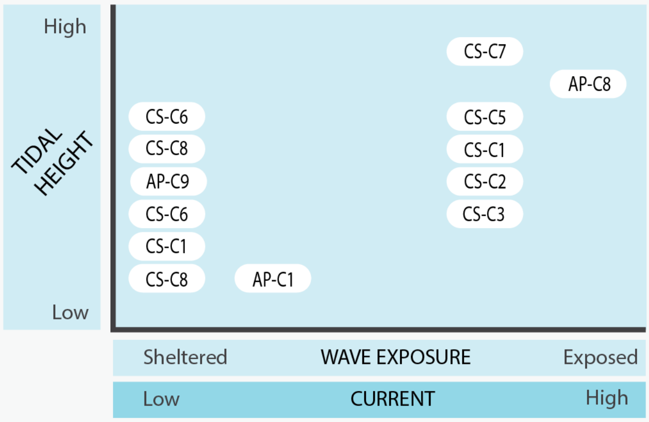
Most of the examples have been deployed between MLWS and MHWS, with MHWN being optimal for many of the measures. An important consideration here is climate change, which will drive sea level rise over the typical design life of engineered structures. There is some opportunity here to consider how IGGI measures may be positioned relative to both the current and future projected tidal frame in order to maximise engineering and ecological performance (see CS-C4).

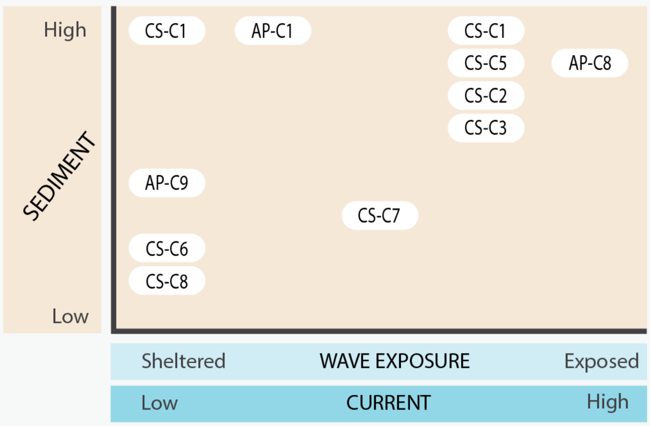
Coastal





Estuary (muddy and clear)





Known limitations or risks associated with these IGGI approaches

The ecological and engineering success of armour and seawall enhancements has been very high globally, with enhancements improving ecological outcomes within 6 to 12 months of deployment relative to business-as-usual approaches. Measures need to be designed for local ecology. Colonisation by native species has been found to reduce the risk of invasive species. There are some risks, design and construction considerations associated with these hard enhancements, as follows:

Risk Factor	Description and Risk Reduction Strategies
Long-term ecological value of material choice	Material choice is crucial alongside texture and microhabitat features; some coastal engineering materials (e.g. granite) may provide less habitat potential than more ecologically favourable materials (e.g. limestone) over the engineering design life. This is because of chemical composition and the way these materials naturally weather and erode over time.
Timing	IGGI measures should be installed to coincide with native species settlement/recruitment windows to reduce risk of invasives.
Deployment and engineering design	Any planned measures must be carefully evaluated in consultation with the engineering contractor, both to ensure performance is not compromised (there is no evidence that measured considered here have done this) and to consider practicality of deployment (e.g., placing blocks with a particular orientation).
Geography	IGGI measures for rocky intertidal species should be used where these provide important habitat stepping stones or nearby natural habitats; where no natural rocky habitat exists vegetated or WWNP approaches should be considered first.
Ecological connectivity & scale	The effects of IGGI measures on the wider food chain are thought to be positive (e.g. CS-C4, CS-C6) but for far there has been limited research on these impacts. IGGI measures can produce significant local biodiversity benefits but the broader-scale benefits (i.e., regional/national biodiversity maintenance) are less clear. Greatest potential comes from wide-spread uptake of a range of suitable local measures.
Coastal squeeze	IGGI measures can be used (in a limited manner compared with managed realignment) to address coastal squeeze where the policy decision is to ‘hold the line’ (e.g., CS-C4 and AP-C8).

Factors that should be considered for vegetated IGGI measures in the intertidal zone include:

Risk Factor	Description and Risk Reduction Strategies
Sediment supply	This needs to be sufficient for the measure being applied to be successful.
Vegetation failure	Planting or seeding can help reduce the risk of vegetation not establishing quickly.
Coastal squeeze	The design life of measures may be impacted by sea level rise and further mainte¬nance may be required to help lower shore communities ‘move in’. For example, fringing marshes or reed beds designed for mid-upper species (e.g. CS-C1, CS-C3) may be replaced with lower marsh species as sea levels rise.
Ecological connectivity and scale	The effects of vegetated IGGI measures on the wider food chain are thought to be positive but there has been limited research on this. IGGI measures can produce significant local benefits but the broader-scale benefits (i.e., regional/national biodiversity maintenance) are less clear. Greatest potential comes from wide-spread uptake of a range of suitable local measures.
Tidal height	When installing features to re-establish salt marsh, height in the tidal column is key, matching local natural salt marsh can prove effective to determine where to place gabions etc.
Gabion design	Gabion structures should be designed to remain intact for long enough for salt marsh to establish and sediment to be accreted, so that if/when the gabion fails the habitat is not compromised. Wire size, mesh size, welding, plastic coating, galvanisation, filling material and installation methods can all affect gabion design life.

Where to learn more

Coombes, M.A., La Marca, E.C., Naylor, L.A., Thompson, R.C. (2015). Getting into the groove: Opportunities to enhance the ecological value of hard coastal infrastructure using fine-scale surface textures. Ecological Engineering, 77: 314-323. https://doi.org/10.1016/j.ecoleng.2015.01.032

Coombes, M.A., Viles, H.A., Naylor, L.A., La Marca, E.C. (2017). Cool barnacles: Do common biogenic structures enhance or retard rates of deterioration of intertidal rocks and concrete? Science of the Total Environment, 580: 1034-1045. https://doi.org/10.1016/j.scitotenv.2016.12.058

Cousins, L.J., M.S. Cousins, T. Gardiner, Underwood, G.J.C. (2017). Factors influencing the initial establishment of salt marsh vegetation on engineered sea wall terraces in south east England. Ocean & Coastal Management, 143: 96-104. Doi: 10.1016/j.ocecoaman.2016.11.010.

Dennis, H., Evans, A., Banner, A., Moore, P. (2017). Reefcrete: Reducing the environmental footprint of concrete for eco-engineering marine structures. Ecological Engineering. https://doi.org/10.1016/j.ecoleng.2017.05.031

Environment Agency. (2008). Estuary Edges Design Guide. http://thamesestuarypartnership.org/our-projects/estuary-edges/

Environment Agency. (2010). Flood & Coastal Erosion Risk Management appraisal guidance. Supporting Document for the Appraisal Summary Table. March 2010.

Environment Agency. (2012). Greater working with natural processes in flood & coastal erosion risk management: A response to Pitt Review Recommendation 27. pp. 74. URL: http://webarchive.nationalarchives.gov.uk/20140329112033/http://cdn.environment-agency.gov.uk/geho0310bsfi-e-e.pdf

Environment Agency, (2015). Cost estimation of coastal protection – summary of evidence. URL: www.evidence.environment-agency.gov.uk/.../SC080039_cost_coastal_protection.sflb.ashx

Evans, A., Garrod, B., Moore, P., Firth, L.B., Hawkins, S.J., Morris, E., Goudge, H., Moore, P. (2017). Stakeholder priorities for multi-functional coastal defence developments and steps to effective implementation. Marine Policy, 75: 143-155. https://doi.org/10.1016/j.marpol.2016.10.006

Firth, L.B., et. al. (2016). Ocean sprawl: challenges & opportunitiesfor biodiversity management in a changing world. Oceanography & Marine Biology: An Annual Review, 54: 193-269.

Firth, L.B., et al. (2013). The importance of water-retaining features for biodiversity on artificial intertidal coastal defence structures. Diversity & Distributions, 19: 1275-1283. DOI: 10.1111/ddi.12079

Hall, A.E (2017) The Ecology and Ecological Enhancement of Artificial Coastal Structures. PhD Thesis. Bournemouth University

Naylor, L.A., J. Dobson, D. Hetherington, F. Maxwell, M.A. Coombes, H. Viles, Metcalfe, D. (2014). Enhancing hard infrastructure for improved multifunctionality. CIRIA Briefing Note, http://www.ciria.org/Events/Enhancing_hard_ infrastructure_for_improved_multifunctionality.aspx.

Naylor, L.A., MacArthur, M., Hampshire, S., Bostock, K., Coombes, M.A., Hansom, J.D., Byrne, R. & Folland, T. Under revision. Rock armour for birds: Ecological enhancement of coastal engineering to provide food for birds, Hartlepool Headland, UK. ICE Journal of Maritime Engineering.

Naylor, L.A., Venn, O., Coombes, M.A., Thompson, RC, Jackson, J.T. (2011). Including Ecological Enhancementsin the Planning, Design & Construction of Hard Coastal Structures: A process guide. Report to the Environment Agency (PID 110461). University of Exeter, 66 pp.

Strain EMA, et al. (2017). Eco-engineering urban infrastructure for marine and coastal biodiversity: Which interventions have the greatest ecological benefit? Journal of Applied Ecology. 00:1–16. https://doi.org/10.1111/1365-2664.12961

How to cite: Naylor, LA., Kippen, H, Coombes, MA., et al. (2017). Greening the Grey: a framework for integrated green grey infrastructure (IGGI). University of Glasgow report. URL: http://eprints.gla.ac.uk/150672/

Coastal Case Studies

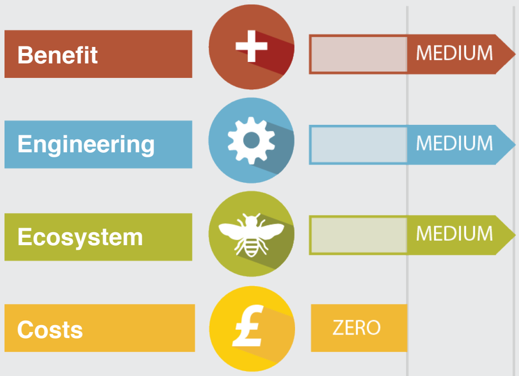
Case Study CS-C1:

Salt marsh on engineered sea defence repair

Summary

The UK has an extensive network of sea defences already in place. Repair and maintenance work accounts for a little less than half the UK Governments planned spending here between 2016 and 2021 (£1bn of a £2.3bn total). Presuming repair costs per metre are significantly lower than new build, the potential for enhancement will be greater in retrofitting existing structures with innovations in green grey infrastructure than in applying them on wholesale replacement or new build scenarios. As an alternative to traditional engineering repairs, twelve experimental stone gabion and clay filled terraces (Fig. 1) were installed in Essex in 2012 by the Environment Agency. The purpose of the repair work was twofold; to protect the toe from wave action and to enhance habitat provision by re-establishing lost salt marsh habitat.

The clay was excavated locally and the borrow pits created additional saline lagoon and/or freshwater habitats.



How does it work?

Sea defences are relatively costly to install, maintain and repair. Climate change predictions describe significant increases in the future frequency and intensity of storm events, while much of the UKs 2100 km of earthen seawall raised after the 1953 North Sea flood event is approaching the end of its design life. The Environment Agency developed some pilot schemes to determine the potential to introduce naturally self-managing systems. Here the traditional repair was enhanced using an extended and raised gabion toe and locally extracted clay backfill to attempt to replace eroded salt marsh.

Where sea level rises inundate these areas within their design life these techniques will be relatively short-term solutions, particularly if the gabions fail and the height of the terrace lowers. However, the repair work is at a similar price to traditional repair, which in itself is not future proofed, and it produces habitat that can accrete material, reduce the impact of chronic and intense wave action (and so reduce the cost of future repair work) is useful in maintaining biodiversity that can improve climate change resilience and provides a source of propagules etc. to spread. It can also provide other valuable ecosystem services, fish nursery and amenity/aesthetic value.

Motivation

An on-site inspection showed that small areas of wall had deteriorated where salt marsh protection was limited or non-existent. In an attempt to regenerate the salt marsh protection, the repaired structure was designed to create habitat (between mid tide level and mean high water neap) that encouraged colonisation by salt marsh species.

Design innovation / Enhancement measure

Replacing traditional like-for-like sea wall revetment repair materials (e.g. Essex blocks or open stone asphalt) with gabion baskets and clay back fill in a toe design that helps re-establish salt marsh habitat in a sheltered estuarine setting.

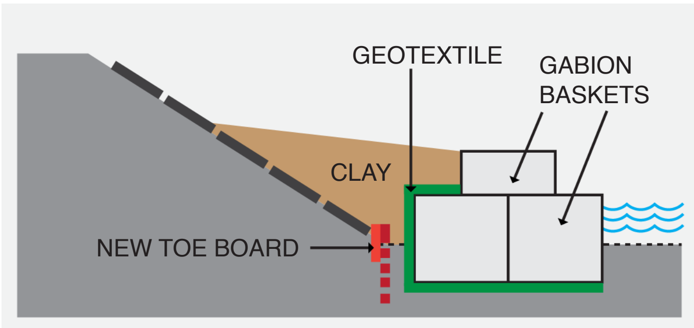
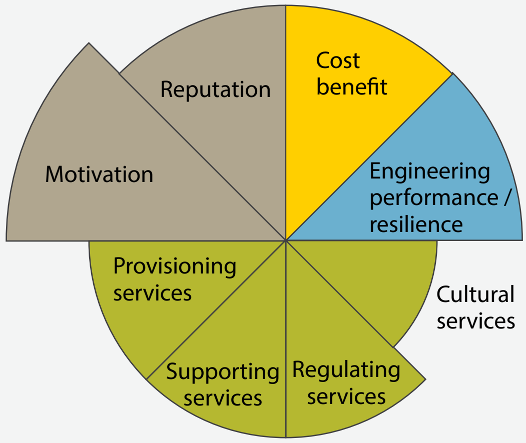


Figure 1. Example of repair work, new berm backfilled with clay behind stone gabions. The clay area provided habitat for saltmarsh plants.

Benefits

The trial vegetated terraces were only very slightly more expensive than traditional repair costs and have the potential to provide significant protection to the defences as well as a range of ecosystem service benefits.

Estimates in 2010 gave ecosystem value figures of, on average, £960 per ha per year for salt marsh (and a range from £200 - £4,500). These values relate to habitat gains (Brander et al, 2008). However, if the area is/could be used as commercial fish nursery, value may be higher. This could be estimated by calculating the difference between the value of land in its current use and the value of land as a nursery. Alternatively, one could estimate the annual revenue of a fish nursery.



Net Cost

The net cost per metre is around £660 to repair revetment and add gabions backfilled with clay.

Direct cost of intervention

If only toe repair is required, the green infrastructure element will form the entirety of the repair at similar cost to traditional repair work. Where other repairs are required further up the revetment then the GI will be an intrinsic component (the gabion baskets and clay backfill) of this larger work.

Cost compared to business-as-usual

To retrofit a terrace it would cost around £660/m, where additional costs are for the gabion baskets and clay backfill. This is very similar to the traditional blockwork repair to the toe that typically costs £631/m (Cousins et al, 2017).

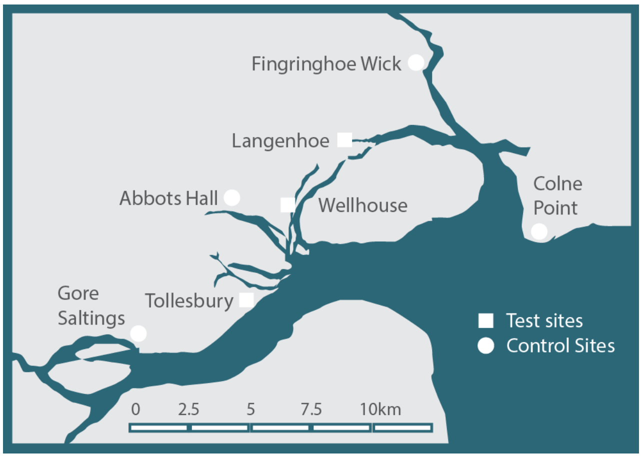
Long-term cost

Salt marsh can protect against wave and storm action. Where significant width of salt marsh becomes established successfully, it may be possible to reduce the height of landward coastal defences. The potential for narrower, fringing saltmarshes (as described here) to provide this benefit needs further testing but they could reduce maintenance and repair costs of the coastal walls they front by buffering waves. Increased storminess may mean that including naturally resilient elements in becomes increasingly important. In the longer term, a limiting factor or these measures may be the ability of the terraces to maintain their flood alleviation and ecological value as sea level rises. These risks also exist for traditional approaches; where space allows future flood alleviation can be set back to provide more intertidal habitat to help maintain ecosystem service benefits (AP-C1).

Engineering performance, inspection and maintenance

The combined gabion and saltmarsh habitat was designed and constructed by the Environment Agency, through their coastal management team, and installed by EA-approved engineering contractors.

The overall integrity of the scheme was tested under significant tidal and storm surge conditions in early December 2013 with no loss of structural integrity. Research shows there was some small channelling at the ends of each section where water flows increased scour, and while this removed some clay sediments, it had no impact structurally. It was postulated by the research team that this could be negated by a slight change in design. They advise a return gabion closing off any flows between the ends and the sloped surface of the berm.



Ecosystem services

Over 22 months of monitoring by the University of Essex found that each terrace provided a narrow strip of otherwise unavailable sediment substrata that had potential to support salt marsh vegetation. Though salt marsh development can take time to fully develop, seven of the twelve terraces showed increased colonisation by salt marsh plant species, up to 85% coverage after 22 months. Factors such as the depth of the gabion, the proximity to existing salt marsh, flow rates and sediment compaction were important factors influencing the ecological success of the design. Studies suggest this could be improved with more precise placing – right level.

An initial driver for the scheme was to mitigate for habitat loss, which was achieved (Cousins et al, 2017). The provision of wider ecosystem services requires additional study. Local salt marsh does provide some habitat for fish (refuge, nursery and feeding) and feeding, roosting and nesting sites for various species of shorebirds.

Recent research suggests relatively small areas are proportionately more productive as fish fry refuges than large areas. Some salt marsh plants are edible and there is some commercial interest in growing samphire, which could increase the benefits of this approach compared to business as usual.

Social value

Although no social value data were gathered within the study, there is evidence to suggest there is some amenity value in natural habitats like salt marsh; landscape aesthetics and as sport and commercial fish habitats.

Who can apply this intervention / technique?

Any landowner, local authority or government agency with suitable grassland habitat.

Scaling up the benefits

Additional trials are currently underway in the South East of England to improve the evidence base and spatial area that it has been tested.

Annual engineering inspections show that on average around 5% or more of the existing infrastructure is failing, so there is potential to include this approach as part of ongoing repair activity. In many areas the installation costs are prohibitive for individual spot fixes (lengthy permitting processes, access (plant and materials)). It is thus better suited as part of larger or more strategic repairs.

Data Quality

The table shows the relative strengths of the Economic, Technical and Environmental data available. They are classified as:

Scheme Specific
part of a PhD or similar detailed research

Expert Judgment
interpretation of the scheme by one or more experts

Wider Supporting Evidence
extrapolated from published work or reports by practitioners.

DATA TYPE	DATA QUALITY / QUANTITY						
	Scheme specific information			Expert judgement		Wider supporting evidence	
	No Data	Limited reported sources	Strong reported sources	Some expert opinion	Multiple experts	Some sources	Multiple sources
COST		●			●		
ENGINEERING		●			●		
ECOSYSTEM SERVICES			●		●	●	

Further information / Contacts

Brander, L.M., et al. (2008). Scaling up ecosystem services values: methodology, applicability and a case study, Report to European Environment Agency https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/487240/LIT_10352.pdf

Cousins, L.J., et al. (2017). Factors influencing the initial establishment of salt marsh vegetation on engineered sea wall terraces in south east England. Ocean & Coastal Management, 143: 96-104. Doi: 10.1016/j.ocecoaman.2016.11.010.

Landscape Institute (2015) Green Bridges Guide. London: Landscape Institute. URL: https://www.landscapeinstitute.org/wp-content/uploads/2016/01/TGN9_15Green-Bridges-Guide_LI-300dpi.pdf

Naylor, L.A., Coombes, M.A., Kippen, H., Horton, B., Gardiner, Cordell, M.R., Simm, J., Underwood, G.J.C. (2017). Developing a business case for greening hard coastal and estuarine infrastructure: preliminary results. ICE Coastal Breakwaters 2017 Proceedings.

Contacts:
Prof. Graham Underwood, University of Essex: gjcu@essex.ac.uk, @GJCUnderwood

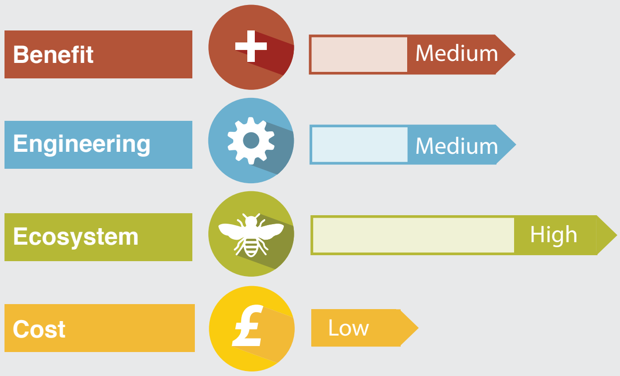
Case Study CS-C2:

Salt marsh creation in an urban area

Summary

Under the Government Sustainable Communities Fund, the Environment Agency aimed to create new mudflat and salt marsh to increase flood storage capacity of Barking Creek (and tributary of the River Thames) and provide Biodiversity Action Plan habitat.

As the area is heavily urbanised, substantial saltmarsh and mudflat habitat had been reclaimed over the past few hundred years. This scheme improved the social, amenity and ecological value of an underused and undervalued species poor grassland site that had limited ecological, social or flood storage value by re-creating one hectare of mudflat and saltmarsh Biodiversity Action Plan habitat. The habitat was built alongside improvements to flood alleviation, adding amenity and ecological value such as creating nursery habitat for commercial and non-commercial fish species and increasing flood storage by 15,000 m³.



How does it work?

Small-scale set back of sea defences on an estuary. Original sea defences were deliberately breached, creating tidal backwater habitats in a sheltered, high sediment load estuarine setting. A 0.1 ha tidal mudflat between mean low water spring (MLWS) and mean low water neap (MLWN) and a 0.9 ha of saltmarsh habitat between MLWN and mean high water neap (MHWN) were re-created, adding 15,000 m³ of flood storage capacity. Brushwood and coir revetment structures were installed, and the structure was allowed to colonise naturally as well as by seeding the upper slopes using locally collected seeds from the river's own seed-bank.

Motivation

This project aimed to increase flood storage capacity on the Thames and provide valuable for local Biodiversity Action Plan saltmarsh and mudflat habitat. It also aimed to address social factors: to improve access via the creation of a new river pathway; to improve the aesthetics of the riverside-area; to provide educational interpretation boards for the general public. Barking Creek is recognised as a valuable feeding and refuge area for a variety of fish species e.g. European flounder, European eel, bass, sand smelt and also supports some commercial European eel fishing (Colclough et al., 2002). Enhancing and extending the upper intertidal habitat was aimed at benefiting these fisheries.

Design Innovation / Enhancement measure

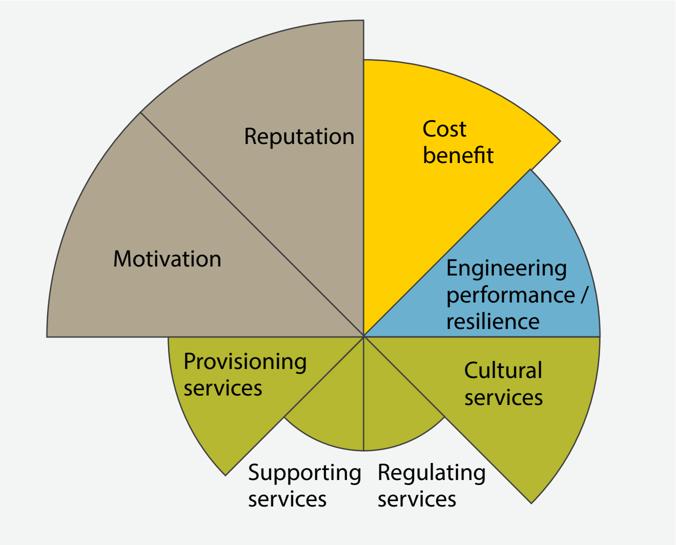
Losing land to water to improve biodiversity and visual amenity. A formal green space behind the tidal defence was changed to create a tidally inundated area. The technique had been used previously, but combining hard engineering around the site and much softer techniques (such as brushwood) ensured the tidal setback remained stable.

Benefits

The benefits of the flood mitigation element were carefully assessed by the Environment Agency to outweigh the costs. The greening elements have proven successful in stabilising the area and have largely improved the aesthetic.

Although a relatively small measure, the inclusion of the ecosystem enhancements will likely have had some localised effects on the environment by providing flood storage, sequestering carbon and helping to clean run-off water (by trapping pollutants) before it reaches the Creek.

Mudflat and saltmarsh rapidly established after installation, improving habitat provision for overwintering birds and providing nursery sites and food for commercially important fish. No data are available regarding public perception of the scheme, but similar enhancement work on the Thames and its tributaries (as well as rivers in other cities) has proven to have positive social affects. There is limited data evidencing these benefits to date, but the EA is currently measuring some of the Water Framework Directive related ecosystem services that these enhancements are providing in the Thames region.



Net Cost

Based on 2006 construction costs, for the habitat re-creation aspect of the scheme only, the net construction cost per m² is estimated to be ~£108. This compares to a total cost of approximately £146 per m² for the combined flood alleviation and habitat re-creation works carried out at the site.

Direct cost of intervention

The construction costs for the habitat re-creation part of the scheme was £210K; this was completed alongside a small amount of flood alleviation repair works that cost £74K (2006 prices). As a result significantly greater enhancements were delivered at this site than would have been possible had the projects been delivered individually. This approach also made best use of the design consultant and contractor services, reducing construction costs. There were also no land purchase costs as the land was already owned by the Environment Agency (EA), providing substantive savings (£900/m², 2017 land prices).

Cost compared to business as usual

This case study was funded via environmental improvement funding (for sustainable communities) from central government, and this option was the deemed the most cost effective during options appraisal. As the EA owned the land, the cost was reduced by approximately £900/m² (£9M per hectare, 2017 prices) compared to having to purchase off-site compensatory habitat. The re-created creek, footpath and landscaping occupied 40% (1 ha) of the total ~2.5 ha owned by the EA. This case study illustrates the potential for small-scale intertidal habitat re-creation projects to provide on-site net ecological gain, reducing the need for costly off-site mitigation. Off-site mitigation would have cost a minimum of £9M (2017 land prices) to purchase land to re-create the habitat elsewhere.

Long-term cost

Long-term maintenance of the scheme is not expected to cost more than for other managed realignment schemes elsewhere as the saltmarsh community is well-established and the gradual slope of the design will make it easier for species to adapt as sea level rises, likely reducing future maintenance costs.

Engineering performance, inspection and maintenance

The existing land level was excavated away to slopes less than 1:7, and clay capped with the newly created sediment surface stabilised with natural posts and brushwood (Environment Agency, 2008). This provided a stable substrate for natural and seeded (2 g/m^2 of locally collected seeds) colonisation that has proven very successful, with 40 cm of sedimentation within 6 months of installation and swift vegetation growth. The set-back has required little or no maintenance since it was created 11 years ago.

This case study demonstrates that well-designed and installed natural brushwood and vegetation bioengineered system can provide low cost, self-regenerating flood storage.

Ecosystem services

Prior to regeneration the Creekmouth site was terrestrial grassland with patches of scrub and invasive *Fallopia japonica* (Japanese Knotweed), providing few ecosystem services for nature or society. The regeneration scheme included habitat re-creation, educational and recreational elements. After breaching, the intertidal area was left to colonise naturally, rapidly attracting many native species. The EA identified four broad ecological zones: (1) the terrestrial zone – approximately 0.5 m below spring high tide level. This comprised of common herbs, including *Lotus corniculatus, Plantagomajor, Tripleurospermum maritimum, Chrysanthemum leucanthemum, Artemisia vulgaris* and *Sanguisorba minor*; (2) the marginal wetland zone – where tidal inundation determines species composition including *Aster tripolium, Apium graveolens, Beta vulgaris, Ranunculus scleratus, Elymus pycnanthus, Agrostis stolonifera* and *Apium graveolens*; (3) and (4) two lower zones of sedimentation where maximum silt deposition occurs, dominated by *Phragmites australis* and *Scirpus maritimus*. Locally, these foreshore habitats are known to be important for overwintering birds such as teal, shelduck, tufted duck, wigeon, gadwell, shoveler, pintail and little grebe. Common whitethroat, sand martins, linnet and oyster catchers were recorded breeding in the foreshore near this scheme in 2000. With the plant species that have colonised the site, it is highly likely that these bird species have also benefitted from the additional habitat.

Estimates suggest that around two thirds of commercially important fish caught are dependent on estuarine habitat in their juvenile years and that the Thames Estuary is a key nursery site for fish (Colclough et al. 2002) where tidal creeks such as Barking provide specialised refugia (Tyner, 1993). There is clear evidence that mudflat and saltmarsh habitat provides fish refugia that are important for maintaining and improving commercial fish populations. Saltmarshes are very dynamic habitats, and short-term quantitative estimates can be highly inaccurate, but fish sampling at realignments similar to this elsewhere in the inner Thames (see CS-C3) have shown there were increases in commercial fish species.

These more natural habitats provide aesthetic and ecological benefit, helping to create a better link between the river and the surrounding area. This was aided through the provision of 310 m of footpaths within wildflower-rich parkland as part of the scheme; these have provided, closer access to the river and the new estuarine habitats. Interpretation panels were also installed to help local users learn about estuarine ecosystems and the value the newly created habitat provides, improving the cultural ecosystem services provided by the site.

Social value

The triple-win benefits of increased flood capacity in an urban area, habitat creation (with commercial and aesthetic value) and improved access make this a potentially appealing innovation.

Who can apply this intervention / technique?

Land managers with responsibility for riparian areas prone to flooding. Specialist guidance may be required where flooding could cause damage to property or infrastructure.

Scaling up the benefits

An increasing array of more environmentally sensitive flood management tools are being developed and described in guidance from “No Intervention” options through to “Working With Natural Processes” (WWNP) and green, or green/grey options. Many projects can include a number of these.

This mainly green grey project was an attempt to improve social, environmental and, to some degree, economic aspects of the Creek mouth, e.g. flood storage to alleviate flood risk, provide environmental education and improve habitat for commercial fish stocks.

Data Quality

The table shows the relative strengths of the Economic, Technical and Environmental data available. They are classified as:

Scheme Specific
part of a PhD or similar detailed research

Expert Judgment
interpretation of the scheme by one or more experts

Wider Supporting Evidence
extrapolated from published work or reports by practitioners.

DATA TYPE	DATA QUALITY / QUANTITY						
	Scheme specific information			Expert judgement		Wider supporting evidence	
	No Data	Limited reported sources	Strong reported sources	Some expert opinion	Multiple experts	Some sources	Multiple sources
COST		●				●	
ENGINEERING			●			●	
ECOSYSTEM SERVICES		●				●	

Further information / Contacts

Colclough, S. R., Gray, G., Bark, A. and Knights, B. (2002). Fish and fisheries of the tidal Thames: management of the modern resource, research aims and future pressures. Journal of Fish Biology, 61: 64–73. doi:10.1111/j.1095-8649.2002.tb01762.x

Colclough, S., Fonseca, L., Astley, T, Thomas, K, Watts, W. (2005). Fish utilisation of managed realignments, Fisheries Management and Ecology, 12: 351

Environment Agency. (2008). Estuary Edges Design Guide. http://thamesestuarypartnership.org/our-projects/estuary-edges/

Tyner, R. (1993). A Fish Population Survey in Barking Creek. Bristol: National Rivers Authority.

Joanna Heisse, Environment Agency:
joanna.heisse@environment-agency.gov.uk

COASTAL

Case Study CS-C3:

Intertidal vegetated terraces

Summary

Only 2% of natural habitat remains along the Thames. The traditional engineered defences that have been employed over many decades do not reproduce the range or quantity of habitats they replace, nor do they encourage colonisation by native species.

Two areas of inter-tidal terracing were created on the Greenwich Peninsula, London; one at Blackwall Point and the other at the Eastern River Wall.

Benefit	MEDIUM
Engineering	MEDIUM
Ecosystem	MEDIUM
Costs	LOW

How does it work?

This enhancement is a structurally engineered design combining both IGGI and traditional grey engineering elemetns. At two locations in Greenwich, sheet pile wall was cut down to near beach level and capped and either sheet piling or a concrete wall was installed between 7-15 m inland. This extended the area between Mean High Water Neap and Mean High Water Spring tide levels, where the newly created intertidal space was designed to provide saltmarsh habitat.

Motivation

The sheet piling was approaching the end of its design life and the area was soon to host the Millennium celebrations at the Dome. The area was heavily industrialised and aesthetically unappealing. The Environment Agency felt there was a good opportunity to repair the sheet piling and improve the area using best practice for nature conservation, fisheries (nursery, refuge and marginal feeding zones) and environmental education. A stated aim was "*To develop and maintain healthy, diverse and attractive inter-tidal ecosystems on the terrace in the long term; to ensure that their ecological development was recorded and disseminated to help other river flood schemes develop*".

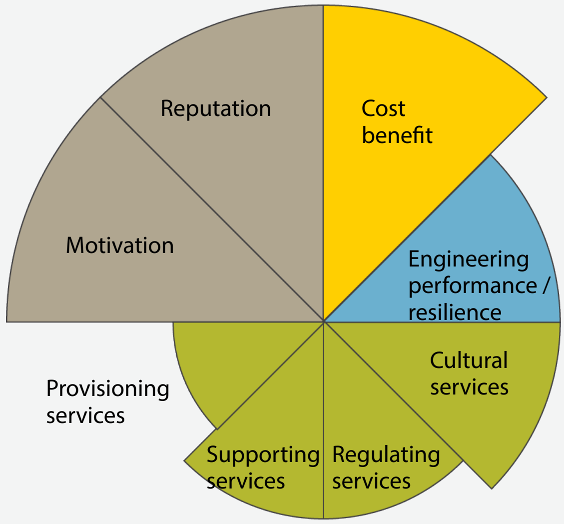
Design Innovation / Enhancement measure

Existing sheet piling that was in poor condition was cut down to near beach level and capped. New sheet piling or a concrete wall was installed between 7 – 15 metres inland. This space between the old and new sheet piling (or concrete wall) was then used to create stepped and/or sloped saltmarsh habitat between mean high water neap (MHWN) and mean high water spring (MHWS) tide levels. Stepped terraces were created using gabions or wooden piles at slopes of 1:7 or less and in-filled with sediment of similar characteristics to that found locally. These areas were planted with saltmarsh species or allowed to colonise naturally.

Benefits

Designed to maximise aesthetic value, this project saved around half the business-as-usual costs and provided a relatively small but important and visually appealing habitat. The wider area was heavily industrialised, urban and densely populated, and was to become the focus for the UK's Millennium celebrations. The cultural services have not been monitored though there is anecdotal evidence that the sites provided significant aesthetic appeal.

Extrapolation from other small-scale estuarine habitat regeneration projects suggest these provide significant benefits for fish (for nurseries, refuge and feeding). The vegetation provides some locally significant primary production and nutrient recycling services alongside potential capacity for run-off retention and amelioration of contaminants/pollutants. The vegetation can accrete material and attenuate erosion from waves. Elsewhere, enhanced riverfront schemes have been shown to uplift property prices by 3 to 10%.



Net Cost

The net per m cost of the terraced saltmarsh habitat component of the £12m scheme is unknown.

Direct cost of intervention

The direct cost of building the terraced habitat included the costs of removing and capping most of existing sheet piling, installing replacement sheet piling and/or concrete wall inland, creating and planting the terraces. Some initial monitoring and replanting of the scheme was also required, along with building footpaths and signage. These costs amounted to £12M (1998 prices), which equates to approximately £17K per linear m.

Cost compared to business-as-usual

The cost of the structurally engineered design involving both newly built set-back defences and saltmarsh terraces was approximately half the anticipated cost of removing, disposing of and replacing the existing sheet piling. During the options appraisal for the scheme (1996 prices), a few different options were estimated over a 60-year whole life cost including full height replacement of the old sheet piling with new sheet piling (£6000 per m) or encroachment using battered terracing (£8100 per m). This compared to £3400 per m to lower the sheet piling by 4.0 m and create an inclined terrace (Atkins, 1996). Discussions with the Environment Agency team have suggested that replacement sheet piling in this estuarine setting would cost between £10K - £24K per m now (2017 prices).

Long-term cost

After some initial difficulties with disturbance of the installed materials (geotextiles, vegetated matting and planted material) the terraces are largely self-managing. Where amenity planting was done there was a need for some maintenance and certain species became dominant, although this could be prevented in future installations. Litter and debris can accumulate quickly and needs to be removed.

Engineering performance, inspection and maintenance

Overall considered to be highly successful, a benchmark design. Some deterioration - gabions breaking down after ten years (thought to be because welded gabions were chosen over woven or plastic coated) and repairs/renewals may be necessary to retain certain terraces.

Initially some wave action led to lifting of the matting and extraction of many young plants, necessitating some replanting, though there was also considerable natural colonisation. Design modifications mean this could be prevented in future installations. Freshwater outfalls exposed the reinforced geotextile mat and eventually looked unsightly.

Overall performance was found not to be reduced – terraces are able to withstand tidal and wake forces. Inspection and maintenance still possible.

Ecosystem services

As the only intertidal vegetated habitat in this part of the Thames, the Millennium Terraces provide a valuable area of habitat. Re-planting directly into the substrate without erosion matting was most successful with Common Reed, Grey Club-rush, Sea Club-rush and Sea Aster, with several species surviving well below or above the main 'saltmarsh zone'. Excessive dominance by Common Reed was seen as the result of a failure to install rhizome breaks.

A design feature – the stepped terraces – appeared to stop some fish from moving up the terrace floor (sampling in 2003 showed the terraces with steep angle frontages restrict demersal species, e.g. Flounder. Other smaller fish like Gobies moved onto the terraces during inundation. Smelt (Osmerus eperlanus) were found deep in the vegetation at the back and front of the terraces. Extensive monitoring has shown intense use of the terraces by Sea Bass and other species.

The additional habitat also provides other opportunities for biodiversity including pollinator species and their food plants. The site provides some degree of water quality control (retaining and remediating run-off), and because the project was an exemplar and the monitoring is on-going, there is some cultural and scientific value. Some aesthetic improvement also was achieved.

Social value

Thought to be high but not assessed directly. In 2001 the Greenwich Peninsula Management Plan stated “the terraces serve a major function in terms of visual amenity for pedestrians, the inhabitants of Central Village and visitors to the Dome”. Economic valuation of urban riverside enhancements show property price uplift in the order of 3 to 10%. This has not been directly meas¬ured here, but the terraces have been used in property marketing literature.

The terraces were constructed primarily for the purposes of nature conservation, fisheries and environmental education. There is no unauthorised access to the terraces and no navigational or mooring function, nor local fishing access. Where ecological and safety constraints permit, access could be improved in other similar schemes by a variety of slipways or floating pontoons.

Who can apply this intervention / technique?

Those involved in installing or repairing riparian, estuarine and coastal defences that currently provide low quality/ low biodiversity habitats.

Scaling up the benefits

A key goal of the scheme was to disseminate the monitoring data: to assist in the guidance and development of other river flood schemes in London and elsewhere.

Data Quality

The table shows the relative strengths of the Economic, Technical and Environmental data available. They are classified as:

Scheme Specific
part of a PhD or similar detailed research

Expert Judgment
interpretation of the scheme by one or more experts

Wider Supporting Evidence
extrapolated from published work or reports by practitioners.

DATA TYPE	DATA QUALITY / QUANTITY						
	Scheme specific information			Expert judgement		Wider supporting evidence	
	No Data	Limited reported sources	Strong reported sources	Some expert opinion	Multiple experts	Some sources	Multiple sources
COST				●			
ENGINEERING					●		
ECOSYSTEM SERVICES		●			●		

Further information / Contacts

Atkins, WS. (1996). Greenwich millennium riverside options study.

Colclough, S., Fonseca, L., Astley, T., Thomas, K., Watts, W. (2005). Fish utilisation of managed realignments. Fisheries Management and Ecology, 12: 351–360.

Environment Agency. (2008). Estuary Edges Design Guide. http://thamesestuarypartnership.org/our-projects/estuary-edges/

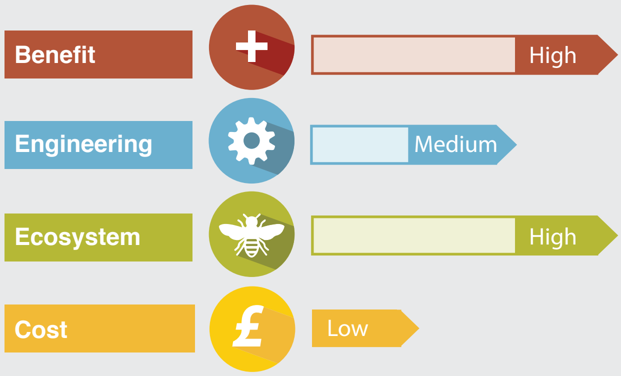
Contacts:
Joanna Heisse, Environment Agency:
joanna.heisse@environment-agency.gov.uk
Dr. Richard Charman, Environment Agency:
Richard.charman@environment-agency.gov.uk

Case Study CS-C4:

Open coast habitat creation using rock armour

Summary

A decision was made to repair and replace the extensive sea defences around Hartlepool, UK. The Headland coastal defences protect 562 residential, commercial properties and key heritage features. These defences, north-east facing vertical masonry and concrete walls were in poor condition, frequently overtopped during storms and suffered significant damage during the winter 2013/2014 storms. The project, funded by the Project for Accelerated Growth (PAG) Scheme, included a partnership between the Environment Agency (EA), Hartlepool Borough Council and PD Ports, with support from the nature conservation body Natural England (NE) for the ecological enhancement as Habitats Directive mitigation.



How does it work?

The design of the scheme included innovative techniques of passive and active ecological enhancement to provide habitat that provided sufficient habitat to support wintering feeding populations of internationally designated bird species. This involved a combination of measures:

- Passive enhancement involving: a) ecologically favourable material choice within cost and engineering constraints and b) placing specially selected naturally textured stones in positions to encourage colonization.
- Active enhancement involving the use of textured form liners (similar to those in AP-C8) when casting wall panels.

This project aimed to build on wider research showing ecologically engineering artificial habitats, either during the construction phase or retrospectively, can result in higher species diversity. Data from on-going comparative studies underpins this case study. University of Glasgow, University of Oxford, Hartlepool Borough Council and Mott MacDonald carried out pre-construction baseline surveys, both at the site and at a neighbouring control site. Monitoring is ongoing; results of the passive enhancement are currently available and are presented here.

Motivation

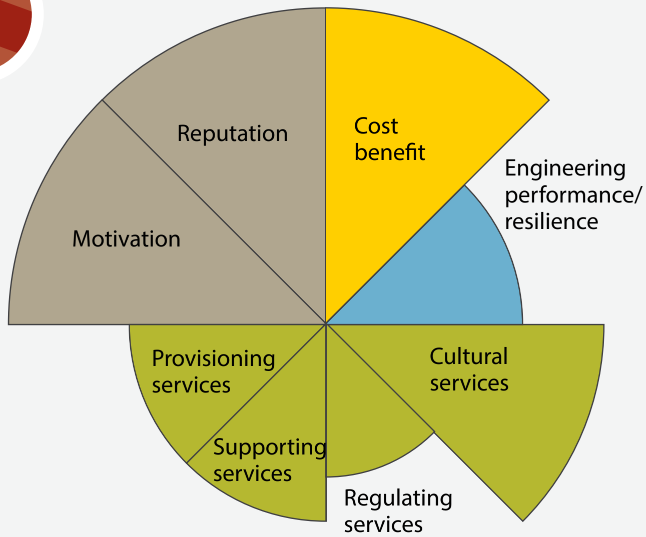
The coastal protection works are within a Ramsar site (JNCC 2008) and a Site of Special Scientific Interest (SSSI) (Natural England 1997) that contains some of the most important overwintering bird feeding sites in Britain for designated species. A key requirement was thus to provide mitigation under the EU Habitats Directive to reduce the ecological impact of habitat losses associated with extending the toe of the defences seaward. The aim was to ensure no adverse effects on the integrity of a Natura 2000 site designated for internationally important waterbirds. It also sought to minimise future habitat losses due to sea level rise and coastal squeeze.

Design Innovation / Enhancement measure

In order to achieve a habitat outcome that most closely mimicked the existing rocky shores at Hartlepool, and offered feeding opportunities for the waterbirds, the scheme employed a combination of passive and active multi-scale enhancements. Passive techniques (e.g. choosing construction materials based on lithology and surface roughness) were used on the rock armour and more active enhancements (similar to AP-C8) sought to improve the habitat and aesthetic value of the wall panels (similar to CS-C6). Both are simple and inexpensive, adding no or nominal additional costs compared to business-as-usual. To date, it is also the largest and only the fourth known operational ecological enhancement of hard coastal infrastructure in the UK (after Shaldon in Devon, the Isle of Wight and Bournemouth) (Naylor et al. 2012; Arc Consulting 2016).

Benefits

The ecological enhancements were crucial to gaining approval for the scheme from Natural England; they allowed the local council to access time-limited central government funding. Ecologically, early monitoring of the scheme suggests that it is meeting the aim of providing a cost effective, ecologically sensitive coastal defence with long-term enhancement value that meets the needs of the local businesses and residents. The textured walls and the ecologically favourable rock armour are performing as well as traditional techniques having survived strong storms during the winter of 2017. It demonstrates it is possible to ensure that the planned engineering resilience to storm events is achieved with the additional benefit of maintaining ecological value and thus providing on site mitigation.



Net Cost

Overall the net cost of the IGGI aspects of this coastal flood alleviation scheme are close to zero. For the passive enhancement, selecting ecologically favourable granite was not onerous nor more expensive, where the recommended rock characteristics were available within an acceptable distance from a customary supplier and could be delivered on time and in sufficient quantity. For the rock armour that was enhanced further via positioning, no extra costs were incurred during construction. Good communication and planning meant that the additional complexities in selecting and placing the appropriate stone blocks to maximise habitat did not add to the build time or costs. For the active enhancement of wall panels using textured formwork, there were modest additional costs, which are detailed in AP-C8. Ecological monitoring has been funded through collaboration with the Universities of Glasgow and Oxford.

Direct cost of intervention

Close to zero. For the passive enhancement, existing expert judgment was used to select suitable rock material from the supplier, and experienced operators placed the rock armour on-site. This did not incur any additional cost as the operator had to make minor adjustments to the deployment procedure to position the rocks to maximize ecological potential. For the active enhancement, it cost an extra £8-£30 per m^2 compared to plain cast formwork (see AP-C8 for more detail).

Cost compared to business-as-usual

No significant increase in cost. Enhanced rock was placed at conventional rates (10m/day/tide). The scheme also won timely approval because of the enhancements – this allowed the council to access time-limited central funding, reducing the local cost burden.

Long-term cost

No additional long-term cost anticipated. This is essentially an adaptation of business-as-usual to accommodate for significant bird population habitat and pre-empt coastal squeeze. If the longer-term ecological outcomes need improving, ideas from AP-C4 – AP-C6 can be added.

Engineering performance, inspection and maintenance

The scheme has a design life of 80 years. Aside from the resulting additional colonisation and biodiversity associated with the IGGI aspects there was no inherent difference in the design, materials or construction that would significantly change the engineering performance, or alter how the structures are to be inspected or maintained. Extensive discussions between the design team, scientists and the construction team ensured benefits were maximised and engineering function was not compromised within the project's budget.

Ecosystem services

Only supporting ecosystem services have been measured in this study. Prior to construction, fourteen bird surveys were carried out over 4 years, and a Phase 1 habitat survey (14 transects over 7 kilometres) undertaken at the site in 2014. These data were compared to two previous biotopte surveys (2003, 2010) and a similar study of a neighbouring rock revetment installed in 2002. Access to the foreshore for baseline monitoring was gained during year 1 of construction where quantitative baseline data were collected on horizontal and vertical shore platform areas not disturbed or covered up by construction. Post-construction, the partially enhanced and enhanced rock armour areas of the scheme were monitored 12-18 months post-colonisation (n = 4, 25x25cm quadrats per area).

Preliminary post-construction monitoring results (12-18 months post-installation) suggest that the new passively enhanced rock revetment has the same biotope as the baseline natural shore platform (Naylor et al. under revision). Species richness on the rock armour (both types) was statistically lower than found on the baseline shore platform. The enhanced areas also appear to support quicker succession, and have species densities more similar to baseline conditions than unenhanced areas of the revetment. For example, key prey species (the limpet *Patella vulgata*) on enhanced rock armour, showed statistically significant abundances similar to the baseline shore platform and significantly higher numbers of limpets than found on partially enhanced rock armour. This preliminary data suggests that passive ecological enhancement approaches can help mitigate ecological impacts of new rock revetments in designated Natura 2000 sites, over timescales as short as 18 months. Monitoring of the scheme is on-going via a University-Local Government collaborative project, and this will provide valuable longer-term data on ecological performance and the ecosystem services. Notably this IGGI measure maintains ecological resilience of Natura 2000 sites now and in the future as coastal squeeze is a larger risk factor, whilst providing a socially desired level of coastal flood and storm alleviation.

Wider ecosystem services stem from the cultural and social value of protected species. There are clear scientific justifications for maintaining Natura sites and other similarly rare and endangered ecosystems, and many people will see an intrinsic value beyond, in what they can provide in terms of cultural service, for social cohesion and identity. The sites proximity to over 500 homes brings the sea and internationally important bird populations into the everyday lives of the locals. It provides services for health, identity and learning, recreation and tourism. The overwintering bird populations are important as a local amenity, for ornithologists, naturalists, amateur nature lovers, and the wider community.

Social value

The public strongly supported the hold the line coastal management policy as the area contains significant cultural heritage, including a scheduled monument, the Heugh Gun Battery; the scheme aims to reduce coastal erosion risk to the community and increase amenity value of the frontage over the next 100 years with the added benefit of maintaining habitat (and thus social value) of the site for overwintering birds. Construction will last for 5 years and is on-going so social perceptions of the ecological enhancements are unknown.

Who can apply this intervention / technique?

The passive and active enhancements carried out here are part of a suite of possible IGGI measures that can be applied to a range of coastal assets include flood alleviation, piers, harbours, stormwater and energy infrastructure. See the coastal and estuarine IGGI business case for more ideas. Many of these are inexpensive relative to the benefits gained and can involve simple modifications to existing engineering practice (e.g. the use of textured formwork).

Scaling up the benefits

There is potential for these and other coastal IGGI measures to be included in conditions for planning agreements and integrated as guidance into Strategic Marine Plans and Local Development Plans for coastal developments. It is also possible to apply these recommendations as part of future tenders, so that contractors are required select ecologically favourable rock armour using active or passive enhancement techniques (see also AP-C2 to AP-C6) and/or to texture smooth concrete surfaces for ecological gain (e.g. CS-C6, AP-C7, AP-C8).

Data Quality

The table shows the relative strengths of the Economic, Technical and Environmental data available. They are classified as:

Scheme Specific
part of a PhD or similar detailed research

Expert Judgment
interpretation of the scheme by one or more experts

Wider Supporting Evidence
extrapolated from published work or reports by practitioners.

DATA TYPE	DATA QUALITY / QUANTITY Hartlepool passive and active enhancement measures						
	Scheme specific information			Expert judgement		Wider supporting evidence	
	No Data	Limited reported sources	Strong reported sources	Some expert opinion	Multiple experts	Some sources	Multiple sources
COST			●			●	
ENGINEERING			●	●			
ECOSYSTEM SERVICES			●	●		●	

Further information / Contacts

Naylor, LA, MacArthur, M., Hampshire, S., Bostock, K., Coombes, MA, Hansom, JD, Byrne, R. & Folland, T. Accepted. Rock armour for birds: Ecological enhancement of coastal engineering to provide food for birds, Hartlepool Headland, UK. ICE Journal of Maritime Engineering. http://dx.doi.org/10.1680/jmaen.2016.28

Kieran Bostock, Hartlepool Borough Council
Kieran.Bostock@hartlepool.gov.uk

Dr Larissa Naylor, University of Glasgow
Larissa.naylor@glasgow.ac.uk

Mairi MacArthur, University of Glasgow:
m.mac-arthur.1@research.gla.ac.uk

Dr. Martin Coombes, University of Oxford
martin.coombes@ouce.ox.ac.uk

Case Study CS-C5:

Sea walls: Vertipools, artificial seashore habitats

Summary

Seawalls are usually seen only as flood alleviation structures rather than as having other possible functions to benefit the wider environment. Where new walls are being installed there is opportunity to include more sympathetic "nature friendly" textured finishes to improve or maintain biodiversity. Where seawalls are already installed, retrofit enhancement measures provide significant opportunities.

- Benefit: Medium
- Engineering: Low
- Ecosystem: Medium - High
- Costs: Low

How does it work?

Vertipools are cast marine concrete units designed to be attached to sea defences to retain water as the tide recedes – they are shaped to replicate a range of natural microhabitats (e.g. rock pools) for shoreline species and are simply fixed with bolts or brackets and nontoxic waterproofing resin. They are durable enough to resist wave and tidal action for > 3 years in moderately exposed and exposed settings. The manufacturers are exploring a range of applications, across the full tidal range from beach level to splash zone and to capture freshwater seepage above high tide and sediment in low energy systems near perched mudflats for worm fauna etc.The potential for them to improve asset resilience is also being explored.

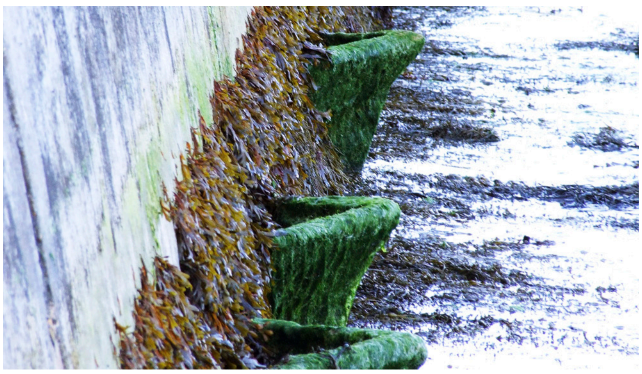
Motivation

To investigate how habitat can be retrofitted onto sea defences. The first two pump-priming projects were funded by community engagement; working with disadvantaged children and young people. Additional seed corn funding, along with monitoring by the University of Bournemouth, enabled a robust evidence base to be built. Vertipools have also now been deployed as part of environmental mitigation and enhancement requirements for ferry infrastructure and road works on the Isle of Wight, and as part of a NERC-funded public engagement project in Edinburgh.

Design innovation / Enhancement measure

Retrofit habitats are provided by retro-fitting prefabricated 3-D concrete units. The current pool designs are tetrahedral shaped cast concrete units with a robust 'prow' for deflecting wave energy. They are fixed in place with simple coach bolts and resin, or a plate. They are designed to provide important water-holding habitat and increase physical heterogeneity of otherwise smooth, homogenous vertical intertidal coastal defences.

To optimise ecological function, it is recommended they be fitted in groups of 5 with around 10 metres between groups. In this way, they provide pockets of high-density habitat along the length of the seawall. A 100m seawall would therefore require 50 Vertipools. Placement at around MLWN may have greatest potential for ecological gains, although future sea level can be considered.

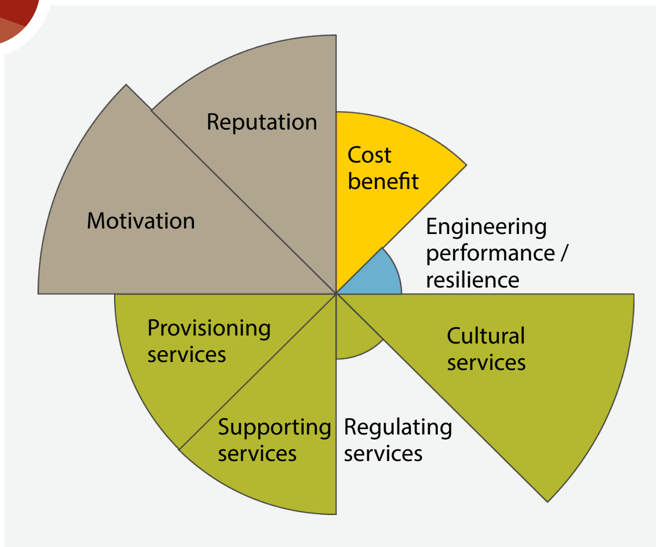


Benefits

Net cost benefits are expected to be low to medium. The trial pool costs are initially relatively high for the volume of habitat created, although the price is predicted to come down with economies of scale. The average price relative to sea wall construction costs are around 5-15%.

Where the pools offer opportunities for community engagement and education, the cultural services may be deemed relatively high, or where they provide mitigation for an otherwise less favoured development they could be considered to improve a schemes reputation.

Initial research shows the units provide some capacity for biodiversity enhancement.



Net Cost

Vertipools might be considered to have a relatively low net cost where the value in providing them is clear, such as:

- in certain planning and permitting circumstances e.g. offsetting habitat loss where new defences are installed and greener infrastructure options are ruled out.
- in engaging the wider public in the processes, the underlying science and the local natural environment (e.g. providing an educational resource - practicals, working with groups of young offenders, etc.).
- in retrofitting to provide habitat for biodiversity, therefore improving climate change resilience, or habitat for commercially significant and/or migratory species).

Direct cost of intervention

Vertipool costs depend on a number of factors including site assessment, planning and design. Installation requires some local and specialist knowledge (an understanding of site characteristics, ecology, substrate and fixings).

Pools can be made on site (and could include a community engagement element) or made and shipped for installation by contractors.

For the case study presented here, the site assessment, planning and design (including installation guide) was approximately £5000. Community engagement costs (including team of 4 practitioners, materials and resources) are estimated at £1000 for a 2 hour ‘drop in’ public consultation session, £2500 for a 4 hr participatory consultation and engagement event, to £3500 for a full day school workshop.

Cost compared to business-as-usual

The costs (after on-going trials are completed and with economy of scale) of 50 Vertipools for 100 m of seawall are estimated at approximately £300 per m (a cluster of 5 pools for every 10 m = 50 pools over 100 m); or £200 per m for 1000 pools to cover 2 km. Although the pools have so far been fitted as retrofit enhancement there are plans to include them on new developments. The costs are a relatively small percentage of the cost of new-build sea wall.

Examples of sea wall costs by type and size (EA, 2010 figures).

	Height	Cost per metre
Raise an existing wall with concrete and stone cladding both sides	1m	£1500 (over 100m)
Sea defence	3.8m	£2000 (over 1200m)
Reinforced concrete wave return wall	2m	£6300 (over 75m)

These figures show significant variation. The cost per metre of seawall installation can depend on source, type, availability and quality of materials, access constraints and weather, as well as the size (length, height and depth) of the wall. Based on these available costs, including Vertipools would increase costs by between 5% and 20% of the cost of raising or building a seawall.

Thus, the cost to an existing seawall being raised 1m over a 100m length would be:

£1800 per metre for one being retrofitted with vertipools compared to £1500 without.

To build a new 2m high reinforced concrete wave return wall it would be:

£6600 with or
£6300 without Vertipools.

There may be further cost savings from including these or similar habitats, including reducing the costs of managing non-native (e.g. Wire weed, *Sargassum muticum*) and invasive species that can dominate ordinary seawalls.

Long-term cost

It is not anticipated that the wall sections with vertipools or the vertipools themselves will require any additional maintenance or repairs compared to business-as-usual, so no additional direct costs are expected.

In addition to the points above, the long-term benefits could be important under some circumstances, for example, where the pools facilitate long-term community involvement in the natural environment – engaging and informing the public to foster long term support in decision making and stewardship.

Long-term savings may accrue in areas where Vertipools or similar inhibit the impact of invasive or non-native species, and where they facilitate climate change resilience through supporting biodiverse ecosystems.

Engineering performance, inspection and maintenance

Vertipools are designed to have no detrimental effect on the engineering performance of the defences, and trials show they can be applied and removed without compromising the structure, and any holes can be safely filled with cementitious material. Their ability to improve asset resilience is under study. No detrimental effects have been found since the first pools were installed in 2013 (3+ years) and the Vertipools have not affected inspection of the seawalls. At some sites sedimentation around pools appears to have increased natural armouring, though their role in sediment accumulation, buffering and improving asset resilience requires further assessment.

They are designed to be installed at a density that would not restrict inspections (see the recommended operational spacing detailed above) and are of a size that would not affect standard maintenance practices.

As the Vertipools are relatively small but pronounced structures, they are unsuitable for places where there is boat traffic and these protrusions need to be factored into detailed designs. Initial trials explored a range of shapes and sizes and ongoing monitoring data may produce options to suit the individual aims and objectives of specific installations.

Ecosystem services

Vertipools, or similar, offer an opportunity to retrofit habitat where currently there is little or none, increasing service provision from a low baseline. On-going assessments show significant colonisation in the pools – both in abundance and diversity – compared to the baseline conditions. After 3 years, the artificial pools increased species diversity on the seawall and attracted mobile fauna previously absent, including fish and crabs. Compared to 8 species recorded on the seawall, 16 species were recorded in the Vertipools including fish (Lipophrys pholis), shore crabs (*Carcinus maenas*), and gastropods (*Patella vulgata* and *Littorina obtusata*). Juvenile and adult life-stages of a range of species were found in the pools.

There is potential to adapt the pools to mimic specific habitat for individual species or target communities more closely. This could provide habitat for migratory species or native species colonising new areas under the effects of climate change, e.g. some anemone species and the rock pool Shanny. Where coastal squeeze becomes significant it is probable that Vertipools would become accessible to species currently surviving in natural pools at lower tidal levels.

Vertipools are designed to provide refuge for a variety of species, including commercially significant species including the edible periwinkle (*Littorina littorea*), edible mussel (M*ytilus edulis*), edible shore crab (*Cancer pagurus*) and the velvet swimming crab (*Necora puber*). Other species which may use the pools when submerged, for refugee and foraging, include intertidal crabs (*Pagurus bernhardus*) and fish (Gobies, Blennies, juvenile commercial fish like Wrasse and Bass). By attracting a range of species, the pools are thought to generate a 'reef halo' effect where nearby biodiversity also increases. This is being explored in 2017 using submerged cameras.

Further study is required to determine how well Vertipools can limit colonisation by non-native and invasive species in other areas. These species can negatively influence the native ecosystems, and visual amenity, and the costs in managing the impact can be considerable and chronic. Other trial pools quickly attracted a non-native sea squirt that was not previously recorded at that location, and the possibility of using the pools to track and act as an early-warning beacon for non-native and invasive species is being explored.

Social value

Young people have been involved in the design and manufacturing stages in some of the installations. The pools at Boscombe are accessible and, along with interpretation boards at the nearby Coastal Activity Centre and Aquarium, they will be incorporated into a Council nature trail and bio-beach attraction.

They have proved successful in engaging the public and University Students, approximately 100 people aged between 8 and 60 at making sessions (sand casting techniques and texture work) – a combination of Royal Society STEM work with Sandown Bay Academy (£5K school fund), Artswork/Hants police project (£5K budget), outreach and engagement work with young people not in education, employment or training (NEETS) and others, including vulnerable young adults in supported accommodation via a housing association.

In addition to the Vertipools providing habitat for commercial and recreationally significant species they are accessible at low tide and provide opportunities to investigate rock pool flora and fauna that are otherwise absent on stretches of heavily engineered coastlines; anecdotally the researchers feel the public appear to have enjoyed exploring these. A 'science beach' has been set up for such installations in The Bay area on the east of the Isle of Wight, a coastal resort receiving up to 500,000 visits a year. The strong design element to Vertipool appearance adds a sculptural quality to public space and this can be emphasised where public art commissioning is project objective.

Who can you apply this intervention/ technique?

Anyone looking to retrofit an established flat sea defence structure, where no alternative working with natural processes or green infrastructure solution is viable.

The vertipools can be deployed at any tidal height in the intertidal zone, and thus far have been successfully tested on moderately exposed to exposed open, non-muddy coasts in SE England.

Scaling up the benefits

The ecological benefits of fitting Vertipools where there is little or no habitat (i.e. on large expanses of vertical concrete) is large. These and other similar structures have the capacity to provide habitat where previously there was little or none, and could support locally significant populations. They can provide habitat in new developments where more conventional green infrastructure options are not possible.

The Vertipools installed thus far are relatively small individual pools, alternative designs could include an array of longer, vertically self-supporting pools in series, providing a range of habitats and benefits up the water column and tidal range. Repairs or new sea walls can be further optimised using a combination of IGGI measures such as textured walls (AP-C7 and AP-C8) and adding habitat features such as Vertipools.

The British coast has extensive hard defences, current pool designs hold 3.5 – 10 litres of water per pool, hence 5 pool clusters provide approximately 17.5 - 50 litres, and each pool provides an approximate surface area of around 0.15m^2 inside and 0.7m^2 outside of rock pool habitat.

The most suitable place for applying this measure is where artificial hard structures either replace or are adjacent to existing rocky shore habitats. In locations where other intertidal substrates underpin the natural habitat, it is important to evaluate whether adding rocky shore habitats will lead to improved ecological outcomes.

Data Quality

The table shows the relative strengths of the Economic, Technical and Environmental data available. They are classified as:

Scheme Specific
part of a PhD or similar detailed research

Expert Judgment
interpretation of the scheme by one or more experts

Wider Supporting Evidence
extrapolated from published work or reports by practitioners.

DATA TYPE	DATA QUALITY / QUANTITY						
	Scheme specific information			Expert judgement		Wider supporting evidence	
	No Data	Limited reported sources	Strong reported sources	Some expert opinion	Multiple experts	Some sources	Multiple sources
ECONOMIC			●			●	
ENGINEERING			●	●			
ECOSYSTEM SERVICES			●	●		●	

Further information

ARC Consulting and Artecology Limited:
Ian Boyd: ian@artecology.design
Claire Hector: claire@arc-consulting.co.uk

http://arc-consulting.co.uk/
http://www.artecology.space/

University of Bournemouth:
Alice Hall: ahall@bournemouth.ac.uk, @AHall_Marine
Dr. Roger Herbert: RHerbert@bournemouth.ac.uk

Case Study CS-C6:

Sea walls: habitat enhancement of replacement walls

Summary

The Elliott Bay Seawall Project in Seattle, USA, incorporates a number of biophilic measures included a textured sea wall with habitat benches, substrate enhancements (beach and marine mattresses), an intertidal corridor, and the transparent material in both the cantilevered deck (new build) and the piers (retrofit) to improve the amount of natural light reaching the shore.

Benefit	High
Engineering	Medium
Ecosystem	High
Costs	Medium

How does it work?

Generations of urban development extended the influence of the city into the bay, impacting on the plants and animals there. Buildings, piers and walkways were built close to and over the water. During sea defence reconstruction the developers integrated several enhancements into the design to improve habitat conditions for native species. These were based on earlier research undertaken by the University of Washington.

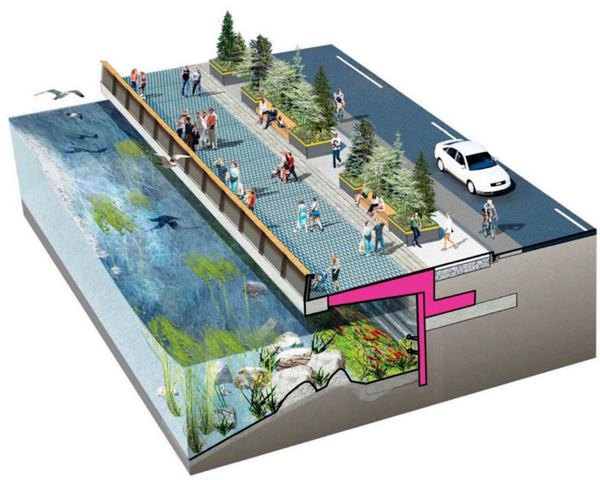
Motivation

The existing sea wall, built between 1911 and 1936, had deteriorated from significant seismic activity and damage from wood ingesting crustaceans (Gribbles). This made the wall unsafe and its ability to withstand future storm and/or seismic events was compromised. Repair and re-development of the near-shore area gave the opportunity to restore habitats lost or negatively impacted by long-term urbanisation, including salmon migration corridors and general improvements to ecosystem productivity.

Elliott Bay is an important juvenile salmon migration route (Duwamish River to the Pacific Ocean). However, shallow-water habitat is limited here, making migration along the shoreline difficult. Over-water structures also produced intermittent dark and light areas that are problematic for small fish to negotiate. A key driver of the scheme was to improve the degraded nearshore habitat for salmon.

Design Innovation / Enhancement measure

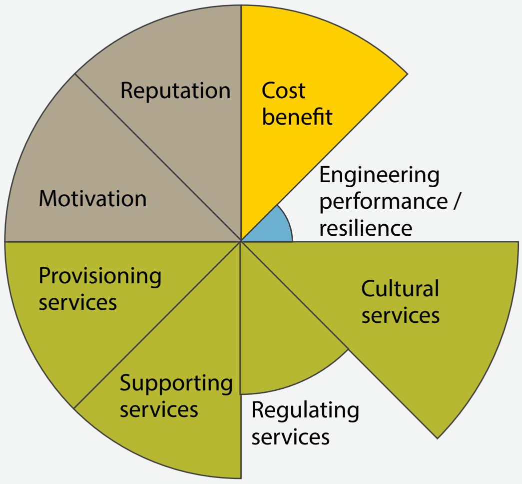
A range of eco-enhancements were used. Most notably, light-permeable materials (glass blocks and grated walkways) aim to reduce shading of the water column by large overwater structures that can affect feeding ability by juvenile salmon. Decades of development and dredging had removed all natural sediments, so some substrate enhancement measures were included to support plant and invertebrate colonisation. Artificial intertidal zones (habitat benches) and marine mattresses (sediment-filled mesh pockets placed at the bottom of the seawalls) were added to create additional protective shallow waters, in place of deep water. The seawalls themselves were also cast using textured formwork that was optimised for ecology and aesthetics.



Benefits

Much of the sea defence work and habitat enhancements were recently completed and the monitoring program has not yet begun. Anticipated benefits include: significantly improved amenity value for the local community alongside improved coastal protection by replacing existing assets in poor condition; enhanced waterfront habitat particularly for salmon; significantly strengthened collaborations between numerous regulatory agencies, private firms, academia and the City of Seattle – this high-profile project has highlighted the potential and importance of ecological considerations in engineering design of major, large-scale infrastructure/re-development works.

These designs were based on robust scientific trials carried out by the University of Washington. They tested designs for ecological enhanced concrete compared to smooth concrete sea walls, to see if this led to improved outcomes for species, including commercially and culturally important fish. They found that textured wall panels with areas of relief (and steps) supported more diverse communities than existing seawalls or the control (flat) panels.



Net cost

$410 million

Direct cost of intervention

Estimated to be $20 million (around 5% of the total project cost)

Cost compared to business-as-usual

Costs of the enhancements (approximately $20 million) were additional to the business-as-usual costs.

Long-term cost

Maintenance costs are unknown but they are not expected to have any impact on engineering performance or inspection routines. Post-construction monitoring of enhancement effects on local ecology is expected to cost an additional $1M to $2M over business-as-usual monitoring, over a 10-year period.

Engineering performance, inspection and maintenance

Specific measures included in the scheme were:
(1) creation of an artificial beach and placement of intertidal benches and stone-filled marine mattresses to create shallow water, low gradient habitat;
(2) incorporation of texture and relief into the seawall face to improve ecological potential within the intertidal and supratidal (accounting for future sea level rise), and;
(3) incorporation of light-penetrating surfaces in the sidewalk above the seawall toe to provide a light 'corridor' for juvenile salmon.

In this relatively sheltered, inland location these integrated green elements are expected to perform as well as any traditional/un-enhanced alternative. Compared to the assets being replaced, the scheme will have significantly improved engineering performance – the enhancement measures are not expected to affect performance or design life in any way. Inspection of the assets is unaffected by the enhancement design – access will not be restricted. On-going analysis of the performance of each element is planned.

Ecosystem services

Studies have not yet been conducted on the new seawall, as construction is still ongoing. Once seawall construction is complete, various elements will be monitored in the long-term. The physical characteristics of the habitat improvements, light penetration, invertebrate colonisation and salmon presence and behaviour will be reviewed. There is a plan to begin studies on light level impacts along the waterfront, including monitoring to determine the effectiveness at (i) creating an effective migratory corridor for juvenile salmonids and (ii) enhancing the marine nearshore ecosystem.

Research shows that migrating young Chinook salmon (Oncorhynchus tshawytscha), Chum salmon (O. keta) and Pink salmon (O. gorbuscha) avoid shaded areas, like those under docks and piers. In addition, they are negatively impacted by reduced availability of food sources in urbanised inshore areas. The scheme is designed to maximise habitat quality for these species by incorporating novel, low shade-casting structures over the water.

The health of the natural environment, natural history, fish, seafood and in particular the vitality of the native salmon populations appear to be very important to the current and historic identity of areas like Seattle.

The overt attempt to improve the urban marine environment visibly provides opportunities for the public to engage in the natural environment and conservation.

There is limited information on how well the new sea walls are performing ecologically, but if successful across the whole scheme, the following services are expected, though some may be relatively small scale: increased primary production, nutrient cycling and increased carbon uptake; natural sedimentation of biogenic material will increase carbon sequestration (therefore improving capacity for climate regulation); improved local biodiversity may increase potential to both decompose and detoxify local pollution (e.g. contaminated urban run-off); enhanced fish populations (both locally and wider commercial fisheries); enhanced social amenity value and public engagement with the waterfront environment, and improved awareness of ecological conservation at the coast.

Social value

Community engagement, commercial opportunities and sustainable infrastructure stability will all be improved by the holistic approach to regeneration of the area.

Who can apply this intervention / technique?

Anyone undertaking a project that involves development over water bodies can review similar alternative technologies and methods of incorporating novel techniques that reduce the impact on light levels through the water column.

Scaling up the benefits

Further research is required to assess the potential to apply the kinds of techniques used in this scheme elsewhere. However, where redevelopment works are planned the approach adopted in Seattle could be applied in many different contexts. Adopting ecologically sympathetic engineering designs more broadly will help maximise connectivity and biodiversity along heavily urbanised coastlines.

Data Quality

The table shows the relative strengths of the Economic, Technical and Environmental data available. They are classified as:

Scheme Specific
part of a PhD or similar detailed research

Expert Judgment
interpretation of the scheme by one or more experts

Wider Supporting Evidence
extrapolated from published work.

DATA TYPE	DATA QUALITY / QUANTITY						
	Scheme specific information			Expert judgement		Wider supporting evidence	
	No Data	Limited reported sources	Strong reported sources	Some expert opinion	Multiple experts	Some sources	Multiple sources
COST	●						
ENGINEERING		●			●		
ECOSYSTEM SERVICES		●			●		

Further information / Contacts

Jeff Bertram, Seawall Project Manager
Jeff.Bertram@seattle.gov

Prof. Jeff. Cordell: jcordell@uw.edu, https://wsg.washington.edu/research/integrating-intertidal-habitat-into-seattle-waterfront-seawalls-phase-2/

Bilkovic, DM, Mitchell, MM, La Peyre, MK, Toft, JD. Eds. (2017). Living Shorelines: The Science and Management of Nature-Based Coastal Protection. CRC Press. ISBN 9781498740029 - CAT# K26671.

Munsch, SH., Cordell, JR, Toft, JD, Morgan, EE. (2014). Effects of Seawalls and Piers on Fish Assemblages and Juvenile Salmon Feeding Behavior. North American Journal of Fisheries Management. 34, http://dx.doi.org/10.1080/02755947.2014.910579

Munsch, SH, Cordell, JR, Toft, JD. (2017). Effects of shoreline armouring and overwater structures on coastal and estuarine fish: opportunities for habitat improvement. Journal of Applied Ecology doi:10.1111/1365-2664.12906

NOAA, 2015. Living shorelines guidance. http://www.habitat.noaa.gov/pdf/noaa_guidance_for_considering_the_use_of_living_shorelines_2015.pdf

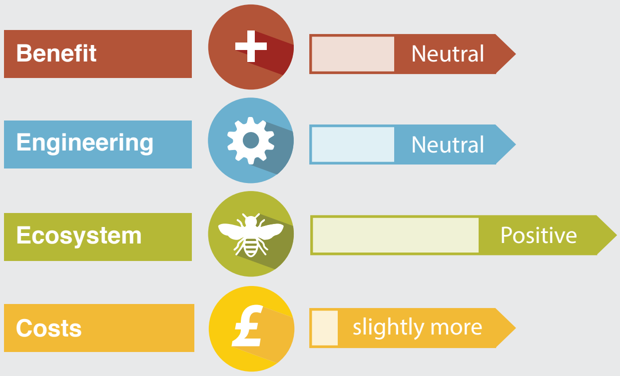
URL: waterfrontseattle.org/seawall

Case Study CS-C7:

Habitat enhancement of stone clad sea walls

Summary

Seawalls are usually seen only as flood alleviation structures rather than as having other possible functions to benefit the wider environment. Where new walls are being installed there is opportunity to include more sympathetic "nature friendly" textured finishes to improve or maintain biodiversity. Where seawalls are already installed, retrofit enhancement measures provide significant opportunities.



How does it work?

Small alterations were made to the mortar pointing between decorative stone cladding of a section of vertical concrete wall during construction of the Shaldon and Ringmore Tidal Defence Scheme. Based on evidence from existing scientific studies, niche habitats (grooves, holes and mini-pools) were created during construction to provide cool/moist refuge for intertidal wildlife at low tide, at three different heights on the wall. Ecological use of these features was compared with adjacent sections of unmodified wall.

Motivation

Primarily EIA Directive and Planning Conditions; mitigation for loss of foreshore habitat and potential coastal squeeze resulting from sea level rise. It was also important for this scheme to achieve an attractive structure with minimal negative visual impact on the surrounding historic conservation area.

Design Innovation / Enhancement measure

The intervention aimed to include habitat for target intertidal ecological communities via modifying an existing engineering design of an otherwise relatively homogeneous seawall. Niche habitats were incorporated into the fabric of a wall during the restoration/partial replacement of a sea defence. The measure used existing scientific evidence to inform the enhancement designs.

Three types of niche habitat were used, all achieved by leaving out occasional facing stones and filling with modified mortar (undertaken by the contractor) at the time of construction. First, grooves were scraped into the mortar based on existing evidence that small-scale (millimetre) grooves attract barnacles. Second, holes a few centimetres wide and deep were made by pushing a wood baton into the mortar. This was based on evidence that these kinds of holes are effective at supporting some species including limpets. Thirdly, small pools were created by placing a sand-filled bag into the recess created by leaving out a cladding stone. Mortar was slightly built up around this to create a lip (to retain water) and the bag was removed once mortar had cured.

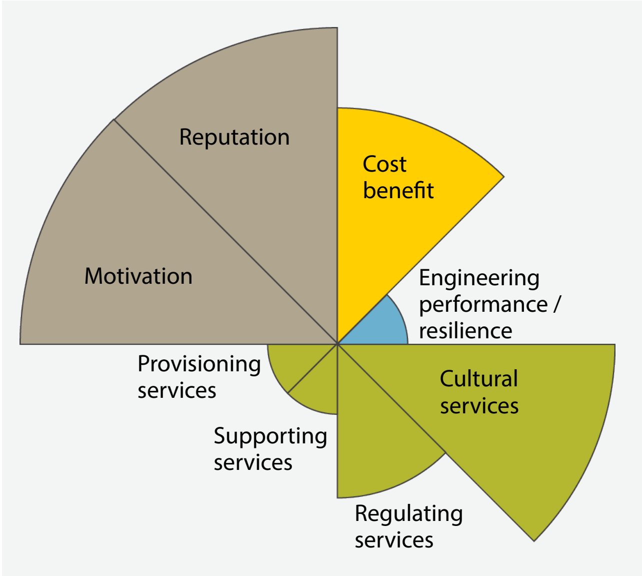
These different approaches were arranged at three different heights towards the base of the wall (the intertidal portion around MHWN), using a spacing that could provide robust scientific evidence during the monitoring period.

Benefits

The scheme was driven by a need to repair the existing sea defence in a sympathetic and visually acceptable way (within a historic conservation area) and to examine the potential to include ecosystem enhancement techniques. The research shows that it these small-scale enhancements are valuable in including habitat where there would be little or none if traditional methods were used.

Historic England has led much work in the UK on the economic values of historic sites, (cultural, aesthetic, educational value) but as yet there is little data on ecological enhancement values. The habitats here are relatively small but the positive results indicate significant benefits may be possible, e.g. for current or future priority species.

To this end the scheme achieved the goal of demonstrating the capacity for habitat to be built into hard, engineering-centric structures, and illustrates the potential for these schemes to provide ecosystem enhancements. The benefits from these greener approaches could be scaled-up to incorporate more habitat. Similar adapted niche habitats might provide interesting features on other restoration projects.



Net Cost

Scale, access and design all impact on the cost of sea defences. The structure here was local stone, and mortar cladding which covered a concrete wall that provides the coastal defence. Cladding of the concrete wall was required as the protection scheme was being build in a historic conservation area. This cladding was designed to provide ecological enhancements. The overall scheme cost around £8.3M in 2010.

Direct cost of intervention

Three direct costs were involved:

1. design and academic consultation = £6,520
2. construction costs = £1,000
3. monitoring for 18 months = £12,450

These costs represented less than 0.25% of the total scheme cost (£8.3M). Importantly, the additional design and construction costs were less than 1/2 of the total costs of the enhancement. Minimal training of contractors was required (< 1 day) to undertake the enhanced construction compared to business as usual. Widespread application of these ideas in future schemes therefore represents a very small additional cost compared to business as usual.

Cost compared to business as usual

The design and use of the niche enhancements had no bearing on the final approved design and construction for the scheme. A business-as-usual scenario (replacing the wall without including enhancement) would be have been £20,000 cheaper overall, but would not have provided any of the benefits identified below.

Long-term cost

Inclusion of the enhancements is not associated with any increased cost in the long term. Monitoring of the modified materials indicated no increase in biological deterioration of the construction materials.

Engineering performance, inspection and maintenance

This form of enhancement has no effect on inspection and maintenance regimes. The incorporated niche habitats do not obstruct or interfere with inspection in any way. Detailed monitoring has shown no negative effects on material integrity associated with the niche habitats. Engineering performance and design life are not affected.

In this scheme the stone cladding was a feature in front of the main structural defence, so the engineering impacts of these enhancements on the structural integrity of the scheme were negligible. All enhancement designs were approved by the overseeing engineer, prior to construction.

Ecosystem services

After a period of 18 months post-construction, nine invertebrate species were found in association with the enhancements. Grazing species (snails) were most commonly found in the holes and pools habitats, which retained water at low tide. The pool habitat supported significantly more species than adjacent, smoother sections of wall after this period, including snails, barnacles and algae. Overall, inclusion of the enhancement led to a greater abundance and diversity of species compared to comparable sections of wall without enhancements.

The enhanced wall is to a small degree successfully functioning as an intertidal habitat, helping support local biodiversity, and compensating for some loss of foreshore (approximately 1m) due to the footprint of wall. While no biological products are harvested from this initiative, part of our design was based on the success of similar interventions in increasing the abundance of a commercially important mollusc (Martins et al. 2010). The site is also close to a cultural and recreational centre and provides opportunities for engagement in the natural and historic environment.

Social value

As yet no data are available for social value. The niche enhancements are visible and accessible at low tide, and may offer some amenity/educational value. The local stone cladding used for facing the wall (of which the mortar joints were enhanced) was specifically chosen to be in-keeping with the surrounding historic landscape.

Who can apply this intervention / technique?

The simple modifications to the wall at Shaldon could be applied to any similar scheme, and could be adapted to suit different types/construction of hard defences. The main limitation in providing habitat enhancements for intertidal species is position of the structure with the tidal frame – which must be low enough to ensure surfaces are below tide for at least part of the day. At Shaldon the wall enhancements had to be positioned around MHWN. Water retaining features and textured surfaces can mitigate desiccation stress higher within the tidal frame (where time of exposure at low tide is greatest), but greater diversity of species may be achieved in association with enhancements placed lower in the intertidal zone.

Some consideration is required for the possibility of recessed habitat niche habitats becoming silted up over time. Whether, and how quickly, this occurs will depend on local water and sediment conditions.

Scaling up the benefits

Similar enhancements could be used across whole defence schemes at little additional cost (~ 0.5% or £100 per metre). The approach adopted here of incorporating small niche habitat features (holes, pools and texture) during the construction, will work best for blockwork/masonry constructions that incorporate mortar. Mortar is easily manipulated prior to curing.

The scale of application of this kind of enhancement at Shaldon was limited, acting primarily as a proof-of-concept for applying academic research to operational structures. Application of these techniques to entire schemes, or multiple schemes along a coastline, would help support local and regional-scale biodiversity, particularly in light of habitat losses from necessary coastal protection works and coastal squeeze.

Data Quality

The table shows the relative strengths of the Economic, Technical and Environmental data available. They are classified as:

Scheme Specific
part of a PhD or similar detailed research

Expert Judgment
interpretation of the scheme by one or more experts

Wider Supporting Evidence
extrapolated from published work or reports by practitioners.

DATA TYPE	DATA QUALITY / QUANTITY						
	Scheme specific information			Expert judgement		Wider supporting evidence	
	No Data	Limited reported sources	Strong reported sources	Some expert opinion	Multiple experts	Some sources	Multiple sources
COST			●	●			
ENGINEERING			●				
ECOSYSTEM SERVICES			●		●		●

Further information / Contacts

Best practice case study:
www.ecrr.org/Portals/27/Shaldon%20Intertidal%20Habitat%20Enhancement.pdf

Coombes, MA. et al. (2015). Getting into the groove: Opportunities to enhance the ecological value of hard coastal infrastructure using fine-scale surface texture. Ecological Engineering 77, 314-323. https://doi.org/10.1016/j.ecoleng.2015.01.032

Coombes, MA, Naylor, LA, Jackson, AC, Thompson, RC. (2012). Shaldon and Ringmore Tidal Defence Scheme: Ecological Enhancement Monitoring Report (18 months post-construction). Report to the UK Environment Agency, University of Exeter and University of Plymouth, UK.

Firth, LB. et al. (2014). Between a rock and a hard place. Coastal Engineering 87, 122-135. http://dx.doi.org/10.1016/j.coastaleng.2013.10.015

Martins, GM. et al. (2010). Enhancing stocks of the exploited limpet Patella candei d'Orbigny via modifications in coastal engineering. Biological Conservation 143, 203-211. https://doi.org/10.1016/j.biocon.2009.10.004

Naylor, LA. et al. (2012). Facilitating ecological enhancement of coastal infrastructure. Environmental Science and Policy 22, 36-46. http://dx.doi.org/10.1016/j.envsci.2012.05.002

Contacts:
Dr. Deborah Dunsford, Environment Agency, Manley House, Kestrel Way, Exeter, EX2 7LQ
Dr. Larissa Naylor: larissa.naylor@glasgow.ac.uk, @biogeomorph
Dr Martin Coombes: martin.coombes@ouce.ox.ac.uk, @MACoombes
Prof. Richard Thompson: r.c.thompson@plymouth.ac.uk

This forms part of Naylor, LA., Kippen, H, Coombes, MA., et al. (2017). Greening the Grey: a framework for integrated green grey infrastructure (IGGI). University of Glasgow report. URL: http://eprints.gla.ac.uk/150672/

Case Study CS-C8:

Intertidal habitat created around a new development

Summary

The plan to expand the Vancouver Convention Centre took the new building out, seaward across 50 m of coastline and 140 m² of marine habitat. Before the federal Fisheries and Oceans Canada authorised this development they stipulated that loss of marine habitat had to be compensated for. An on-site mitigation plan was approved and construction was completed in 2009. Three enhancements were built including a series of stepped, pre-cast, concrete "benches" were attached to, and extended out from, the perimeter of the structure (both buildings and the promenade), around the west, north, and east aspects. The benches provide habitat connectivity to the existing shoreline, allowing safer passage of salmonids through the development.

Benefit	High (mitigation enabled construction)
Engineering	Low
Ecosystem	Medium
Costs	Low

How does it work?

The intertidal mitigation includes three measures: a habitat skirt, feature rocky intertidal habitats and the use of glass blocks on the promenade to allow natural light onto the intertidal and subtidal communities. This was complemented by creation of subtidal marine habitat; this case study focuses on the intertidal habitat elements. Collectively, these features were designed to optimise the potential for a diverse range of marine habitats and species that would colonise the site.

For the habitat skirt, the three shore-facing perimeter faces of the marine foundation were fitted with 500 metres of bioengineered intertidal habitat skirt structure, consisting of a series of stepped, precast concrete benches supported by precast concrete frames attached to a specially designed cast-in-place perimeter concrete beam.

The concrete stepped "bench" design increases surface area and retains moisture during low tide conditions. Several features were added to the top surface of the benches to promote marine growth; a continuous depression, or trough that mimic rock pools by retaining water when the tide recedes, and exposed aggregate on the top surface to increase the variability of the surface texture and elevation to create habitat features. The other intertidal habitat features are described below.

Motivation

The aims were to maximise vertical and horizontal ecological connectivity to create habitats for a diverse mix of intertidal marine life. On site ecological mitigation was required as part of a federal and city level initiative to provide a continuous habitat corridor and protect from predators for salmonids. It aimed to promote the growth of marine organisms that support the higher food chain and be robust enough to withstand the harsh marine environment over the lifespan of the building, including wind and vessel generated wave loading, floating debris impact and salt-water corrosion.

The high profile nature of the site (i.e. an iconic development) meant that the ecological enhancements had to complement the architectural design.

Design innovation / Enhancement measure

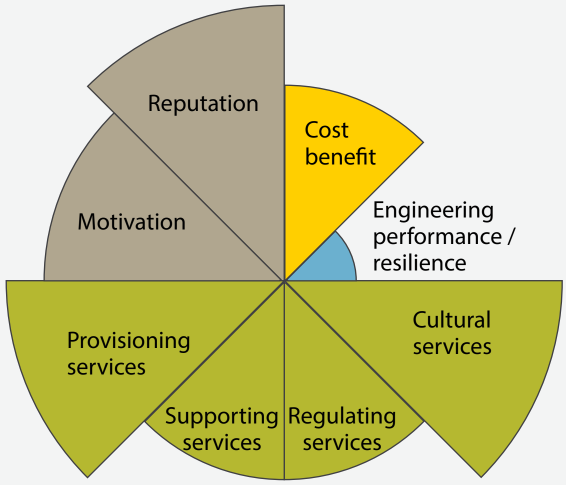
The habitat skirt includes 362 precast slats that were fitted into 76 frames, creating a large 5-tiered staircase structure that is 477 m long and provides 6,122 m² of surface area. The horizontal surfaces and sloped vertical edge of the habitat skirt mimic the replaced gradual slope and re-establish coastal marine habitat for many invertebrates that support predatory species such as sea otters, and provide connectivity with the existing coastline for migrating juvenile fish, specifically salmon.

Benefits

The cost of the ecosystem enhancement can be considered intrinsic to the project, as on site mitigation was required for encroaching over the intertidal area. The engineering performance has not been compromised, although unexpectedly high colonisation was an initial concern to engineering performance post-construction, but engineering performance has not been adversely impacted (9 years post-construction).

Through providing mitigation for the building of the Convention Centre (and the associated cultural and economic benefits) and in the habitat enhancement for native and iconic species such as sea otters and salmon, the skirt provides important cultural, supporting and provisioning services.

The improved habitat sequesters more carbon than a business-as-usual alternative through enhancing levels of primary production (and nutrient recycling).



Net Cost

Whole construction project = $CDN 615 Million.

Direct cost of intervention

The Convention Centre cost $CDN 615 Million, of which $CDN 20 Million was related to the marine ecological mitigation components. This comprised $CDN 8.3 Million for the habitat skirt and the remaining $CDN 11.7 Million was the cost of the structural components (bigger concrete beams, more piles) required to support the habitat skirt.

Cost compared to business-as-usual

This equates to a ~3% increase in total construction costs for the entire scheme. If off site mitigation were possible, this would have cost on the order of $CDN 3 Million to purchase and enhance compensatory habitat, less than 0.5% of the total project budget. However, as the scheme's design caused substantive habitat loss and damage to a protected marine ecosystem, planning permission would have been impossible without the on site mitigation in this case study.

Long-term cost

No data is available as the scheme is less than 10 years old.

Engineering performance, inspection and maintenance

A scientific advisory panel advised the Consultant on an ecological design that met engineering and habitat requirements and was approved by the regulator (The Fisheries and Oceans, Canada). The engineering design was modified to incorporate the habitat skirt.

The engineering performance has not been affected to date (8 years post-installation); the additional load of unexpectedly high colonisation was an initial concern post-construction but this has not impacted on engineering performance.


Photo Credit: Advisian

Ecosystem services

The habitat skirt did not replicate the pre-existing conditions precisely (e.g. for current and light exposure) but species' population similarity was greater than 65%. The bare substrates behaved similarly to the control. While the hard substrates could be expected to colonize in 2 to 4 years, minor microhabitat and elevation differences led to different ecological outcomes between sites; generally species richness decreased with elevation, linked to greatest species recruit in association with vertical connectivity with the sea floor. Species richness was greatest in pools around MLWN to MHWN and on vertical habitats at around MLWS.

Although a working harbour with a high potential for invasive species, this was not found to be an issue.

At the right tidal height, the skirt provides refugia and nurseries for juvenile crabs and other species leading to niche expansion from the presence of tide pools. Economically relevant species include dungeness crab, blue mussels and juvenile salmon. Estuarine conditions are particularly important to salmon development. Feeding opportunities can be relatively high and predation pressures low, particularly where high turbidity and estuarine and riparian vegetation provide cover. Around half of the Sockeye and pink salmon populations locally are harvested commercially (around 1 million Sockeye and 1.5 million pink) across the USA Canada border area. These and other species support extensive commercial, recreational and First Nation food, as well as social and ceremonial fisheries.

Increased primary production, most significantly by macro-algae and kelps, and subsequent increased biological activity up the food chain, will also increase nutrient recycling locally.

Social value

The skirt is not a physical recreational resource and cannot be accessed directly, though it does form the basis of a number of activities – as an exemplar at international conferences and other knowledge sharing events, including activities with graduate students locally. The provisioning services it provides are also the source of important cultural heritage and recreational benefit for society in the region.

Reputation

The Convention Centre has been granted LEED platinum-level certification, partly for the innovative marine habitat mitigation measures. It is thought to be the only convention centre with this designation making it a world-leading design concept. The centre also won the Professional Convention Management Association's (PCMA) Environmental Leadership Award (2010).

Who can apply this intervention / technique?

Any developer or government agency that is responsible for the design or approval of coastal infrastructure that impacts on the coastal and marine environment. Whilst these measures were done as part of required mitigation, they also could be used to ensure net gain, reduce risks of coastal squeeze for habitats under a changing climate and demonstrate corporate social responsibility.

Scaling up the benefits

The Convention Centre was a relatively large-scale project that created a shadow over around 140 m2 of sea floor, damaging the ecosystem beneath it. The combination of subtidal and intertidal habitat creation features has proven to successfully mitigate for the habitat loss and provide important ecosystem services. The principles in this scheme could be scaled up to whole estuary initiatives, or be used elsewhere for other habitat mitigation requirements at the scale of individual developments.
Other factors to consider when designing coastal ecological enhancements; the degree of wave exposure and water movement, temperature averages and extremes, light levels, methods of recruitment, stresses (limiting factors are generally considered to be inter-species and intra-species competition at lower levels, physical stresses higher up the tide). See the coastal business case for more detail on these factors.

Data Quality

The table shows the relative strengths of the Economic, Technical and Environmental data available. They are classified as:

Scheme Specific
part of a PhD or similar detailed research

Expert Judgment
interpretation of the scheme by one or more experts

Wider Supporting Evidence
extrapolated from published work or reports by practitioners.

DATA TYPE	DATA QUALITY / QUANTITY						
	Scheme specific information			Expert judgement		Wider supporting evidence	
	No Data	Limited reported sources	Strong reported sources	Some expert opinion	Multiple experts	Some sources	Multiple sources
COST			●		●		
ENGINEERING		●			●		
ECOSYSTEM SERVICES			●		●		

Further information / Contacts

Slogan, J.R. 2015. Evaluation of Design, Environmental, and Sustainability Attributes Affecting Urban Fisheries Restoration Habitat in Vancouver, British Columbia, Canada. Unpublished PhD Thesis, University of British Columbia.

URL: http://www.vancouverconventioncentre.com/about-us/environment

Dr. Daniel Leonard, Advisian Group:
Daniel.leonard@advisian.com
Nick Page, Vancouver Park Board:
nick.page@vancouver.ca
Dr. Jamie Slogan, Ph.D., R.P.Bio:
jamesslogan@hotmail.com

Coastal Art of the Possible

Vegetated tidal mudflat creation

What is the measure?

Artificial mudflat habitat – sheet piling was removed and the replacement defence was set back by 6 meters with rip-rap toe to create a new mud flat habitat on the banks of tidal river Camel, Wadebridge, North Cornwall.

Primary driver

Replacement of the sheet pile was identified as essential for the protection of a housing development, as existing sheet piles were suffering from corrosion (accelerated low-water corrosion). There was an opportunity to set the new sheet pile wall further back, to create space within the tidal and fluvial channel to catch small amounts of intertidal sediment and create an artificial mudflat habitat.

Benefit

This solution had the additional benefits of habitat creation, sedimentation in addition to reduced inspection, maintenance and repair costs (reduced corrosion) which make the business case economically robust, particularly in the longer-term.

Cost

This investment relative to the rest of the private development is moderate.

Engineering

It was not possible to refurbish the existing piles as this would not have provided the 100 year design life that was agreed as part of the planning permission for the new residential development. To achieve the 100 year design life a replacement sheet piled wall was selected which required protection to minimise corrosion rates. By setting back the piles from the edge of the channel the lower section could be protected by using fill material and only the upper section needed to be protected using concrete cladding. Designed not to compromise performance, inspection or maintenance, new pile walls extend the lifespan of this section of defence. Subject to regular asset inspection.

Asset resilience

This option installs new piles to extend the life of the defence in this location.
Long-term benefits are Medium.

Ecosystem services

Small realignment of sheet piles gave the opportunity for a stone / rock toe to the defence. This was designed to catch estuary sediment and provide a small feeding zone for estuary birds. Set back defence also provides a wider channel to accommodate fluvial and tidal events. Benefits not measured.

Social

Sheet piles were clad with a cast in-situ concrete facing. The facing provides corrosion protection and a more attractive finish to raw sheet pile. A form liner was used to mimic vertical slate walls that are a traditional finish in the Camel Estuary and North Cornwall. Landscape and visual impact was considered during design. An initial design was to have a cantilevered walkway over the space though this was not delivered in final construction.

Reputation

Renovation and improvement of the local defences may have helped the developer when selling the houses although there is no data.

Policy

The replacement flood defence wall could not be installed further into the estuary due to the loss of habitat that this would cause. The setback defence resulted in a net increase in intertidal habitat and the residential development was designed to be adequately defended from coastal flood risk over its lifetime by using raised defences and elevating floor levels above the predicted flood levels for Wadebridge.

Further data

Contact:
James Burke / Frank Newell,
Environment Agency Bodmin Office, Cornwall, UK.

Art of the Possible

Bioblock

What is the measure?

Precast habitat-enhancement unit comprising multiple habitat types that can be used as part of intertidal rock armour coastal defence structure. One 5.4 tonne BIOBLOCK (1.5 m × 1.5 m × 1.1 m or 2.48 m^3) was deployed as part of a new rock groyne.

It was tested on a moderately exposed coast at Colwyn Bay, West Wales, UK, 2012.

Primary driver

To improve the habitat and ecological potential of hard engineered structures.

Benefit

Supporting ecosystem services were measured in this study. The pools supported higher diversity than neighbouring similar, exposed surfaces and where they were included the overall species diversity increased. There are clear ecological benefits from the prototype BIOBLOCK; Units could be adapted to encourage rock-pooling to enhance cultural benefits; the prototype cost of a single unit compared to BAU was expensive, however mass production would reduce costs and improve the benefits (ecological and cultural).

Cost

Per unit cost: £2000 for the mould, casting, transport and deployment of the prototype BIOBLOCK which is equivalent to £800/m3. This compares to between £63 – 93/m3 for rock groynes (EA 2015, 2010 prices). The bioblock is between 9 – 13 times more expensive per unit compared to business as usual rock armour units used in rock groynes. Mass production of the BIOBLOCKS would reduce their costs. Further details on costs can be found in Firth et al. 2014.

Engineering

Expert judgement by engineers assumed no impact on engineering function of the groyne rock revetment. A BIOBLOCK can replace any rock armour unit on a defence structure and should last >10 years.

Ecosystem services

The BIOBLOCK supported greater biodiversity than the surrounding rock revetment. The range of habitat types (rock pools, ledges, overhangs, pits) rather than any one particular habitat type drove this pattern.

Policy

Influenced by the Marine and Coastal Access (UK) Act 2009 and the UK Marine Policy Statement 2011 which states that developments should avoid harm to marine ecology and biodiversity and provide opportunities for “building-in beneficial features”.

Further Data

Firth, LB et al. (2014). Between a rock and a hard place: environmental and engineering considerations when designing coastal defence structures. Coastal Engineering, 87: 122-135.

Contact:
Dr Louise Firth: louise.firth@plymouth.ac.uk
@Louise_Firth_IE

URL:
www.theseusproject.eu/
www.urbaneproject.org

Armour drill-cored rock pools





What is the measure?

A technique for increasing water-retaining features on horizontal or gently sloping substrates; it was tested by retrofitting sets of four 150 mm diameter holes at either 50 mm or 120 mm deep per rock armour unit using a core drill, between MLWS and MHWS, on a granite rock armoured breakwater in Tywyn, Wales.

Primary driver

To test efficacy of retrofitted water-retaining features in improving ecosystem enhancement.

Benefit

Supporting ecosystem services were measured in this study. The pools supported higher diversity than neighbouring similar, exposed surfaces and where they were included the overall species diversity increased; however, the unit cost makes them expensive compared to business as usual.

Cost

£2000 of labour for 4 days drilling to make 40 rock pools on existing rock armour. Four (150 mm diameter) holes were drilled per rock armour unit (assumed to be $1m^3$), costing ~£200 per m^3. This compares to between £42 – 107/m^3 for rock armour (2010 prices, (EA, 2015)). Four pools per m^3 are between 2 to 5 times more expensive than business as usual per retrofitted unit. Cost per retrofitted pool was ~£50 but savings would be possible if pools were drilled prior to installation rather than as an on shore retrofit.

Engineering

The size and density of holes did not undermine the engineering performance, nor alter the inspection or maintenance regimes of the rock armour.

Ecosystem services

The pools supported higher biodiversity than surrounding surfaces without water-retaining features where the unaltered, exposed areas of the structure reached species saturation after 6 months. In comparison, after 30 months, more species were still arriving in the rock pools and saturation had not been reached. When compared to natural rock pools, the artificial pools supported a similar number of species; however, community structure differed.

Reputation

Awarded the 'Most Innovative' design at the 2014 CIRIA Big Challenge Awards and is included in CIRIA's 2015 Coastal and Marine Environmental Site Guide.

Policy

Influenced by the Marine and Coastal Access (UK) Act 2009 and the UK Marine Policy Statement 2011 which states that developments should avoid harm to marine ecology and biodiversity and provide opportunities for "building-in beneficial features".

Further data

Evans, A.J. et al. (2016). Drill-cored rock pools: an effective method of ecological enhancement on artificial structures. Marine & Freshwater Research 67: 123-130. doi.org/10.1071/MF14244

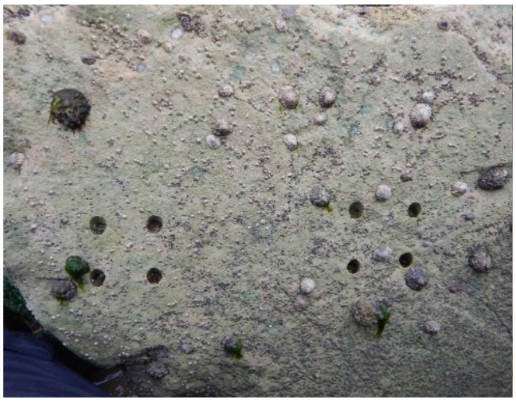
Contacts:
Dr. Ally Evans: Ally.Evans@aber.ac.uk, @AllyAllyj
Dr. Pippa Moore: pim2@aber.ac.uk, @Pippa_J_Moore
Dr. Louise Firth: louise.firth@plymouth.ac.uk, @Louise_Firth_IE

Art of the Possible

Armour pits and grooves

COASTAL

AP-C4



What is the measure?

Granite and limestone rock armour were retrofitted with habitat features by drilling (arrays of 4 holes, 16 mm diameter x 20 mm deep) and scoring the rock armour with petrol saw/angle grinder (to mimic mining artefacts). Score marks were 2 mm x 600 mm x 10 mm deep above and below a central 1 mm x 600 mm long by 20 mm deep groove. The coarser middle grooves were chiselled out to create rough surface texture on the base and sides.

The created habitat features were tested at Runswick Bay, N. Yorks and Boscombe, Poole Bay, Dorset (both moderately exposed sandy shores).

Primary driver

To test the efficacy of increased surface heterogeneity and retrofitted water retaining features in improving ecosystem enhancements of rock armour.

Benefits

Improved ecological outcomes (increase in species diversity on granite) compared to business-as-usual were found after 12 months. Additional cost of adding the holes varied by material type but ranged from 15% to 100% more expensive than business-as-usual.

Costs

The cost of retrofitting holes into rock armour varied by material type. Limestone was less expensive to retrofit (£10/m³ or 4 hours for 48 boulders) than granite (£55/m³ or 2 hours to retrofit 12 boulders). This cost is then scaled up to m³ to compare it with standard Environment Agency rock armour prices for rock revetments. This equates to ~£17/m³ and £88/m³ in additional costs to add the enhancements onto limestone and granite, respectively. Standard rock armour for revetments costs between £42 – 107/m³. Adding drill holes to the granite rock armour would be approximately 1.2 to 2 times the business as usual costs for commercial rock armour. This means it would cost between £130 -£195/m³ for combined rock purchase and drilling costs. For limestone these costs would be lower, adding between 15-40% to the cost of business as usual rock armour, thus costing between £84-£150/m³.

Engineering

No discernible negative impact. The size and density of the holes were too small to adversely impact on the engineering performance of rock armour.

Ecosystem services

Both sites were monitored for 12 months where
Both sites were monitored for 12 months where
limestone had higher overall species richness and diversity than the granite rock armour. For both rock types (granite and limestone), there was a significant increase in species richness and species diversity in the holes and grooved treatments compared to the business as usual unenhanced control. The increase in species diversity was greatest in the grooved treatments.

Species of commercial importance (e.g. crabs) were only found in the enhanced areas. This demonstrates that simple enhancement techniques can provide improved supporting ecosystem services (e.g. habitat provision). Other ecosystem services were not measured as part of this study.

Policy

No specific mitigation requirement; the habitat creation assisted approval of the Runswick Bay coastal defence scheme by the Marine Monitoring Organisation and Natural England, as it is within a Marine Conservation Zone.

Further Data

Hall et al. (2017). Improving habitat heterogeneity on coastal defence structures. ICE 2017 proceedings.

Contacts:
Alice Hall: ahall@bournemouth.ac.uk, @AHall_Marine
Dr. Roger Herbert: RHerbert@bournemouth.ac.uk

Concrete rock pools

What is the measure?

Artificial concrete rock pools were created on a causeway in Galway Bay, Ireland (made of precast concrete hollow-core Shepherd Hill energy dissipation (SHED) units). The water-retaining features were made by pouring quick-drying concrete around buckets in the base of the SHED units. The buckets were removed when the concrete set, leaving 10-14 cm diameter and 10-12 cm deep depressions (~1250 cm^3 volume). In total, 80 pools were created: 20 in the upper (0.4 m above MHWS) and 20 in the lower (1.9 m below MHWS) shore on both the eastern (sheltered) and western (exposed) sides of the causeway.

Primary driver

To test efficacy of artificial concrete rock pools/water-retaining features in improving ecosystem enhancement at different shore heights in the tidal column.

Benefit

The trial pools proved successful in increasing biodiversity on the causeway, and illustrate how enhancements at different heights can provide a range of ecological responses over time. No studies were done on wider ecosystem service and engineering benefits.

Cost

Eighty pools cost approximately 3000 € (including labour, materials and equipment) extra beyond the normal grey engineering costs for the SHED units, the equivalent of 38 € per pool.

Engineering

inspection or maintenance of the SHED units. The City Council Engineer approved these enhancement design. Long term – the pools and SHED units survived the winter storms of 2014; storms with a 1% chance of occurrence annually.

Ecosystem services

After the initial 12 months the lower and exposed pools supported greater diversity than the upper and sheltered pools respectively. However, after 24 months, all sheltered pools became inundated with sediment, creating muddy habitats, while the lower exposed pools became colonised with greater total diversity than the upper exposed pools; showing that <20 exposed pools can improve biodiversity outcomes. For rare species, more pools would be required.

Reputation

Galway City Council provided advice and permission for the work and this research helps the city understand and promote their rich biodiversity (see: https://www.irishtimes.com/news/environment/a-rock-pool-for-life-to-cling-to-1.1405371).

Policy

Currently, there are no policy drivers in Ireland to promote this work. Similar projects in the UK are influenced by the Marine and Coastal Access (UK) Act 2009 and the UK Marine Policy Statement 2011 which states that developments should avoid harm to marine ecology and biodiversity and provide opportunities for "building-in beneficial features".

Further data.

Firth, LB., et al. (2016). Eco-engineered rock pools: a concrete solution to biodiversity loss and urban sprawl in the marine environment. Environmental Research Letters, 11(9), p.094015.

Contacts:
Louise Firth: louise.firth@plymouth.ac.uk
@Louise_Firth_IE
Steve Hawkins: S.J.Hawkins@soton.ac.uk

This work was a collaboration by Plymouth University, Southampton University, Marine Biological Association of the UK and Galway-Mayo Institute of Technology.

Art of the Possible

Armour breakwater enhanced concrete

COASTAL

AP-C6

What is the measure?

Different design features were created through experimental modifications during the maintenance of concrete armour units fronting an existing detached breakwater in Plymouth Sound. New habitat was added by drilling 400 small water-retaining holes per concrete armour unit; each hole was 14mm or 22mm in diameter and 25mm long with a slight downward angle.

Primary driver

To introduce habitat (small water retaining pools, holes and surface roughness) in 100 tonnes cast concrete armour on breakwater. To demonstrate the influence of small modifications to concrete cast armour defence units on the diversity and abundance of local marine species.

Benefit

The results demonstrated that the productivity and biodiversity of hard, offshore breakwater structures can be improved by retrofitting habitat features into concrete armour units. Such an approach could be applied to other armour units made of either rock or concrete.

Cost

The armour units used on the breakwater are 42 m^3 truncated pyramids that are 3200 mm x 6850 mm at the base, 2430 mm x 5100 mm at the top, and 2350 mm high. Each unit was retrofitted with 400 holes by drilling. On average, it took 8 to 10 hrs, costing £60 - £75 m^2 (assuming an hourly rate of £30), or £240 to £300 per armour unit.

As part of routine maintenance, twelve – 15 new concrete armour units are added to the breakwater per year; the cost of these are unknown. Creating the enhancement via drillings adds an additional annual cost of ~£240 to £300 per unit. The Environment Agency's (2015) offshore breakwater armour cost per metre is between £1750 - £3304 (2007 prices). Adding 100 holes per m^2 would be a modest cost increase – between 2-4% per metre.

Engineering

These relatively very small modifications are not believed to have a detrimental impact on engineering performance, alter its resilience and/or weaken the structure in any way.

Ecosystem services

Breakwaters are generally seen as being of low habitat value, predominantly because they are topographically less complex than natural rocky shores (Firth et al. 2011). Adding surface complexity simply by drilling relatively small holes into the units adds habitat to these extensive coastal structures. However, colonization rates and outcomes for individual species can be difficult to predict and site-specific studies would be required to assess and plan modifications to encourage desired outcomes.

Social

While the enhancement area is not accessible to the public, the improved biodiversity can benefit society through improved habitat for species that support commercial or recreational marine activities.

Reputation

No specific reputation data were collected in this study. These techniques could be used in future schemes to address local planning, climate change or biodiversity issues.

Further Data

Juliette Jackson, 2014. The influence of engineering design considerations on species recruitment and succession on coastal defence structures. Plymouth University

Contacts:

Dr Juliette Jackson: jjackson@seadreameducation.com

@JeJackson31

Prof. Richard Thompson: R.C.Thompson@plymouth.ac.uk

URL: https://pearl.plymouth.ac.uk/bitstream/handle/10026.1/4781/2015%20Jackson%20704999%20PhD.pdf?sequence=6

Textured concrete for biodiversity

What is the measure?

Millimetre-scale grooves applied manually using a wire brush to concrete during casting/curing designed to improve the rate of settlement and abundance of barnacles and associated species.

Tests were carried out on wave exposed, open coasts in Cornwall.

Primary driver

To test if we can improve the ecological potential of marine concrete infrastructure for early colonists (barnacles), compared with business as usual plain-cast concrete.

Benefit

Simple inexpensive additions (mm-scale grooves) to the manufacture process led to a 7-fold improvement in biodiversity compared to plain cast concrete after 3 years for limited additional cost. Barnacle colonisation was increased through texturing which has been shown to improve asset resilience (AP-C9).

Cost

Limited additional labour was required during casting (30 minutes per m^2) adding approximately £15/m^2 to the manufacturing cost, representing an increase of between 0.3% and 6.6% compared to BAU. EA figures for 2010 suggest a range between £0.5k and £5.5k per m^2 for sea wall defences. AP-C8 demonstrates that this scale of texture can be readily manufactured using textured formwork.

Engineering

Concrete panels are produced as normal with the only manufacturing change being adding striations with a wire brush. Structures colonised with organisms like barnacles will have no or negligible impact on engineering performance, service life or maintenance.

Asset resilience

Increased cover of barnacles has also been found to improve concrete and rock resilience to weathering-related deterioration in field and laboratory trials (AP-C9).

Ecosystem services

Only supporting ecosystem services were measured by this study. Results show that more than double the number of barnacles was found on grooved concrete than plain-cast concrete in < 6 months. Increasing barnacle abundance (via texturing) also increased invertebrate species richness (a 7:1 ratio) after 2 to 3 years.

Social

Textured concrete is often more aesthetically pleasing than smooth alternatives. Facilitating sedentary species like barnacles and seaweeds can also exclude less attractive, slippery ephemeral green algae and reduce disturbing maintenance works through increased asset resilience (AP-C9).

Policy

Can assist in meeting requirements to maximise ecological potential under the Water Framework Directive.

Further Data

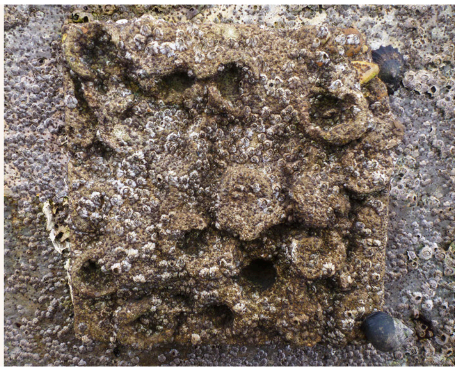
Coombes, M.A., et al. (2015). Getting into the groove: Opportunities to enhance the ecological value of hard coastal infrastructure using fine-scale surface textures. Ecological Engineering 77: 314-323.

Contacts:
Dr. Martin Coombes: martin.coombes@ouce.ox.ac.uk
@MACoombes
Dr. Larissa Naylor: larissa.naylor@glasgow.ac.uk
@biogeomorph

URL: www.biogeomorph.org/coastal/coastaldefencesbiodiversity

This forms part of Naylor, LA., Kippen, H, Coombes, MA., et al. (2017). Greening the Grey: a framework for integrated green grey infrastructure (IGGI). University of Glasgow report. URL: http://eprints.gla.ac.uk/150672/

Textured concrete for sea walls



What is the measure?

Testing mm to cm scale surface texture designs to ecologically enhance vertical coastal structures (e.g. defences, walls, piers, pilings) compared with industry standard smooth plain-cast concrete. Eight different tile designs (184 tiles, 150 x 150 x 40 mm) were placed at mid to upper tidal level on north facing vertical seawalls at Saltcoats harbour, Scotland (sheltered), Blackness pier, Scotland (muddy, semi-exposed estuary) and on a sea wall on the Isle of Wight, England (moderately exposed). Tiles were cast in two material types: marine concrete and natural cement-based concrete.

Primary Driver

To establish the largest trial of ecologically enhanced text panel designs across the UK to determine which surface textures are optimal for enhancing species richness and diversity.

Benefit

Adding surface texture to concrete structures that are typically plain-cast by design increases the quantity and quality of habitat available for rocky intertidal species. The only additional cost for future applications would be the design and production of textured formwork.

Cost

For these prototypes, the cost of formwork design, production and deployment of 184 test tiles was approximately £8500. This equates to £33/m^2 for the initial production; however, the silicone formwork can be reused up to 20 times, reducing the costs to < £2/m^2. where the silicone moulds can be re-used at least 20 times reducing the cost per m^2. If commercially available textured form liners are used it would cost £8-30 per m^2 more than BAU. This is a small increase (0.1 - 0.6%) in cost based on suggested EA 2010 figures for sea wall of around £5,500 m^2.

Engineering

The test tiles did not compromise the engineering performance of the structure as they were affixed onto the existing surface using natural cement and/or marine epoxy; future integral, pre-cast design would not affect performance, inspection and/or maintenance.

Asset Resilience

Many of the tile designs attracted high abundances of barnacles in as little as 6 months post-installation (over one settlement season for barnacles). High barnacle abundance has been found to reduce weathering-related deterioration in field and laboratory trials (AP-C9); there is potential to use some of these designs in future formwork to improve asset resilience.

Ecosystem Services

Only supporting services were measured in this study. Ecologically enhanced tiles with greater habitat complexity hosted higher abundance and species richness than plain-cast counterparts after six months.

Policy

A further test of these tiles has helped deliver the Edinburgh Living Landscape's action plan.

Reputation

The trial at Saltcoats Harbour has assisted the local council in demonstrating they are exploring ways of enhancing the multifunctionality and ecosystem services of hard coastal structures to inform their shoreline management and coastal protection plans.

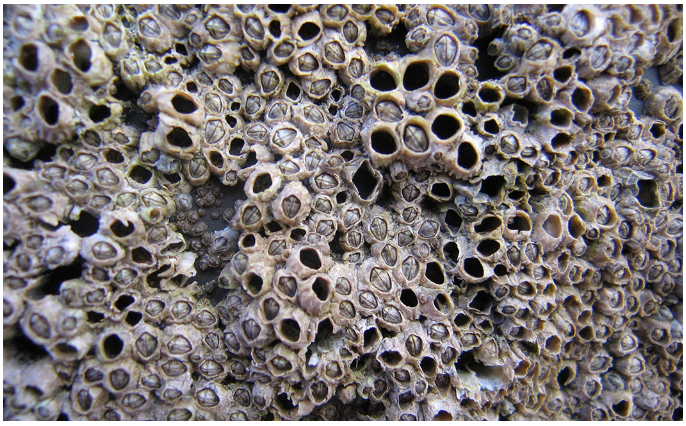
Further Data

MacArthur, M. et al. (2017). Ecologically Enhancing Coastal Infrastructure. Geophysical Research Abstracts Vol. 19, EGU2017-921-1.

Contacts:
Mairi MacArthur: m.mac-arthur.1@research.gla.ac.uk
@macmairi1
Dr. Larissa Naylor: larissa.naylor@glasgow.ac.uk
@biogeomorph
Ian Boyd, Artecology: ian@arc-consulting.co.uk

URL: meetingorganizer.copernicus.org/EGU2017/EGU2017-921-1.pdf

Bioprotection of engineering assets



What is the measure?

A cover of barnacles or seaweed buffers porous rock and concrete. Alongside ecological gain, encouraging colonisation can improve asset resilience by limiting weathering, heating/ cooling, wetting/drying and salt ingress.

Primary driver

To illustrate how ecological enhancement for biodiversity gains can provide additional engineering benefit, by improving asset resilience through limiting weathering-related deterioration. Tests were carried out in the field (Cornwall and Dorset) and in the laboratory.

Benefit

Benefits include improved asset resilience of hard structures with high cover of barnacles and seaweeds, that also provide supporting habitat for other species (AP-C7).

Cost

No direct data available.
Bioprotection may reduce required frequency of maintenance and repair/replacement by extending service life. Economic benefits will vary depending on type of asset, existing inspection and maintenance regime, and the type of materials, location and extent/type of biological growth. Compared to a non-enhanced option, financial benefits from reduced deterioration are estimated (based on expert judgement) to be low to medium over the medium- to long-term.

Engineering

Seaweeds: the range and extremes of surface temperatures were consistently reduced in field conditions under seaweed compared to bare surfaces, by an average of 56% and 25%, respectively. Short-term (minutes to hours) thermal cycling during low tide was reduced under seaweed (78%) as were variations in moisture (71%). Buffering by canopy-forming species of temperature and moisture reduced deterioration of mudstone rock. After 100 laboratory thermal cycles, loss of surface strength was reduced by more than 50% compared to bare rock, and actual breakdown of the material (measured as loss of mass) was reduced by up to 79%. Seaweeds are thought to reduce the frequency of damaging salt crystallisation events. Similar effects are expected for materials such as concrete.
Barnacles: compared to bare 'business as usual' surfaces, barnacle cover reduced peak temperatures (to 10 mm depth) by 1 to 5 degrees and short-term thermal cycling (15-30 minute) in the order of a few degrees, depending on material type (limestone, granite and concrete were tested). This is thought to limit damage to hard assets caused by 'fatigue' caused by repeated expansion and contraction.
The concentrations of damaging salt ions were also lower under a cover of barnacles compared to bare surfaces after a period of 2 to 3 years. The strength of these effects varied (positively) with barnacle abundance - the greater the cover of barnacles the greater the buffering effect.

Asset resilience

Results suggest that asset resilience to weathering related deterioration risks is increased through bioprotection.

Ecosystem Services

For details of possible ecological benefits, see specific enhancement measures in other case studies and AP examples. Reduced maintenance could improve ecological outcomes as disturbance to ecology would be reduced.

Social

Possible reduction in the frequency of repair/ replacement could reduce disturbance of local residents during repair works.

Policy

An 'additional' benefit to wider enhancement for ecological mitigation can help meet National Infrastructure Strategy goals of "improved multifuncionality, resilience and sustainability".

Further Information

Coombes, M.A., et al. (2017). Cool barnacles: Do common biogenic structures enhance or retard rates of deterioration of intertidal rocks and concrete? Science of the Total Environment 580, 1034-1045.

Coombes, M.A., et al. (2013). Bioprotection and disturbance: seaweed, microclimatic stability and conditions for mechanical weathering in the intertidal zone. Geomorphology 202, 4-14.

Gowell, M.R., et al. (2015). Rock-protecting seaweed? Experimental evidence of bioprotection in the intertidal zone. Earth Surface Processers and Landforms 40, 1364-1370.

Contacts:
Dr. Martin Coombes: martin.coombes@ouce.ox.ac.uk
@MACoombes
Dr. Larissa Naylor: larissa.naylor@glasgow.ac.uk
@biogeomorph

URL: www.biogeomorph.org/coastal/bioprotection

This forms part of Naylor, LA., Kippen, H, Coombes, MA., et al. (2017). Greening the Grey: a framework for integrated green grey infrastructure (IGGI). University of Glasgow report. URL: http://eprints.gla.ac.uk/150672/

Eco-enhanced stormwater outfalls

What is the measure?

Prototype design of a wave tile (for a pre-cast concrete unit) to improve ecological and social value of stormwater outfalls; these outfalls are a common feature of coastlines worldwide and to date, are an infrastructure type where ecological enhancement potential has not been explored. The test tiles were deployed as retrofits for this trial but could be built into future pre-cast units using textured formwork.
Tests were carried out on wave exposed, open coasts in Cornwall, UK.

Primary driver

To test if we can improve the ecological suitability marine concrete infrastructure, compared with business-as-usual plain-cast concrete, whilst maintaining its use as a low tide footpath. It was specifically designed to create suitable crevice and water-holding habitat for mobile species along with a clear path for people to walk along – so that habitat and human activity can be catered for on the stormwater outfall.

Benefit

The overall social and ecological value of the wave tile compared to the business-as-usual standard option shows the high benefits of multifunctional designs; with both public perception and ecological response of the test tile being greater than business-as-usual. The only additional cost for future applications would be design and production of textured formwork during the construction phase.

Cost

For this prototype, the cost of design, production and deployment of test tiles was approximately £2000 (~£1000/m^2). Re-using the silicone mould up to 20 times reduced the costs to £50/m^2. If using commercially available textured form liners, these may be a little more expensive to clean and re-use (~£8-30 per m^2 more than the business-as-usual).

Engineering

The test tiles did not compromise the engineering performance of the structure; future integral, pre-cast design and ecological colonisation of these would not affect performance, inspection or maintenance. In zones were barnacles were in high abundance, the biology may improve asset resilience to weathering-related deterioration (AP-C9) without impacting on human use of the outfall as a footpath.

Ecosystem services

A three-fold increase in animal and double the algal species diversity was found on the wave tile compared to the ordinary smooth concrete surface in less than 6 months. Animal abundance increased 30 fold on the wave tile compared to the business as usual, ordinary smooth concrete surface.

Social

In a survey of 25 respondents, 64% of people preferred the wave tile design compared to business-as-usual; they felt it was likely to provide more ecological value than the business-as-usual smooth concrete alternative. They also used the outfall for walking and launching kayaks.

Further data

Metcalfe, D. 2015. Multispecies Design. Unpublished PhD Thesis. University of the Arts and Falmouth University.

Contacts:
Dr. Daniel Metcalfe: danimetcalfe@gmail.com
@Danimetcalfe

Dr. Larissa Naylor: larissa.naylor@glasgow.ac.uk
@biogeomorph

URL: http://www.danimetcalfe.com/index.php/research/multispecies-design/