Marine
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Evidence Supporting the Use of Environmental Remediation to Improve Water Quality in the South Marine Plan Areas

MMO Project No: 1105

February 2016

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UNIVERSITY OF Hull
Institute of Estuarine and Coastal Studies

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Contents

List of Figures

List of Tables

List of Acronyms

AoS	Appraisal of Sustainability
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CSSEG	Clean and Safe Seas Evidence Group
Defra	Department for Environment, Food and Rural Affairs
EA	Environment Agency
JNCC	Joint Nature Conservation Committee
MCAA	Marine and Coastal Access Act 2009
MMO	Marine Management Organisation
MSFD	Marine Strategy Framework Directive
OSPAR	Oslo-Paris Convention for the Protection of the Marine Environment of the North-East Atlantic
RBD	River Basin Districts
RBMD	River Basin Management District
RBMP	River Basin Management Plans
SAC	Special Area of Conservation
SPA	Special Protection Area
UKMMAS	Marine Monitoring and Assessment Strategy
UKNEA	UK National Ecosystem Assessment
UWWTD	Urban Waste-Water Treatment Directives
WFD	Water Framework Directive

Executive Summary

Under the Marine and Coastal Access Act (2009), the UK Government introduced a number of measures to deliver its vision of 'clean, healthy, safe, productive and biologically diverse oceans and seas', including the introduction of a marine planning system. The Marine Management Organisation (MMO) was established under this Act and has responsibility to develop marine plans for distinct inshore and offshore areas of English seas on behalf of the Secretary of State. This report provides evidence to support marine planning regarding the possible use of environmental remediation to improve water quality in the South Inshore and South Offshore Marine Plan Areas (hereafter south marine plan areas).

Water quality in the south marine plan areas was reviewed, using the Water Framework Directive (WFD) river basin management districts (RBMD) to divide the south marine plan areas into sectors falling within the South West RBMD and the South East RBMD. A scoring system was developed and applied to summarise water quality issues within these two management districts, using a three-class relative measure for nutrients and ecological status, microbiological status and chemical pollution where 3 is good and 1 is poor; insufficient evidence was available to classify water bodies for excessive turbidity. A water quality index for each site is given as the sum of these three measures, with the average water quality index in the western sector being 7 (out of 9) whilst the eastern sector averaged 6 (out of 9). This report focuses on potential bioremediation options for improving water quality in relation to reducing nutrient loading, microbial contamination, chemical contamination and turbidity.

A review of potential bioremediation options to address these four water quality issues was undertaken. The review focussed on four main types of bioremediation (using filter feeders, seaweeds, seagrasses, and saltmarsh and *Phragmites* reedbeds) and summarised the positive and negative attributes of each. Based on the findings from the literature and taking into account the required and desirable attributes of bioremediation approaches, this report identifies 13 potential bioremediation options applicable for UK coastal waters which would each address one or more of the water quality issues of interest in the south marine plan areas.

Each bioremediation option identified as being of potential use was then outlined, presenting a summary of the approach, technical considerations and an overall assessment of feasibility, an estimation of costs, an assessment of bioremediation performance for each of the four water quality issues identified, an assessment of feasibility and an overall summary. The overall performance of each bioremediation option is presented as a radar plot to illustrate its performance in relation to each water quality issue, cost and ecological and technical feasibility.

In addition to assessing the performance of bioremediation options at the UK level, an assessment of sustainability, using the literature and expert judgement, was undertaken based upon 10 tenets of sustainable management, with each bioremediation option being scored with respect to each of the 10 tenets. Where the bioremediation options comply with the tenets, such responses to anthropogenic changes in the marine system will be sustainable, protect the environment and be pragmatic, especially where the economic imperative is paramount. As such they are likely to be more acceptable to wider society. An overall score for each option was derived to provide a simplified, indicative measure of the likely level of sustainability associated with each of the bioremediation options. A semi-quantitative assessment focussed on the impact of each bioremediation option on the provision of ecosystem services and societal benefits was also was also undertaken (again based on the literature and on expert judgement). Applying an ecosystem services approach enables the complexity of the marine system to be divided into a series of functions, which can be more readily understood by marine managers, policymakers and stakeholders. Based on the UK National Ecosystem Assessment framework, each ecosystem service and good/benefit was scored against a baseline of the level of ecosystem services currently provided by UK coastal and marine waters with respect to the potential impacts (both positive and negative) of each bioremediation option on ecosystem service delivery. In order to avoid the potential for double-counting, only the scores for the goods and benefits were carried forward to provide an overall percentage score for the potential changes in societal benefits as a result of the implementation of each bioremediation measure.

The overall performance scores for each potential bioremediation option are presented, together with the scores for sustainability and potential additional societal benefits achieved. It is not intended that these figures are summed (or otherwise integrated) across the parameters for each potential bioremediation option to derive a single option score. Rather, it is anticipated that decisions on method applicability will be informed by each of the parameters independently. A framework for how this information could be used to identify optimum bioremediation options is presented, which recognises the importance of site-specific considerations in the final choice of bioremediation options.

In order to demonstrate the application of the approach a matrix was created to show the potential of each of the 13 bioremediation options to improve water quality for constituent water bodies within the south marine plan areas. Worked examples are presented, namely for the Exe Estuary and Poole Harbour, to show how the selection of an appropriate bioremediation technique could be done.

Bioremediation is then considered in the context of the existing draft south marine plans policies (as available at the time of writing this report, March 2015). There is a potential for significant negative interaction to occur between bioremediation and 12 of the draft policies e.g. bioremediation would act against the policy: S-TR-2c (static objects); S-TR-2d (tourism or recreation); S-TR-3c (public access); S-CAB-1b (cable landfall sites); S-TIDE-1b (tidal energy); S-DD-2b (dredging/disposal); S-GOV-1b (displacement); S-AGG-3c (aggregates); S-PS-2b (static infrastructure); S-PS-3b (navigation routes), and S-PS-4g (ports expansion). Competition for space on the seafloor or at the sea surface is the cause of conflict in most of these cases.

A further sub-set of 13 draft policies were identified for which a direct or indirect role of bioremediation was broadly supportive of the policy. For these draft policies, details of the justification for linking bioremediation to the policy are provided, along with which bioremediation options might be feasible, any additional system benefits, the monitoring required, how to measure success, conclusions and gaps in knowledge. The degree of support offered by bioremediation varies between the different policies. Bioremediation would strongly support policy S-WQ-3b (activities that can deliver an improvement to estuarine water quality), and also the mitigation element of policy S-WQ-2b (proposals that have an adverse impact upon estuarine water quality). Policy S-BIO-7c (water filtration ecosystem service supported) is clearly relevant for all of the bioremediation services listed in this report, but particularly so for those utilising filter-feeding bivalves. However, for those policies that are supported by bioremediation, not of all the 13 bioremediation options will apply. For example, policy code S-BIO-1C (proposals with adverse effects on natural flood defence or carbon sequestration) would be relevant for bioremediation options using seagrass, managed realignment or *Spartina* management options.

The evidence presented in this report can be used to further refine the existing draft marine policies. It is important to consider whether bioremediation is of sufficiently high importance to warrant a policy in its own right. Although marine bioremediation and ecosystem restoration has not yet been used significantly in the UK (other than for managed re-alignment), evidence presented in this report suggests that its use should be encouraged, for example through policy and associated objectives.

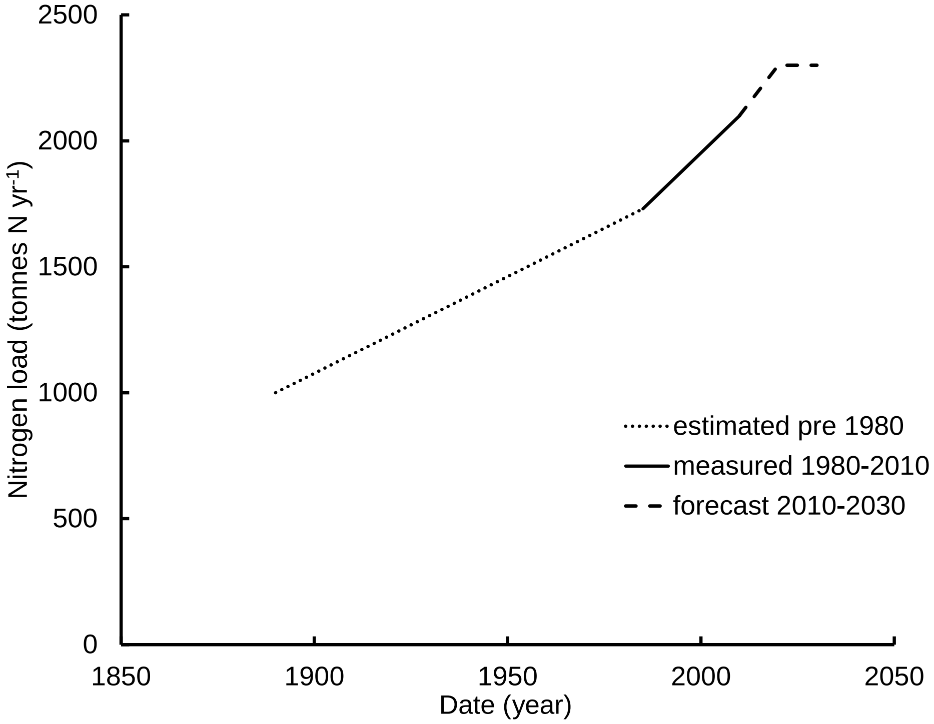
1. Introduction

1.1 Pressures on coastal water quality

Human activity has modified many biogeochemical cycles to the extent that anthropogenic use or modification of certain resources now outweighs natural rates of change (Vitousek *et al.*, 1997; Fowler *et al.*, 2013). Hence, the phrase 'the Anthropocene age' was proposed to indicate when global cycles became significantly influenced by humans (Lewis and Maslin, 2015). Anthropogenic impacts can be seen in many ecosystems, but coastal zones in particular have shown large changes over the past century. Pollution of coastal waters from excess nutrients, microbial contamination and hazardous chemicals has caused localised declines in water quality. The transport of nitrogen (N) from the land to the global ocean has greatly increased, from an estimated 18.7 million tonnes N in 1950 to 80 million tonnes N in 2000 (Mackenzie *et al.*, 2002, Fowler *et al.*, 2013), increasing eutrophication (Cloern, 2001). UK coasts and estuaries are often sites of high population growth and economic activity, and receive inputs of nutrients and waste materials from the land. Nutrient loading to some UK estuaries and enclosed water bodies has also increased (Figure 1) and water clarity of heavily impacted seas such as the North Sea and Baltic has decreased (Fleming-Lehtinen and Laamanen, 2012; Capuzzo *et al.*, 2015).

Treatments for improving coastal water quality can be expensive (Conley *et al.*, 2009). The costs for changing agricultural practices to reduce nutrient loading in the catchment of a eutrophic site, Poole Harbour, were estimated at £48,000 to £74,000 per tonne of nitrogen (Bryan and Kite, 2012). That receiving estuary was estimated to require a reduction of at least 550 tonnes nitrogen (thus returning to 1980s loading; Figure 1) before any improvement in water quality can be expected. A more expensive option is to remove nitrogen directly during the sewage treatment process, in which case the costs increase to £160,000 to £220,000 per tonne N (Bryan and Kite, 2012). Even where loadings have been reduced, e.g. following improvements in wastewater treatment, reversal to good quality in the receiving water may not be guaranteed. The accumulation of nutrients within sediments and a reduction in the regulatory capacity of the coastal system (primarily by the loss of benthic filter-feeders) explain the complex and unpredictable nature of responses to nutrient reduction (Duarte *et al.*, 2008). Additional intervention will then be required (Viaroli *et al.*, 2008; Möllmann *et al.,* 2009) such as the protection or restoration of coastal ecosystems together with nutrient control measures (Fulweiler *et al.*, 2012). Denmark has invested heavily in reducing the export of nutrients to its coastal waters by more than 30%, yet water quality indicators such as water clarity or algal blooms have not responded (Carstensen *et al.*, 2012). Movement of nitrogen through soils, groundwater, then rivers is slow, and the Environment Agency recognises that it may take several decades until an improvement in water quality is shown following nutrient reduction measures (Environment Agency, 2014a).

Figure 1: Increase in nitrogen loading to Poole Harbour (Bryan and Kite, 2012).



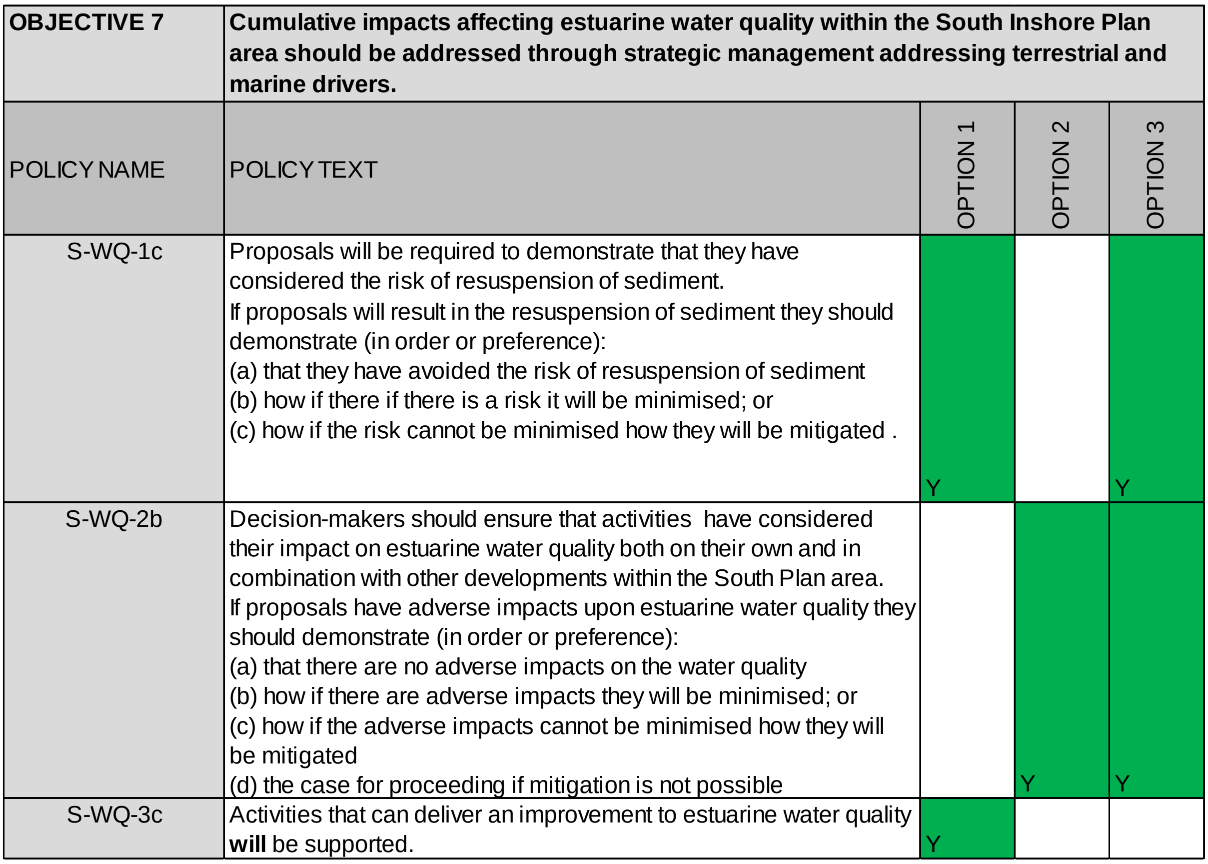
1.2 Planning to improve water quality

Under the Marine and Coastal Access Act (2009), the UK Government introduced a number of measures to deliver its vision of ‘clean, healthy, safe, productive and biologically diverse oceans and seas’, including the introduction of a marine planning system. The Marine Management Organisation (MMO) was established under this Act and its responsibilities include developing specific marine plans for distinct inshore and offshore regions of the English marine area. The first plans were launched for the East of England in 2013 (The East Inshore and Offshore Marine Plans; HM Government, 2014) and plans for the South coast, including inshore and offshore waters, from Folkestone to the Dart estuary are under development.

Charting Progress II (UKMMAS, 2010) highlighted the risk of degradation for the south marine area, with water quality issues further identified in the South Plan Analytical Report (MMO, 2014a) in relation to climate change, dredging, cumulative effects and recreational activities. In February 2015, the MMO put out to consultation the draft South Inshore and South Offshore Marine Plan Areas options report (MMO, 2015a). It should be noted that these draft plan policies are used to inform this work as they were available at the time of writing; however there may be subsequent changes in these policies as they proceed through the consultation process.

The options report sets out the draft vision, objectives and options developed as part of the planning process. Objective 7 of the options report specifically relates to the cumulative impacts affecting water quality. The planning process looked at alternative approaches, termed ‘Options’, in developing the plan, in order to address issues raised and achieve the plan objectives. A key part of the approach was to draft policies of ‘high’, ‘medium’ and ‘low’ strength, to be applied according to the evidence base. The selection of options is an iterative process, combining scientific evidence and stakeholder opinions. It is especially important that wording of the options is clear and consistent, to help the managers and developers in the region. Example draft policies for water quality in the South Inshore and South Offshore Marine Plan Areas (hereafter the south marine plan areas) are given in Figure 2. This report provides evidence to support the draft marine plans with respect to bioremediation and water quality.

Figure 2: Extract from the South Marine Plan Areas Options Report (MMO, 2015a) showing the water quality objective and options for the south marine plan areas.



OBJECTIVE 7	**Cumulative impacts affecting estuarine water quality within the South Inshore Plan area should be addressed through strategic management addressing terrestrial and marine drivers.**			
POLICY NAME	POLICY TEXT	OPTION 1	OPTION 2	OPTION 3
S-WQ-1c	Proposals will be required to demonstrate that they have considered the risk of resuspension of sediment. If proposals will result in the resuspension of sediment they should demonstrate (in order or preference): (a) that they have avoided the risk of resuspension of sediment (b) how if there if there is a risk it will be minimised; or (c) how if the risk cannot be minimised how they will be mitigated .	Y		Y
S-WQ-2b	Decision-makers should ensure that activities have considered their impact on estuarine water quality both on their own and in combination with other developments within the South Plan area. If proposals have adverse impacts upon estuarine water quality they should demonstrate (in order or preference): (a) that there are no adverse impacts on the water quality (b) how if there are adverse impacts they will be minimised; or (c) how if the adverse impacts cannot be minimised how they will be mitigated (d) the case for proceeding if mitigation is not possible		Y	Y
S-WQ-3c	Activities that can deliver an improvement to estuarine water quality **will** be supported.	Y		

Different strength options are denoted by the final letter of the policy code, from “a” (low) to “c” (high)

1.3 Objectives

The current project aims to provide an evidence base for marine planning on the possible use of environmental remediation to improve water quality in the south marine plan areas. The project objectives are:

1. Review and summarise existing available information on the use of different remediation approaches in the improvement of water quality.
2. Provide criteria by which potential sites for environmental remediation might be identified and mapped using GIS and, if feasible, map sites for environmental remediation in the South Inshore Marine Plan Area.

3. Draw conclusions with regards the feasibility of using the different environmental remediation approaches to help improve water quality for the south marine plan area.
4. Provide recommendations regarding the next steps required to enable use of environmental remediation in the south marine plan areas, including practical advice on establishing and implementing the approaches.
5. Summarise how the outputs of objectives 1-4 link back to draft plan policies. In addition, consider how the outputs might inform the monitoring approach for the south marine plans to facilitate evaluation of the potential effectiveness of water quality policies.

2. Water quality in the south marine plan areas

The Department for Environment, Food and Rural Affairs (Defra) has responsibility for water quality. The Clean and Safe Seas Evidence Group (CSSEG) of the UK Marine Monitoring and Assessment Strategy (UKMMAS) provides evidence to support Defra in compliance with the EU Marine Strategy Framework Directive (MSFD[1]) and the Water Framework Directive (WFD[2]). Charting Progress II marked the last full assessment of water quality at a UK scale, with a CSSEG feeder report (Law and Maes, 2010) providing evidence on aspects of water quality such as eutrophication, hazardous substances and microbial contamination. The feeder report notes that levels of monitored contaminants in open seas are falling and though they are not strongly affected by pollution, certain inshore areas still show high levels of inorganic nutrients. Eutrophication problem areas were fewer than in the previous Charting Progress report (Defra, 2005), restricted to certain harbours and semi-enclosed areas. Inputs of microbiological contamination from sewage treatment plants had fallen significantly because of investments in infrastructure following the implementation of the EU Urban Waste-Water Treatment Directive (UWWTD). Coastal waters in general are thus in good health, apart from some localised problem areas.

In the Strategic Scoping Report (MMO, 2013b), that draws on evidence from the CSSEG feeder report (Law and Maes, 2010), the MMO emphasise the importance of water quality for the overall health of the marine system. A summary of ecological and chemical water quality in each of the marine plan areas is provided as part of the Strategic Scoping Report. Present and predictions of potential future water quality in the south marine plan areas are summarised in the South Plan Analytical Report for the area (MMO, 2014a). It is recognised that water quality, and bathing water quality in particular, has improved since the mid-1980s due to investment in treatment facilities. River Basin Management Plans (RBMPs) developed and implemented under the WFD, as well as the Shellfish Waters Directive (repealed in December 2013 and incorporated in the WFD) and the UWWTD are the main delivery mechanisms for current and future improvements. The marine plans of the MMO are another important route for maintaining or improving ecological quality. The Environment Agency, the MMO and other regulators will work together across the land-sea interface to ensure that water quality objectives are met.

The South Marine Plan Areas Futures Analysis (MMO, 2013b) provides a detailed assessment of the current status, and anticipated future status, of water quality in the region. The report notes that whilst there is an improving trend in water quality across the plan areas, there is still a requirement (under the WFD) to reach good status for many coastal and transitional waters which are currently ranked as moderate or failing. Some water bodies will not reach a good status as the mitigation measures required would be ‘disproportionately expensive’ or ‘technically not feasible’. On the 6 to 20-year timescale of the marine plans there are also increasing pressures which may act to slow, or reverse, the improvements in water quality. For example:

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[1] Directive 2008/56/EC

[2] Directive 2000/60/EC

- More frequent and intense storm events linked to climate change, resulting in an increased frequency of potential storm overflows.
- Population growth putting more demand on the sewerage network and water companies to dispose of waste water.
- Urban creep increasing the impermeable nature of the catchment and thus promoting the rapid response of watercourses to rainfall events.
- Diffuse urban and rural pollution from wider catchment areas.

There are four types of water quality issues of concern in the south marine plan areas: excessive nutrient concentrations and disturbed ecological quality, microbial contamination of shellfish and bathing waters, chemical pollution, and elevated turbidity. The first three issues are addressed in part by the WFD, bathing water and food hygiene regulations. The last, elevated turbidity, occurring in coastal waters because of resuspension of sediments, disrupted seabed integrity and increased coastal erosion and may be exacerbated by human activities (MMO, 2015a). The existing regulations and the geographic variability of the different water quality problem types will be discussed and summarised in the following sections, using the most recent data from the second assessment cycle of the WFD where possible. The review begins with details of the relevant legislation in section 2.1, then examines existing monitoring programme outputs for the western (section 2.2) and eastern (section 2.3) parts of the south marine plan areas. Water quality issues across the region are then summarised in section 2.4 using a scoring system developed for this project based on measured nutrient and ecological, microbiological, chemical, and turbidity indicators. The most important physical descriptors of the different water bodies such as area, flushing time, depth and tidal range are then tabulated. The section closes with a summary of existing measures in place to improve water quality.

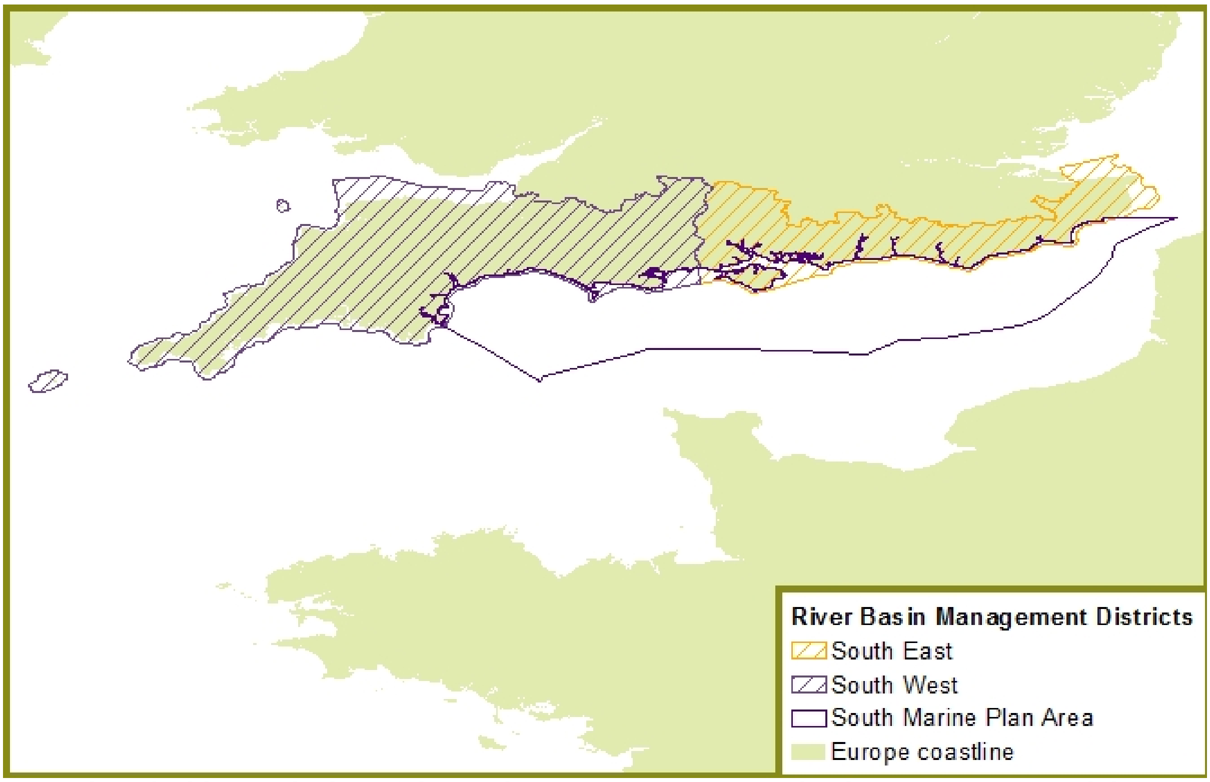
2.1 Water quality status under national and international legislation

2.1.1 Water Framework Directive

The WFD is one of the most important pieces of legislation for rivers, transitional and coastal waters out to 1 nautical mile. Under the WFD, defined river basin districts and coastal waters must reach at least ‘good’ status by 2015, and the WFD defines how this should be achieved through the establishment of ecological and chemical targets for surface waters. The WFD operates on a ‘one out, all out’ principle in which a failure to meet a target level for one indicator (‘element’) leads to an overall failure to achieve good status. There are five classes for ecological quality ranging from bad, through poor, moderate and good to high, and a binary pass/fail classification for chemical water quality. Groundwater is also classified under WFD for quality and chemical status.

The status of waters on the South coast of England is given in the following section, (updated with respect to MMO (2013b)) and is based on more recent Environment Agency reporting up to 2014. River Basin Districts (RBD) form the assessment units for Environment Agency / Natural Resources Wales plans to manage waters under WFD; these RBMPs are drawn up for the ten river basin districts in England and Wales. Each management plan describes the pressures acting on water quality in its region and gives a description of current status as well as targets for future water quality. Plans for each RBD are updated and released on a 6-yearly cycle, and the end of the first WFD cycle is in 2015. The second cycle of plans is being produced following the results of a consultation (which closed in April 2014) with stakeholders and planners from other agencies including the MMO. Two RBDs cover the region of interest for this report (Figure 3).

Figure 3: The south marine plan areas showing river basin management districts under WFD.



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2.1.2 Food hygiene (shellfish)

In addition to the classification for transitional and coastal waters under WFD, designated shellfish waters have their own quality assessment systems under EC Regulation 854/2004, Annex II, Chapter II, A. Shellfish flesh samples for microbiological testing are collected from each production area on a monthly basis and counted for *E. coli*, the statutory indicator organism. The highest quality for shellfish is Class A where shellfish contain less than 230 *E. coli* bacteria per 100 g of flesh; molluscs from Class A waters can be harvested directly for human consumption. To obtain Class B, 90% of sampled animals must contain less than 4600 *E. coli* bacteria per 100 g of flesh and 10% of samples must not exceed 46,000 *E. coli* bacteria per 100 g of flesh. Class B shellfish can go for human consumption after purification in an approved plant, or after relaying in a Class A area, or after an EC approved heat treatment process. The lowest category, Class C, is given when all samples contain between 4600 and 46,000 *E. coli* bacteria per 100 g of flesh. In this case, in order to use for human consumption, the harvest must be relaid for at least two months in an approved relaying area followed, where necessary, by treatment in a purification centre, or after an EC approved heat treatment process. Harvest from shellfish waters is prohibited if a sample contains above 46,000 *E. coli* bacteria per 100 g of flesh. Sampling for shellfish hygiene takes place throughout the year. The classification of a shellfish bed can be given either as an annual status (also called seasonal status), or as a long-term status denoted as ‘LT’.

2.1.3 Bathing waters

For bathing waters, the UK is currently in a transition period as monitoring agencies move from the original to the stricter, revised Bathing Water Directive (2006/7/EC). Bathing water quality is now monitored using the new assessment system in which a higher quality is given when counts of *E. coli* and intestinal enterococci are below 100 colonies per 100 ml. A count of between 100 to 2000 *E. coli* colonies per 100 ml gives the second category, meeting the minimum requirement. Counts of more than 2000 *E. coli* colonies per 100 ml will cause the beach to fail to meet the standard. Water samples are collected weekly over the bathing season and a mean value over the previous four years of sampling is used to produce the current year’s status.

2.1.4 OSPAR eutrophication

OSPAR uses a multi-stage eutrophication assessment process quite different from the ‘one out, all out’ rule of the WFD. The first assessment of the UK was published in 2002, followed by a second report in 2007 (Defra (OSPAR Commission), 2008). Using an internationally-agreed Comprehensive Procedure, the first stage of an OSPAR eutrophication assessment is to examine the winter nutrient (nitrate) concentrations in coastal waters. Following this screening, if there are no indications of anthropogenic enrichment, a water body is deemed to be a non-problem area. Water bodies indicating nutrient enrichment are then examined further, firstly for signals of accelerated phytoplankton growth and then for undesirable disturbance. The latter is defined as low oxygen concentrations, fish and benthos kills, altered phytoplankton community composition, or occurrence of toxins in shellfish.

Non-problem areas under OSPAR correspond to waters with good or high ecological status under the relevant eutrophication element of a WFD assessment. Also, waters already identified by WFD and UWWTD as sensitive to eutrophication are classified as problem areas under the OSPAR assessment procedure.

2.1.5 Marine Strategy Framework Directive

Under the MSFD, which covers seawards from the estuarine bay-closing lines and the coastal high water mark, environmental status is addressed via 11 Descriptors (Borja *et al.*, 2013). Although the indicators required to determine whether Good Environmental Status is met for regional and sub-regional areas have not yet been agreed by Member States, the monitoring proposals were submitted by the Member States in 2014 (Defra, 2014) and the management measures proposed by the UK have just been subject to a consultation exercise[3] and will be submitted to the European Commission later in 2015.

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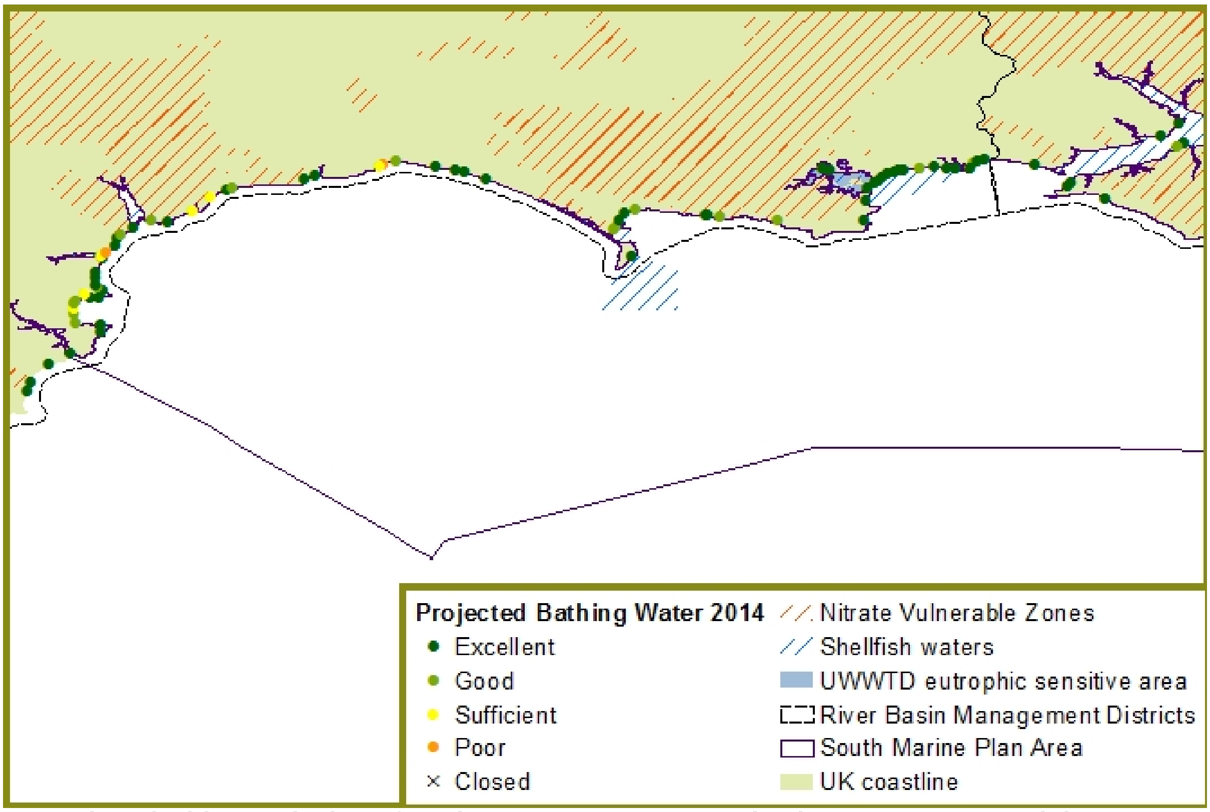
[3] https://www.gov.uk/government/consultations/marine-strategy-framework-directive-msfd-proposals-for-uk-programme-of-measures accessed 27/4/15

2.2 The South West River Basin Management District

This report examines the sector of the South West RBMD falling within the south marine plan areas, from Christchurch Highcliffe in the east, to the western limit of the south marine plan areas at the western entrance of the Dart estuary (Figure 4). Areas of specific concern within the western sector of the south marine plan areas will be identified using evidence from the water quality, shellfish and bathing water monitoring programs.

Figure 4: Water quality designations and bathing water quality (Urban Waste Water Treatment Directive) in the western sector of the south marine plan areas.



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There are water quality issues in the western sector of the south marine plan areas related to nutrient inputs and ecological status, microbiological contamination and chemical pollutants (Figure 4). The relevant area of the South West RBD plan (Environment Agency, 2009a) contains the catchment areas South Devon, East Devon and Dorset including the Dart and Exe estuaries. A large investment in treatment facilities over the past three decades by the water companies has resulted in an overall improvement in water quality (MMO, 2013b) but issues still remain.

From the western limit of the south marine plans area, the Devon South WFD coastal water, which includes the mouth of the Dart estuary, had a good ecological and chemical status in the 2013 assessment[4]. Conditions in the Dart estuary proper will be described below in section 2.3.1. Further to the east, the next coastal water body is Lyme Bay West, covering the area from the eastern entrance of the Dart Estuary to Beer Head. This water body had good ecological status (high status for the sub-element dissolved oxygen) but failed on chemical status for the priority hazardous substance tributyltin and its compounds. Torbay is a distinct WFD water body, which had good status for all ecological components (high status for dissolved oxygen) but failing chemical status due to elevated levels of mercury and its compounds. The Teign Estuary had a moderate ecological status due to its surface water supporting elements, but had good chemical status. The Exe Estuary will be described in detail in section 2.3.2.

In Dorset, the coastal water body Lyme Bay East was classified as good for ecological (dissolved oxygen was not assessed, but the indicator phytoplankton blooms was classed as high), and chemical status. The Fleet Lagoon was classed as of moderate ecological status due to phytoplankton blooms and high dissolved inorganic nitrogen, and classed as good for chemical status. The Fleet Lagoon was listed as a potential problem area in the latest OSPAR assessment (Defra (OSPAR Commission), 2008). Portland Harbour and Weymouth Bay were classed good for ecological and chemical status, as was the large WFD Dorset / Hampshire water body which covers the coastal region between Portland Bill and the western Solent. These areas had been previously classified as moderate ecological status in the first WFD assessment (from 2010 to 2013), primarily due to dissolved inorganic nitrogen concentrations exceeding threshold values. Poole Harbour does have distinct water quality concerns which are discussed in section 2.3.3.

For bathing water quality, in the latest Blue Flag classification (www.blueflag.org) there are six high-quality Blue Flag beaches between the Dart and Sidmouth, and a further nine between Swanage and Christchurch. Statutory monitoring of designated bathing waters in 2014[5] showed for the 85 beaches in the west of the south marine plan areas that 55 had the highest standard of excellent, 19 classed as good, eight as satisfactory (Wembury, Mothecombe, Paignton Sands, Torre Abbey, Shaldon, Budleigh Salterton and Ladram Bay) and two as of poor bathing water quality (Teignmouth Town and Lyme Regis Church Cliff beach). There are clusters of beaches with lower than excellent quality in Torbay and around Lyme Regis.

Under Food Hygiene legislation, there are no shellfish waters in the western part of the south marine plan areas that are currently achieving Class A status. Most were graded as Class B or long-term Class B (B-LT) in the most recent reporting period[6], with exceptions being the shellfisheries in the Teign (Devon Valley, blue mussels (*Mytilus* spp.)), Poole Harbour (Wareham Channel, palourdes (*Tapes* spp.) and

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[4] Data from EA Catchment Explorer, accessed 21/4/15 http://environment.data.gov.uk/catchment-planning/

[5] Data from EA Bathing Water quality, http://environment.data.gov.uk/bwq/profiles/ accessed 21/4/15

[6] http://www.food.gov.uk/sites/default/files/Classification%20list%2011%20March%202015_0.pdf accessed 20/4/2015

cockles (*Cerastoderma edule*)) all of which received the lower Class C grading. Two inactive (declassified) shellfish beds in the Dart Estuary were also Class C.

The OSPAR region ‘South West England Coast’ extends from Land’s End in the west to an eastern limit at Portland Bill. The most recent OSPAR assessment of eutrophication assigned a ‘non-problem’ status to the whole of this region (Defra (OSPAR Commission) 2008; OSPAR, 2010). In the case of the South West English coast, winter nutrient concentrations were found to be lower than a critical threshold and the region was not investigated further (Foden *et al.*, 2010).

Further details of water quality and pressures causing changes in water quality are given in the sections below for specific examples of the Dart and Exe estuaries, and Poole Harbour. These are sites where water quality is known to be an important issue (MMO, 2013c; 2014a).

2.2.1 The Dart Estuary

The Dart is a steep-sided ria-type estuary, formed by a river valley which was drowned by rising sea-level, and typical of the south west region. The area of the estuary is 8.6 km^2, and a population of 41,000 in the 470 km^2 catchment gives a low population density; there are no major conurbations, and animal numbers exceed humans. The entrance to the estuary is narrow and steep-sided with a central channel of 10 m depth. The channel deepens inland to 25 m between the towns of Dartmouth and Kingswear. Due to the steepness of the sides, there is very limited intertidal area at the entrance of the estuary. Broader tidal flats and saltmarsh are found in the middle sections of the Dart Estuary, giving an overall intertidal area of 3.1 km^2. Inputs of freshwater to the estuary are highly variable and respond rapidly to rainfall events in the catchment. A mean flow rate of 11 m^3 s^{-1} was given in a hydrographic study of the estuary by Thain *et al.* (2004), and an estimated flushing time of between 7 days to 11 days has been reported (Cefas, 2010).

The Dart WFD transitional water had a classification at the end of the first reporting cycle of WFD in 2013 of moderate status for ecology and good for chemical status and this remains the case at the start of the second WFD cycle. Throughout the first cycle of WFD from 2009-2013, the water quality indicator of phytoplankton blooms was classed either high or good, and remained high for the start of the second reporting cycle of WFD in 2013. Dissolved inorganic nitrogen concentrations were consistently at the moderate classification level, and dissolved oxygen concentrations were in the high class. The Dart is not classified as eutrophic, nor does its catchment have a nitrate sensitive status under the EU Nitrates Directive. This indicates a better status with respect to eutrophication than the neighbouring Avon, Salcombe and Kingsbridge operational catchment which shows eutrophication symptoms in the form of opportunistic green algal blooms in the estuary (Environment Agency, 2014b). Angiosperms (saltmarsh and seagrasses) were not assessed in the first cycle of WFD but were classified as at good status at the start of the second cycle in 2013. Despite a good chemical status throughout 2009-2013 in the first cycle of WFD, the most recent values show the Dart now failing chemical status due to mercury levels exceeding their statutory limit (the new Environmental Quality Standard for mercury is lower). The Devon South and Lyme Bay East coastal waters surrounding the Dart estuary were classed as moderate in the first cycle of WFD reporting, and are now classed good for ecological and chemical status.

The main water quality issue in the Dart estuary is a low-scoring microbiological status with respect to shellfish. Mussels and Pacific oysters (*Crassostrea gigas*) are grown at two sites in the estuary, producing a combined annual harvest of 25 tonnes and employing six fishermen (Cefas, 2010). The native oyster, *Ostrea edulis*, is not present in the Dart. Mussels consistently exhibit higher levels of *E. coli* contamination than oysters when sampled for sanitary surveys of the estuary (Cefas, 2010) and shellfish areas higher upstream in the estuary tended to have higher levels of faecal bacterial contamination than those near the mouth. The operational Dart oyster beds are at present (11th March 2015) graded as Class B-LT with three declassified mussel areas being at Class C or Class seasonal B, following a downgrade in 2009.

Bacteria from the predominantly agricultural catchment of the Dart are brought into the estuary from the surrounding small streams and rivers. Farmyard manure and slurry applied to fields, particularly in the autumn, are the main source of microbial contamination. Heavy rainfall events are associated with, but are not the only cause of, increased bacterial loading (Campos *et al.*, 2011). Temporary stratification events associated with neap tides and elevated freshwater inflows may also increase the exposure of molluscs to microbial contaminants.

2.2.2 The Exe Estuary

The Exe Estuary has multiple designations as a site of national and international significance for wildlife. It is protected as a Special Protection Area (SPA) and Ramsar site due to internationally-important wading bird populations, as a Site of Special Scientific Interest (SSSI) also for wintering wildfowl and waders, and a Special Area of Conservation (SAC) due to rare habitats at Dawlish Warren (Langston *et al.*, 2003a) The estuarine area designated as an SPA site covers 23.5 km^2. The estuary is 15 km long and funnel-shaped with a constricted opening caused by the Dawlish sand spit. At high tide the area of water within the estuary is 18 km^2. Its maximum depth is 13 m and the estuary is notable for its extensive intertidal areas (59% of the total area). A large tidal range, combined with the relatively shallow depth indicates that the estuary has frequent water exchange with the open sea. The Exe Estuary receives inflows of freshwater at a mean of 25 m^3 s^{-1} from a large catchment of 1,500 km^2. A flushing time of 6 days was estimated using a modelling approach to calculate the time taken for half the salinity content to be replaced by freshwater (Manning, 2012). Inflows are mainly from the strongly seasonal River Exe and the human population at the 2011 Census was estimated at 377,000 (Cefas, 2013). The catchment has a rapidly-expanding human population[7], and a further 28,500 new homes are planned for the region.

The upper extent of the intertidal zone is limited by the presence of regionally-important infrastructure such as the main rail line to the south west. With sea-levels predicted to rise throughout this century, keeping the balance between protecting infrastructure and upholding the integrity of natural features within the estuary is

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[7] A lower estimate of 235,100 was given in the 1995 Exe Catchment plan (http://ea-lit.freshwaterlife.org/fedora/repository/ealit:2556/OBJ/20000987.pdf, accessed 22/4/15), and a population of 294,000 was given in the ‘State of The Exe 2014’ report (Exe Estuary Management Partnership 2014b).

likely to be a challenge. Various short-, medium-, and long-term options for managing flood defences and maintaining the morphology of the estuary are under consideration by the Environment Agency (Environment Agency, 2013). The South West RBD plan aims to “develop and start delivering a habitat creation programme to offset losses of important coastal habitats through sea-level rise and climate change, focusing on opportunities in the Severn, Exe and Tamar Estuaries” (Environment Agency, 2009a).

An active estuarine management community was supported by European funds until February 2015, with an appointed management officer, an informative website[8] and annual stakeholder meetings. The Exe management partnership has recently heard presentations on strategic plans for the region from both the MMO (south marine plans) and the Environment Agency (South West River Basin Management Plans).

The Exe catchment is managed as a nitrate vulnerable zone. Conditions in the catchment deteriorated between WFD assessments in 2009 and 2013 (Environment Agency, 2014a) with a decrease in good quality waters and an increase in moderate, poor and bad class areas. This decrease may be due to physical modifications, and changes to flow and pollution from urban and agricultural sources. The risk of invasive non-native species is highlighted as a future problem.

Indications of the eutrophication status of the estuary itself are contradictory. An older review of ecosystem status during the process of designation for SAC status (Langston *et al.,* 2003a) described the Exe as “exhibiting symptoms of eutrophication”, referring to high biological oxygen demand and occurrence of phytoplankton blooms throughout the 1980s. The estuary was not listed as a problem area by Defra at that time due to the assumed rapid flushing rate and lack of evidence. A more recent water quality study by the Exe Estuary Management Partnership (2014a) concluded that although the site was failing the WFD standard for dissolved nutrients, macroalgae and phytoplankton, monitoring data indicate that “the high nitrogen levels are not causing a biological problem”, and hence the Exe is “at low risk of a biological eutrophication problem”. At the start of the second cycle of WFD in 2013, the Exe water body was classified as of good status for the indicators phytoplankton blooms and macroalgae, moderate for angiosperms, moderate for dissolved inorganic nitrogen and high for dissolved oxygen. With the supporting element of surface water also at moderate, and under the WFD one-out-all-out principle an overall class of moderate was given. The presence of intertidal seagrass beds in the Exe, and large subtidal seagrass beds near the mouth of the estuary (Figure 5), indicates that compared to other South coast estuaries, local turbidity levels are sufficiently low to allow light to reach the seabed and nutrient levels are not sufficiently high to cause overgrowth of seagrasses by epiphytic algae.

The chemical status of the Exe in the second cycle of WFD was of failing quality due to a breach of the environmental quality standard for fluoranthene and tributyltin. The Exe also failed for tributyltin in the closing assessment of the first cycle of WFD.

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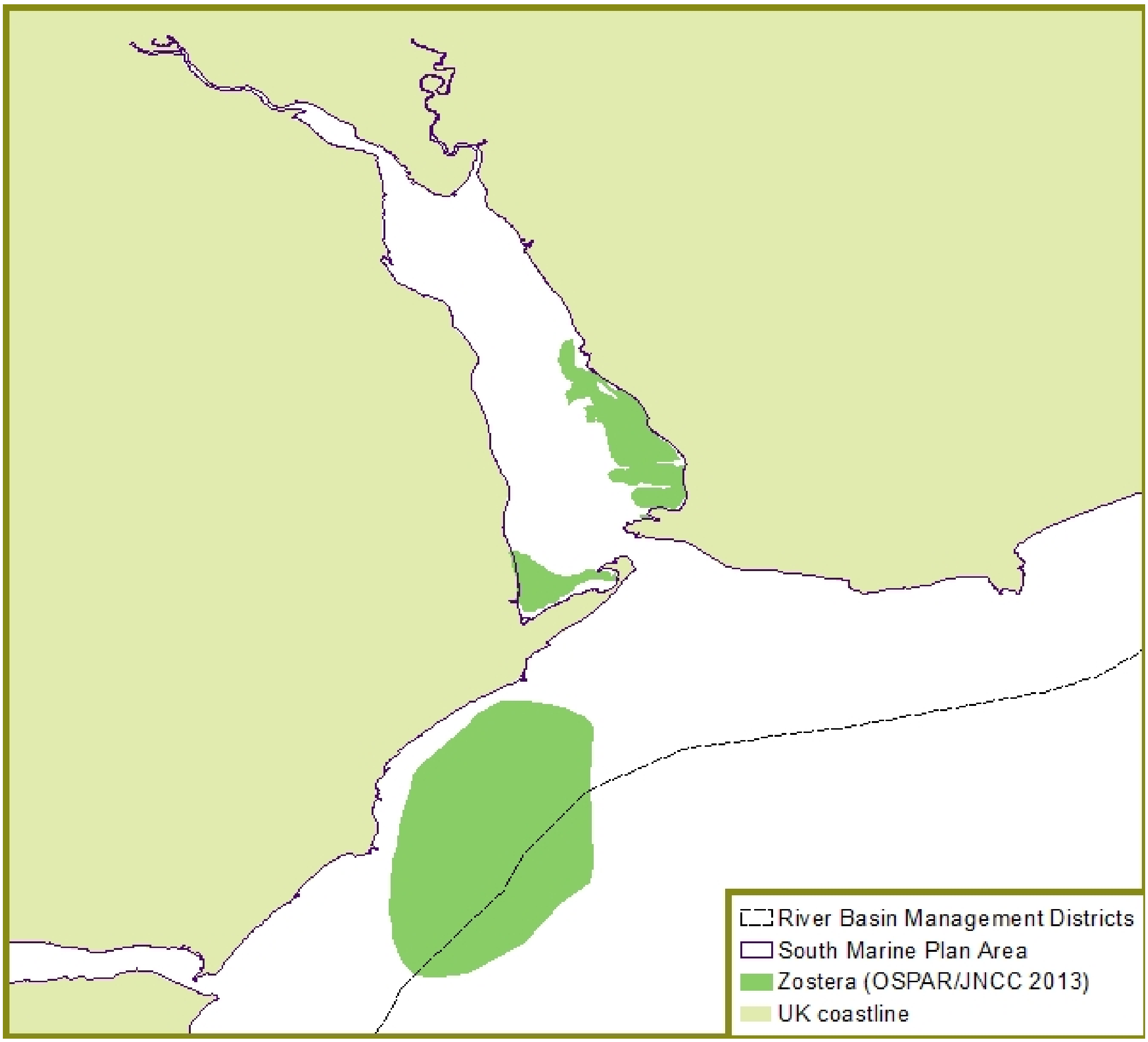
[8] https://www.exe-estuary.org/ , accessed 21/4/15

Figure 5: Distribution of the seagrass *Zostera* sp. within and near to the Exe Estuary.



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The evidence for a water quality status of less than good quality with respect to microbiological contamination in the Exe Estuary is stronger than that for eutrophication. The Exe Estuary is said to have a poor record of compliance with the Shellfish Directive with occasional closures of shellfish beds. There are important shellfish areas within and immediately outside of the estuary. Mussels are the largest resource, the annual landings from the Exe being the largest in the South West. Seed mussels are brought in from subtidal sites near the mouth of the estuary and grown on to market size in three zones (Exe approaches, Dawlish Warren, Powderham). The present landings are 150-170 tonnes per year, but there is potential to increase this to 2,500 tonnes (Cefas, 2013). The operational mussel fisheries at Starcross to Powderham, Dawlish to Starcross and Exe Approaches have the status B, B-LT and B-LT respectively.

Pacific oysters, *Crassostrea gigas*, have been grown in the Exe on trestles until recently, and there are plans for an experimental cultivation of the native oyster, *Ostrea edulis*. There was a downgrade of the Pacific oyster beds at the Pool fishery from Class A to Class B in 2007 (Cefas, 2013) and Pacific oyster beds at Sowden End were reclassified as C in 2010 and the fishery closed thereafter. With the present lack of oyster growing, the beds at Pool and Creek are declassified and have class B-LT status. Small-scale fisheries and hand-collection are in operation for palourdes (*Tapes*), cockles and mussels from wild beds. A strong negative influence of salinity on faecal coliform counts from shellfish in the Exe Estuary confirms that bacteria are brought into the system by freshwater inflows (Cefas, 2013).

Tourism is of high economic importance in East Devon and bathing water quality is an important indicator. There are five designated bathing waters around the Exe Estuary and all were projected to have excellent or good quality in 2014 under the revised Bathing Water Directive. To the west of the estuary, Dawlish Town beach has improved from a sufficient score in 2011 and 2012 to good in 2013 and 2014. Dawlish Warren and Dawlish Coryton Cove beaches have consistently been classed as excellent. To the east of the Exe Estuary, Exmouth Beach scored as good throughout 2011 to 2014, and neighbouring Sandy Bay was classified as excellent in the past five years.

2.2.3 Poole Harbour

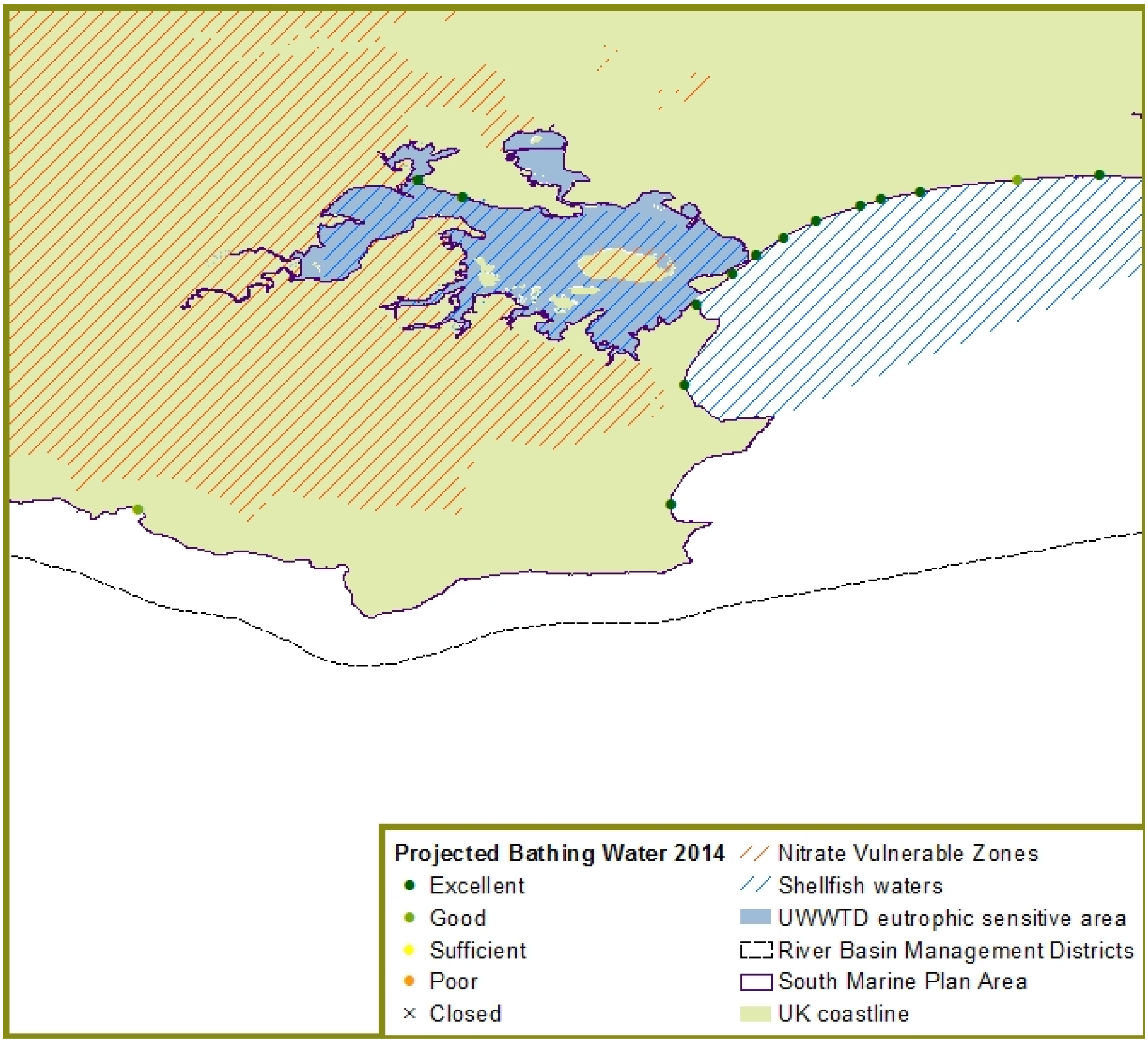
Poole Harbour is one of the largest lowland estuaries of Europe with a large catchment of 800 km^2 (all under nitrate vulnerable zone status), and a human population of 161,000 (Cefas, 2012). The estuary shoreline exceeds 100 km and is separated from the sea by a single entrance, 370 m wide. The tidal range is low (1.8 m at spring tide) and a strong salinity gradient is present. A double high tide, small tidal range and narrow mouth result in a lagoon-like effect with a low flushing capacity of the water of the harbour (residence time of water in the main harbour, 3-4 days; Bryan and Kite, 2012). Freshwater inflows are mainly from the rivers Frome and Piddle and average 6.1 m^3 s^{-1}. A long time-series of water quality measurements on the rivers showed a sustained, linear upwards trend in nitrate concentration from 1965 (Frome) and 1975 (Piddle) to the mid-2000s (Howden and Burt, 2009). Poole Harbour has multiple conservation classifications due to its unique range of habitats and importance for wading birds and wildfowl. It was classified as a SSSI in 1991 and a SPA in 1999, and is also a designated European Marine Site and Ramsar site. Under the WFD, the protected habitats need to be maintained and where appropriate restored to good ecological status. As a SPA it is required that Poole Harbour is maintained in favourable condition to preserve its conservation interest features.

Poole Harbour has a history of contamination and hypernutrification resulting in its designation as a Sensitive Area (Eutrophic) and Polluted Waters (Eutrophic) under the UWWTD and Nitrates Directives respectively, due to high dissolved nutrient levels in the harbour (Langston *et al.,* 2003b). These designations trigger an OSPAR classification of potential problem area for the main water body of Poole Harbour, and a problem area for Holes Bay, a northern inlet of the harbour. The current load of nitrogen into the harbour is approximately 2,100 tonnes N y^{-1} (Figure 1). As a result of the high nutrient load there has been an increase of opportunistic green macroalgal growth on the tidal flats. The Environment Agency ‘Strategy for managing nitrogen in the Poole Harbour catchment to 2035’, suggests that inputs should be reduced by 20%, to approximately 1,730 tonnes N y^{-1}. The Environment Agency has recently funded a preliminary investigation into the feasibility of using the prolific green algal mats as a form of bioremediation to remove nitrogen from the system (Capuzzo and Forster, 2014). The presence of excessive macroalgae caused the ecological status of the Poole Harbour water body to be poor (2009) or moderate (2010-2013) during the first cycle of WFD. Dissolved inorganic nitrogen was classified as moderate between 2009 and 2013 under the first cycle of WFD, and dissolved oxygen was high. In years when assessments were made, phytoplankton blooms were in the WFD classes good or high. The first assessment of the second cycle of WFD resulted in a moderate status for macroalgae and dissolved inorganic nitrogen, thus a moderate overall ecological status. Poole Harbour has consistently failed for chemical status under both cycles of WFD due to the concentration of tributyltin compounds.

Various fisheries are practised in Poole Harbour and are worth approximately £2 million per year. Oysters, cockles, mussels and clams represent most of the catches and aquaculture products with both farming and wild-catch fisheries practised. Aquaculture beds cover an area of 182 ha (1.82 km^2) and are used for growing native oysters, Pacific oysters, cockles, Manila clams, and mussels. Due to the importance of the shellfish industry, there is an extensive microbiological monitoring programme in Poole Harbour (also bathing water surveillance at two designated beaches – Rockley Sands and Poole Harbour Lake; Figure 6). Sewage discharges from the major treatment works at Poole, Wareham and Lytchett receive ultraviolet disinfection before release, thus the major sources of microbial contamination are expected to be from the various rivers entering the Harbour, or from non-treated storm surge overflows. The natural wild mammal and bird populations of the harbour and its islands are also sources of contamination. All shell-fisheries currently receive Class B-LT certification, except the Wareham Channel *Tapes* spp. and cockle beds which are Class C.

Bathing water quality for the beaches in and around Poole Harbour was classified as excellent for 2014 for all beaches: Lake and Rockley Sands inside the harbour, and Shell Bay North, Shore Road, Sandbanks, Canford Cliffs and Branksome Chine near the entrance to the harbour.

Figure 6: Water quality designations and bathing water quality (Urban Waste Water Treatment Directive, UWWTD) in Poole Harbour.



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2.3 The South East River Basin Management District

Over 3 million people live in the South East RBMP area with major centres of populations around the Solent and at Brighton. The south coast of England is expected to have 270,000 new homes and associated infrastructure by 2026 (Defra, 2009). The area supports a wide range of habitat types, from the exposed mesotidal[9] coastline of the South West Isle of Wight, to sheltered meso- and macrotidal estuaries such as Chichester Harbour. The catchment units within the South East RBMP are New Forest, Isle of Wight, Test and Itchen, East Hampshire, Arun and West Streams, Adur and Ouse, Cuckmere and Pevensey Levels, Rother and Stour. The marine and estuarine water quality challenges relating to this part of the south

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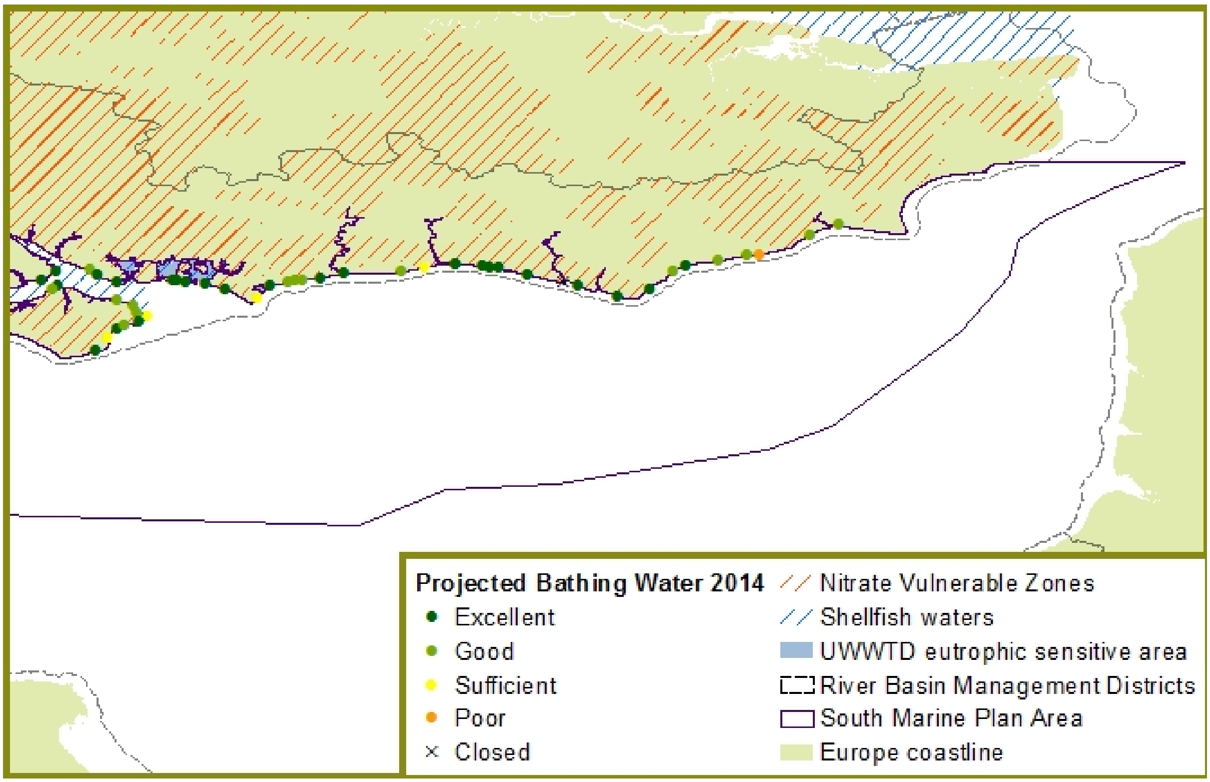
[9] meso-tidal (2 to 4 m tidal range), macro-tidal (more than 4 m tidal range)

marine plan areas listed in the RBMP are: pollution from nitrates, organic matter, pesticides and phosphate, and changes from physical modification and excessive sediment loads from erosion (Figure 7). Biodiversity in the estuaries and harbours suffers from an excessive growth of green seaweed caused by excess nitrogen from treated sewage effluent and agricultural runoff. There are additional problems caused by over-siltation, partly due to intensive agriculture, which can impact fish populations and reduce growth of submerged aquatic vegetation. The catchment of the Solent is also vulnerable to pollution incidents from the extensive sewerage and drainage infrastructure and the many industrial estates. The Environment Agency consultation document for the next cycle of WFD (2015-2021) notes that the long-term nature of the eutrophication problem may take decades to reverse due to the slow movement of nutrient-rich groundwater through the catchment. The eastern sector of the south marine plans has important shellfish operations in The Solent and its harbours and inlets (Southampton Water, Portsmouth Harbour, Langstone Harbour and Chichester Harbour), but there are no designated shellfish waters east of Chichester Harbour. There are 44 designated bathing beaches on the mainland from Milford-on-Sea in the west to Folkestone in the east, with a further 14 bathing beaches on the Isle of Wight.

Figure 7: Water quality designations and bathing water quality (Urban Waste Water Treatment Directive, UWWTD) in the eastern sector of the south marine plan areas.



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The OSPAR assessment unit Eastern English Channel for the UK waters from Portland Bill in the west to Dungeness in the east had elevated levels of winter nutrients and was therefore subject to the full Comprehensive Procedure (Defra (OSPAR Commission), 2008). This assessment unit was classified as a non-problem area (with medium confidence) based on evidence that, in spite of nutrient enrichment, there was no accelerated growth or undesirable disturbance. OSPAR assessment unit The Solent was also an area of interest due to elevated nutrients, but further investigation classified this as a non-problem area as there was no evidence for accelerated growth or undesirable disturbance. The data used in these assessments were collected from 1999 to 2005.

The water quality status of coastal and estuarine WFD water bodies in the eastern sector of the south marine plan areas will be described in detail. At the western limit of this sector, a large WFD coastal water body, Dorset/Hampshire, extends from St. Catherine’s Point on the south coast of the Isle of Wight to the entrance of the Solent and west to include Poole Bay. This water body was classified as good for ecological and chemical quality in the opening assessment of the second cycle of WFD. Whilst there were no past occurrences of failing chemical status, dissolved inorganic nitrate was at the moderate classification in occasional years of the first WFD cycle (2010, 2012, and 2013). Bathing water quality under the revised Bathing Water Directive was excellent for all beaches in the Dorset/Hampshire coastal water body in 2014.

The south east coast of the Isle of Wight to the mainland coast from Selsey Bill to Hayling Island are included in the WFD water body Isle of Wight East, and were rated as having good ecological and chemical quality in 2013. The Isle of Wight has six designated bathing beaches in this water body. Currently, two are not at good or excellent status under the revised Bathing Water Directive (Shanklin and Bembridge were classed sufficient).

A single WFD coastal water body, Sussex, encompasses the area from Selsey Bill east to Beachy Head. This area was at moderate ecological status in the most recent assessment due to the surface water supporting element. Phytoplankton blooms, dissolved oxygen and dissolved inorganic nitrogen were all at high or good status. Chemical status for this water body was also good. There are no shellfish or aquaculture operations in this area, but there are 16 bathing beaches with variable water quality. The lowest classifications were for Selsey and Lancing beaches which only recorded the sufficient level in 2014; other beaches were good or excellent. Pagham Harbour is an OSPAR eutrophication problem area.

The Sussex East WFD coastal water body covers the Sussex coastline from Beachy Head to Dungeness in Kent. This coastal water body was assessed as moderate ecological quality and good chemical quality in the first round of the second cycle of the WFD. The lowest-scoring ecological element which gave the overall moderate classification was hydromorphological supporting elements, indicating that physical modifications to the coastline are necessary to improve quality (e.g. replacement of hard shoreline defences with managed realignment; Environment Agency, 2014c). The water quality for the Sussex East bathing beaches showed mixed results. Seven of the eight beaches showed good or excellent, but Hastings Pelham beach has repeatedly been classified as poor between 2011 and 2014. The final section of the south marine plans eastern area between Dungeness and Folkestone is the WFD coastal water body Kent South. This water had good chemical status under the second cycle of WFD, and a moderate ecological classification due to the supporting element (surface water) criteria. Of the six bathing beaches in this water body, only one (Littlestone) was classed sufficient, all others were excellent or good.

2.3.1 The Solent and associated water bodies

Under the WFD, The Solent consists of a large coastal water body and several estuaries and harbours with water quality problems for failing chemical status and eutrophication. The physical characteristics of the different assessment units are given in Table 1. Freshwater inflows vary greatly between the smaller sites such as Pagham Harbour with an inflow of 0.1 m^3 s^{-1}, to Southampton Water with an inflow of 16.7 m^3 s^{-1}. Modelled flushing times vary from 2.2 days (Newton Harbour) to 13.5 days (Southampton Water). The main Solent water body had moderate ecological status in the first assessment of second cycle WFD in 2013, the element with the lowest classification being angiosperms. Concentrations of phytoplankton, macroalgal blooms, dissolved oxygen and dissolved inorganic nitrogen were all in the good category. The Solent failed for chemical status in 2009, 2012 and 2013 for the presence of tributyltin compounds, and is currently classed as fail for those compounds.

Fisheries for native oysters (*Ostrea edulis*) and hard clams (*Mercenaria mercenaria*) at Chilling to Gilkicker Point are currently assessed as of B-LT status. The eight designated bathing beaches of The Solent were classified in 2014 as excellent or good under the revised Bathing Water Directive.

Of The Solent estuaries and enclosed water bodies, Newton Harbour, Medina, Eastern Yar on the Isle of Wight, and Portsmouth, Langstone and Chichester Harbours were all reported as OSPAR eutrophication problem areas (Defra (OSPAR Commission), 2008). Lymington currently has a moderate ecological status and good chemical status; this area does not have shellfisheries or bathing waters. To the east, Beaulieu River currently has a good status for ecology and chemistry. Water quality problems are more severe in Southampton Water, which at the start of the second cycle of the WFD had a moderate ecological status due to dissolved inorganic nitrogen (noting that the fish element is rated as poor). The macroalgae element was classified as moderate for some of the previous assessment years under the first cycle of the WFD. The chemical status of this water body was classed as fail under the second cycle of the WFD due to benzo(a)pyrene, brominated diphenylether and tributyltin. Whilst there are no bathing beaches in Southampton Water, shellfish beds for native oysters and clams are presently classed as B-LT.

Portsmouth Harbour has a moderate classification for ecological status, with angiosperms, macroalgae and dissolved inorganic nitrogen all at moderate status. The level of tributyltin compounds caused a fail for chemical status. In contrast, neighbouring Langstone Harbour was currently classed as good ecological and chemical status. Chichester Harbour also had no chemical problem under the 2013 WFD assessment, but had moderate ecological status due to macroalgal coverage and elevated dissolved inorganic nitrogen.

The Solent harbours hold important shellfish resources. In Portsmouth Harbour, hard clam beds are currently classed as B-LT, but *Tapes* spp. are currently Class C. Langstone Harbour has a hard clam bed which is class B, and Chichester Harbour has native oysters with different levels of classification. Dell Quay and Prinstead have class C, Thorney has class B and other areas are all B-LT.

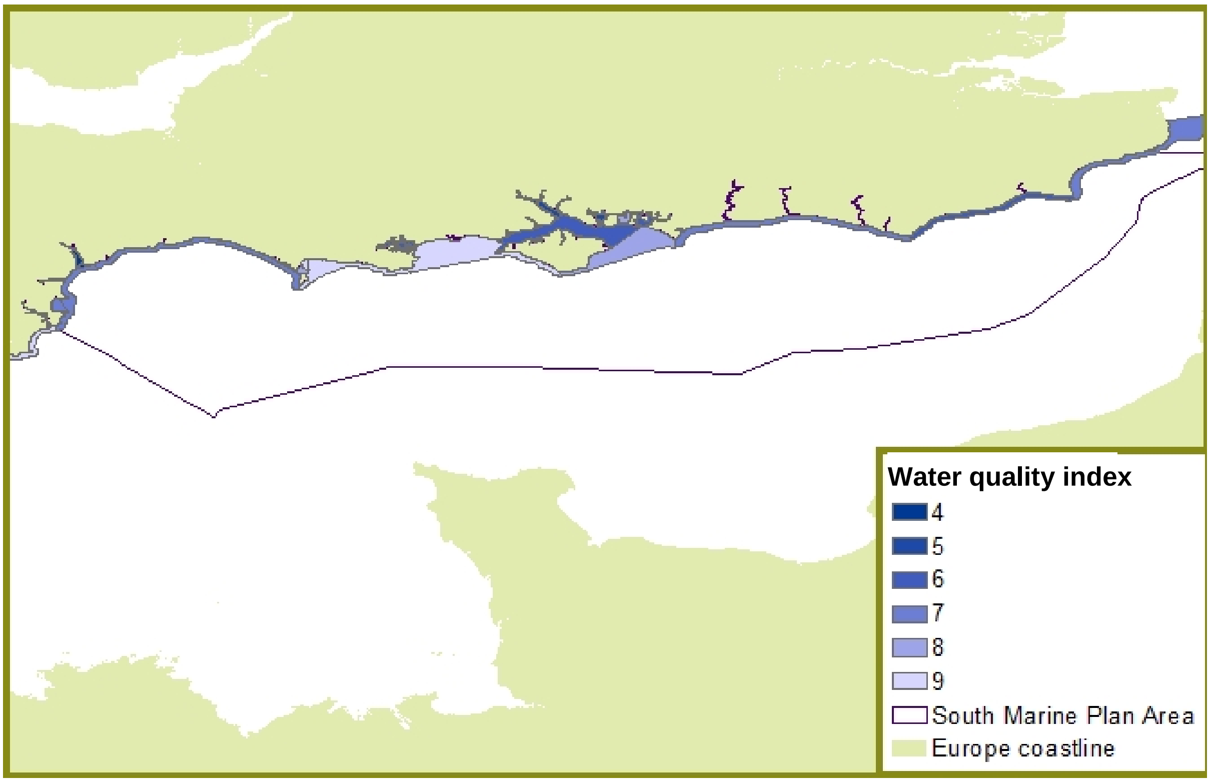
2.4 Synthesis of water quality across the south marine plans area

A scoring system has been developed for the purposes of this work to summarise water quality issues across the south marine plans area, using a three-class relative measure for nutrients and ecological status, microbiological status and chemical pollution. There was insufficient evidence to classify water bodies for excessive turbidity for this report and it is emphasised that unless specifically attributed to activities such as dredging and dredged material disposal, turbidity levels are often naturally high in estuarine areas. The geographic units chosen for sub-dividing and mapping the area are the WFD transitional and coastal assessment units. The relative measure is:

- Nutrients and ecological status are scored with a value of 1 if the water body is poor, 2 if moderate, and 3 if good or excellent.
- Microbiological contamination values are scored according to the lowest values recorded within the geographic region, with a value of 1 for the presence of a poor bathing beach and/or Class C shellfish water, 2 for a satisfactory bathing beach and/or Class B / B-LT shellfish water and 3 if all beaches were at good or excellent and shellfish water at class A. Not all WFD units contain a bathing beach or designated shellfish water; in this case a default value of 2 was used.
- Chemical status of the water body is scored with a value of 1 if the water failed for two or more chemicals, 2 for a failure for one chemical, and 3 for good chemical status.
- A water quality index for each site is given as the sum of nutrients and ecological status, microbiological contamination status, and chemical status values with a maximum score of 9. An equal weighting was used for the individual components in this assessment. The average score for all 23 WFD areas in the south marine plan areas was 6.8.

The issues determining inshore water quality across the south marine plan areas are summarised in Table 1, with Table 2 showing the relevant physical characteristics for the transitional waters of the region, and Table 3 giving an initial indication of the types of habitat present. The physical characteristics and types of habitat present will go some way to defining the most appropriate bioremediation option for a specific site (section 4). The distribution of the water quality scores is shown in Figure 8 for the area is a whole, with details of The Solent shown in Figure 9.

Figure 8: Distribution of the derived water quality index (Table 1) for WFD coastal and transitional waters across the south marine plans area.



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In the western sector of the south marine plan areas, the average water quality index was 7.0. Three sites had the maximum score of 9 (Devon South, Weymouth Bay, and Dorset/Hampshire); 58% of waters were given a 3 for ecological status and 58% had good chemical status. The lowest scoring sites were the Exe Estuary with an index of 4 (the lowest value in the entire south marine plans area) due to moderate ecological status, microbial contamination of shellfish and two chemical exceedances. The Dart Estuary also had a low index of 5. Although nutrient concentrations in the Dart and Exe are high, there are no symptoms of eutrophication. This is either due to low residence times, or the processing and/or sequestration of nutrients by natural sinks. Poole Harbour and the Teign Estuary had values of 6. Eutrophication is, however, a severe problem in Poole Harbour with widespread green algal mats causing undesirable disturbance as defined in the UWWTD.

The eastern sector of the south marine plan areas has a slightly lower average water quality index of 6.6, with a lower variance of values. All indices were in the range from 5 to 8. The lowest scoring sites were Southampton Water and Portsmouth Harbour with an index of 5 (Figure 9). For these sites, failure to meet standards for two hazardous chemicals and presence of a Class C shellfish water resulted in scores of 1 for chemical status and microbiological status respectively. The best water quality, using the evidence presented here, with summed scores of 8, was to be found in the Beaulieu River, Langstone Harbour and the Isle of Wight East coastal water body.

Figure 9: Distribution of the derived water quality index (Table 1) across the Solent region.

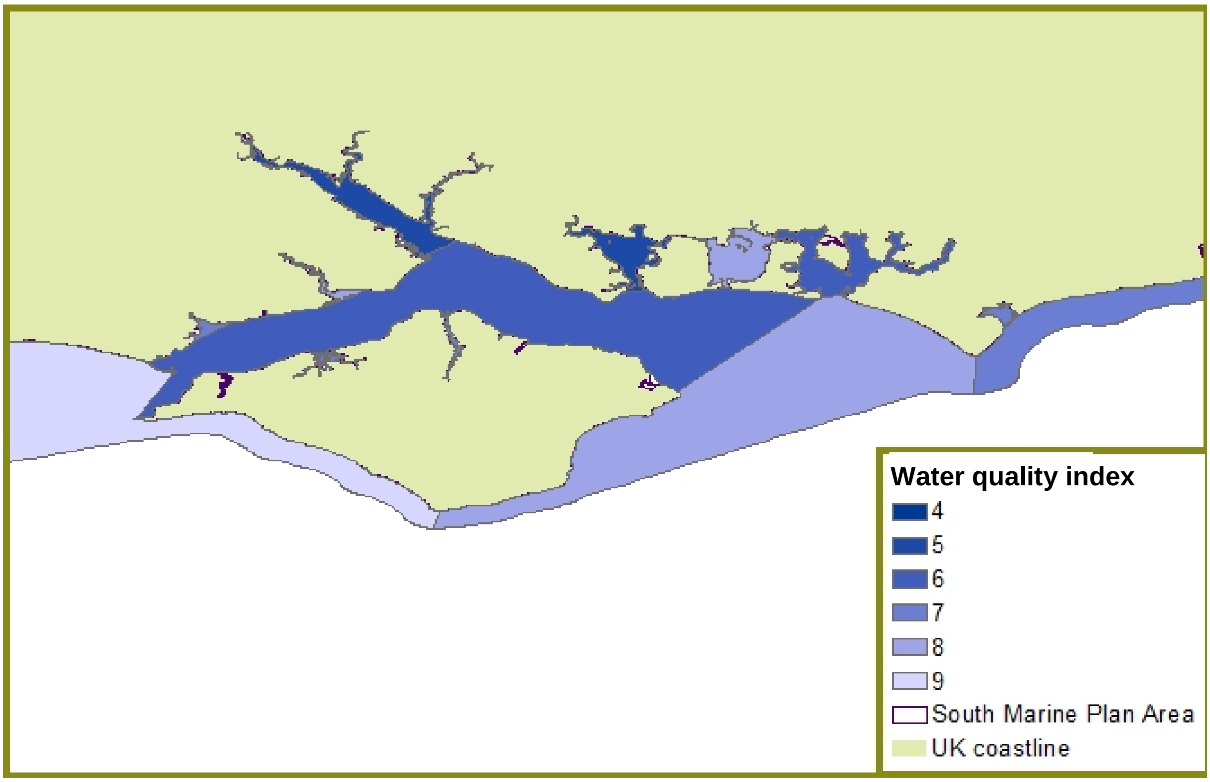

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Table 1: Relative assessment of water quality across the south marine plan areas.

EA RBMD	Water body	Unique GIS reference code	Nutrients and ecological	Micro-biological	Chemical	Total	Comments
SW	Devon South (coastal)	GB620705550 000	3	3	3	9	
SW	Dart (transitional)	GB650705530 000	2	1	2	5	Class C shellfish waters Chemical status reflects mercury levels
SW	Lyme Bay West (coastal)	GB650705150 000	3	2	2	7	Chemical status reflects tributyltin levels
SW	Torbay (coastal)	GB640704540 001	3	2	2	7	Chemical status reflects mercury levels
SW	Teign (transitional)	GB640704540 003	2	1	3	6	*Mytilus* at Class C. Teignmouth beach poor
SW	Exe (transitional)	GB650806420 000	2	1	1	4	Oyster beds closed (Class C rating). Chemical status reflects fluoroanthene and tributyltin levels
SW	Lyme Bay East (coastal)	GB640704540 002	3	1	3	7	Lyme Regis beach currently poor.
SW	Fleet Lagoon (transitional)	GB620806560 000	2	2	3	7	
SW	Portland Harbour (coastal)	GB620806110 002	3	2	3	8	
SW	Weymouth Bay (coastal)	GB520804415 800	3	3	3	9	
SW/SE	Dorset/Hampshire (coastal)	GB520704202 800	3	3	3	9	
SW	Poole Harbour (transitional)	GB580705210 000	2	2	2	6	Class C shellfish but bathing water excellent. Chemical status reflects tributyltin levels
SE	The Solent (coastal)	GB680806320 000	2	2	2	6	Angiosperms Chemical status reflects tributyltin levels

EA RBMD	Water body	Unique GIS reference code	Nutrients and ecological	Micro-biological	Chemical	Total	Comments
SE	Lymington (transitional)	GB580705130000	2	n.d.	3	7	Total assumes microbial value is 2
SE	Beaulieu River (transitional)	GB510804505600	3	n.d.	3	8	Total assumes microbial value is 2
SE	Southampton Water (transitional)	GB580705140000	2	2	1	5	Chemical status reflects bromodiphenyl ether and tributyltin levels
SE	Portsmouth Harbour (transitional)	GB680805270000	2	1	2	5	Class C shellfish Chemical status reflects tributyltin levels
SE	Langstone Harbour (transitional)	GB510804605900	3	2	3	8	
SE	Chichester Harbour	GB680805070000	2	1	3	6	Class C shellfish
SE	Medina (transitional)	GB510080077000	2	2	3	7	
SE	Newtown River (transitional)	GB510804605800	2	2	3	7	
SE	Isle of Wight East (coastal)	GB520704201400	3	2	3	8	
SE	Sussex (coastal)	GB570704700000	2	2	3	7	
SE	Pagham Harbour (transitional)	GB520704202100	2	2	3	7	
SE	Sussex East (coastal)	GB520710101700	2	1	3	6	Poor bathing water at Hastings
SE	Kent South (coastal)	GB520710101600	2	2	3	7	

Table 2: Morphological and hydrodynamic data describing the transitional waters of the south marine plan areas. Data from the Estuaries Database[10].

Water body	Geomorphological type	Area (km^2)	Mean Tidal Range (m)	Mean depth (m)	Area intertidal (%)	Mean freshwater flow (m^3 s^{-1})	Flushing time (d)
Dart (transitional)	Ria	8.3	2.9	9.5	36%	1.3	11.2
Teign (transitional)	Ria	3.5	2.6	5.1	59%	1.3	6.3
Exe (transitional)	Bar Built Estuary	18.0	2.6	4.9	59%	16.2	6.2
Poole Harbour (transitional)	Bar Built Estuary	33.1	0.9	2.2	54%	6.1	3.8
Newtown River (transitional)	Bar Built Estuary	1.9	1.5	1.4	89%	0.2	2.2
Medina (transitional)	Coastal Plain	1.6	2.5	7.4	46%	0.2	8.9
Lymington (transitional)	Coastal Plain	2.5	1.6	1.9	79%	15.0	3.0
Beaulieu River (transitional)	Bar Built Estuary	3.1	2.3	2.5	76%	0.1	3.7
Southampton Water (transitional)	Coastal Plain	30.9	2.7	11.5	35%	16.7	13.5
Portsmouth Harbour (transitional)	Bar Built Estuary	16.4	2.8	4.9	61%	0.6	6.2
Langstone Harbour (transitional)	Bar Built Estuary	18.9	3.0	3.2	79%	0.4	4.1
Chichester Harbour	Bar Built Estuary	30.1	3.0	3.0	79%	0.6	3.8
Pagham Harbour (transitional)	Bar Built Estuary	2.6	2.9	2.6	92%	0.1	3.2

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[10] http://www.estproc.net/EstProc_library.htm accessed 11/05/2015

Table 3: Presence of key ecological habitat types with respect to bioremediation which are present in the transitional waters of the south marine plans area. Data from the Estuaries Database[11].

Water body	Saltmarsh	Sandflats	Rock	Mudflats	Seagrass
Dart (transitional)	x		x	x	
Teign (transitional)	x	x		x	
Exe (transitional)	x	x		x	x
Poole Harbour (transitional)	x			x	x
Newtown River (transitional)	x			x	
Medina (transitional)	x			x	
Lymington (transitional)	x			x	
Beaulieu River (transitional)	x			x	
Southampton Water (transitional)	x	x		x	
Portsmouth Harbour (transitional)	x	x		x	x
Langstone Harbour (transitional)	x	x		x	x
Chichester Harbour	x	x		x	x
Pagham Harbour (transitional)	x	x		x	x

2.5 Existing water quality improvement measures in place

There are several existing measures which seek to improve water quality. The WFD aims to improve ecological condition and restore riverine, estuarine and coastal habitats (details in the Environment Agency Mitigation Manual[12]). Nitrate Vulnerable Zones have been established in the catchments of estuaries deemed sensitive to eutrophication. Within the NVZ, land-owners are encouraged to use best practice to minimise the loss of nitrates from fertilisers and manure. RBMPs from the first and second cycle of the WFD detail the types of management measures in place to protect water quality. In addition to improvements to waste-water treatment in the South West RBD, there are also catchment-specific schemes aimed at using nature-based solutions to manage water quality. One such conservation effort focussed on improving important upland habitats is the Dartmoor Mires on the Moors Project[13] which aims to restore blanket bog habitat by re-wetting techniques in order to increase the retention of water.

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[12] http://evidence.environment-agency.gov.uk/FCERM/en/SC060065.aspx accessed 11/05/2015

[13] http://www.dartmoor-npa.gov.uk/lookingafter/laf-naturalenv/dartmoormiresproject accessed 11/05/2015

Under the UWWTD, sensitive areas are identified: those waters that are thought to be eutrophic or at risk of becoming eutrophic and so in need of protection through the provision of sewage treatment with the level of treatment depending on the sensitive nature of the waters. Highly naturally dispersing areas and areas with low densities of population equivalents will require less treatment than sensitive waters. The nature of a sensitive area will influence the form of tertiary treatment provided: for example bathing and shellfish waters sensitive areas will be protected by UV or ozone treatment, and waters adversely affected by nutrients in discharges will receive phosphorus and/or nitrogen reduction. However, events such as storm sewer overflows, misconnection of domestic piping and rainfall running off farms and roads can cause untreated water to enter the coastal system.

Considerable improvements have been made and are expected to continue due to investment and upgrade of treatment facilities. However, it is likely that the easiest improvements have been made and that further improvements will be disproportionately expensive. Further improvements in terrestrial areas will be expensive, particularly for Poole Harbour (Bryan and Kite, 2012) hence alternative marine management options to improve water quality should be considered in marine planning.

2.6 Confidence summary

A confidence rating was assigned based on the expert judgement of at least three project team scientists. The aim was to assess the underlying data used in each section and judge the strength of the evidence against specific confidence criteria:

- Low confidence: Data quantity is low or absent, and underlying cause-effect relationships have yet to be established.
- Medium confidence: Monitoring programmes are operational, and/or a body of peer-reviewed literature exists. A sufficient quantity and quality of data is available to allow a basic assessment to be made. Cause-effect relationships e.g. between pressures and responses are understood, and are already used as a basis for management.
- High confidence: A large quantity of high-quality marine evidence is available, as well as a substantial amount of peer-reviewed literature on the subject. Underlying questions have largely been answered and predictive models are available to further increase our ability to manage.

The confidence rating for data within section 2 is MEDIUM: the South coast water bodies are well characterised with respect to microbial contamination due to bathing water and shellfish hygiene sampling programmes with good spatial and temporal resolution. Eutrophication status is also clear for the inshore WFD waters as the pressure (dissolved nutrient concentrations) and symptoms of the ecosystem response, undesirable disturbance due to excess nutrients, can be detected by the Environment Agency monitoring programme. Offshore sampling for eutrophication is sparse and confidence would be low in linking cause and effect of any trends. The sampling frequency for chemical status monitoring has not been considered in this report. There is no assessment programme for turbidity or water clarity at present, and confidence would be low for the detection of any improvement or deterioration.

3. Review of environmental remediation options

This section aims to review and summarise existing available information on the different remediation approaches that have been used in the improvement of water quality. The section begins with a general introduction to the principles of bioremediation and ecosystem restoration, and discusses the value associated with natural ecosystems and the services they provide. Bioremediation approaches are then discussed in detail and scored for a range of attributes to enable a quantitative summary to be made. For each approach, criteria are provided by which potential sites for environmental remediation might be identified at a later stage.

3.1 Approaches to bioremediation and ecosystem restoration

It is recognised that coastal water quality is closely linked to the effects of activities in the catchment (where management action is traditionally focussed), but is also dependent upon healthy and functioning intertidal and subtidal benthic habitats. Recognising the interactions and feedbacks between various components of the coastal ecosystem is critical to being able to manage water quality (Cloern, 2001; Duarte *et al.,* 2008; Carstensen *et al.,* 2011). There are various strategies for safeguarding or increasing ecosystem services[14]: a passive approach to restoration (i.e. by removing the stressor) will protect existing habitats from further deterioration whereas an active approach, such as bioremediation, will seek to increase the delivery of certain ecosystem services (Elliott *et al.*, 2007). There are several different bioremediation options for the coastal and marine environment, each with different requirements.

Nature-based solutions are a possible and often preferable approach to remediating coastal water quality problems and include either restored natural habitats from existing degraded habitat, or newly created habitat. A definition of the terminology regarding restoration ecology and bioremediation is given below. An important distinction is between active and passive restoration techniques (Elliott *et al.*, 2007). In either case, the goal is to improve the environment to deliver greater ecosystem services. Ecosystem services, such as provision of clean water, are defined as “the outputs of ecosystems from which people derive benefits” (Watson *et al.*, 2011) although more commonly they are now regarded as the services supported by ecosystems from which society derive benefits only after the introduction of human capital (complementary assets) (Atkins *et al.*, 2011a).

Bioremediation has several definitions but is regarded here, following the definition of the US Environmental Protection Agency, as the use of biological agents, such as bacteria, animals or plants, to remove or neutralise contaminants, as in polluted soil or water. Most frequently it is used to describe treatments involving micro-organisms in a terrestrial or industrial setting, e.g. waste water treatment or soil contamination. In a marine context, it is frequently mentioned in combination with seaweed grown together with aquaculture facilities. Bioremediation can be either *in situ* or *ex situ*, in which the latter involves removing the contaminated material and treating it elsewhere. Other definitions are of a bioremediation industry, often requiring

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[14] the link between ecosystems and the benefits that they provide for society

biotechnology. Bioremediation is also one of the regulating ecosystem services (Defra, 2012), and it is mentioned as an undervalued ecosystem service by Beaumont *et al.* (2010) when referring to the self-purifying abilities of the system.

Restoration ecology is the science of actively and/or passively restoring an ecosystem to a previous (or different) state; in management it aims to recreate, initiate, accelerate, or augment the recovery of an ecosystem that has been degraded by a range of environmental and human-induced threats and events (including but not limited to storm events, disease outbreaks, boat groundings, overfishing, phase shifts, and loss of keystone herbivores). Ecological restoration is a dynamic process and should allow for the use of innovative restoration techniques. The latter may include the active ecological recovery or enhancement of keystone or foundation species that create or maintain habitat or ecosystem services upon which other marine species (and people) depend. Restoration may also include removing introduced species that are harmful to the ecosystem as a means of restoring balance. Ecosystem-scale restoration has been used on natural communities including seagrass, mangrove and hard bottom communities.

Nature-based solutions and green infrastructure are terms used to describe the use of ecosystem services to mitigate a problem (European Commission, 2013). Nature-based solutions may offer more resilience to climate change, provide multiple ecosystem services, have high rates of return on investment and often involve an ecological restoration project (Defra, 2013). Green infrastructure more usually applies to projects in urban areas to generate cleaner air, better water quality and health benefits. The alternative, ‘grey infrastructure’ approach uses traditional technological solutions such as sewage treatment works or building of dams, which usually offer only single functions. The replacement cost method of determining a solution can be used when calculating the price of reaching a certain ecosystem quality target (e.g. WFD good status); this is the difference in cost with and without the contribution of ecosystem services, or the cost of additional grey infrastructure which would be required to replace green infrastructure (Gren, 2013).

Natural capital (Costanza *et al.*, 1997) has been used in the EC Biodiversity Strategy (European Commission, 2011), and in the UK to describe the state of national ecosystem services. Following a government White Paper in 2011, ‘The Natural Choice’, which had the challenging aim of encouraging the current generation “to be the first generation to leave the natural environment in a better state than it inherited”, a Natural Capital Committee was established by the Treasury to assess and report on the methodology, accounting principles and indicators required to add natural capital to annual financial reporting. The Natural Capital Committee has recommended good water status as a key indicator of England's natural capital, reflecting its economic importance (Environment Agency, 2014d). Natural capital is recognised as an important evidence requirement to support marine planning (MMO, 2013b); the options report for the south marine plan areas refers to maintaining natural capital against a background of climate change (MMO, 2015a).

Assimilative capacity is a term used to determine the ability of the system to receive and degrade, disperse and assimilate waste without long term effects (McLusky and Elliott, 2004). For example, the capacity of a water body to assimilate organic wastes without a long-term reduction in dissolved oxygen levels. **Carrying**

capacity was originally an ecological term to describe the ability of an area to support higher predators such as fish or birds through the provision of space or prey. It is now also used as a socio-economic term to denote the ability of an area to support human activities (Elliott *et al.,* 2007). As such it may be synonymous with assimilative capacity.

3.2 Methods for assessing suitability of bioremediation options

3.2.1 Literature review to select possible bioremediation options and determine attributes

The types of marine and estuarine species and habitats that have previously been used in bioremediation were reviewed and summarised under the groupings: filter-feeders, seaweeds, seagrasses and managed realignment. Each group contains several different topics corresponding to a combination of species or habitat and a bioremediation technique. This analysis gave 13 discrete options for in-depth study.

The most recent values from the literature for specific aspects of bioremediation performance, e.g. filtration capacity, and other relevant details such as conservation status and presence or absence in the south marine plan areas were reviewed for each option. The potential of each option for bioremediation was then tabulated with a list of the required and desirable factors (Table 4) used in the assessment.

The outputs of this review are presented in section 3.3.

Table 4: Required and desirable attributes of techniques suitable for bioremediation approaches.

Necessity	Attribute
Required	• Species selected have a clear bioremediation capability • Ecologically feasible – the scaled-up approach must be within the capacities/carrying capacity of the host habitat • Technically feasible – the scaled-up approach must be possible within current technological capabilities • The approach must be located where it can interact effectively with the target issue • Economically feasible • Bioremediation activity should not generate additional, severe environmental problems
Desirable	• Species selected have a documented bioremediation capability • Species are native and naturally suited to high density culture • Bioremediation management/cost is minimal • Bioremediation is self-sustaining • Remediation species are already used within the aquaculture industry • Remediation sites can be located at the source of the targeted input or problem • Bioremediation activity should not generate additional environmental problems • Remediation products are marketable and used to offset programme costs

Based on the review and following the attributes outlined in Table 4, it was possible to identify several potential bioremediation approaches. These approaches were then considered in terms of appropriateness for applications within the south marine plans areas (section 4).

For each bioremediation approach, the following topics were briefly described or scored (on a 1 to 3 scale – see Table 5):

1) A summary of the approach including details about (i) the required inputs and apparatus (required infrastructure), (ii) ongoing management, and (iii) locational requirements.
2) Technical considerations and an overall assessment of feasibility.
3) An estimation of (i) initial costs, (ii) ongoing costs, (iii) marketable value of harvested products, (iv) spatial requirements, and (v) overall cost of scaled-up bioremediation operations.
4) Bioremediation considerations and individual assessments of bioremediation performance for each of the four issues of interest.
5) Ecological considerations and an overall assessment of feasibility.
6) An overall summary

As the required bioremediation effect size was not known, assessments of technical, ecological and economic feasibility have been made on a 1 – 3 scale (0.5 increments) using expert judgement informed by the review of remediation options undertaken so far. This scale is described in more detail in Table 5. Expert judgement has been used to generate feasibility, performance, cost and area attribution. Whenever possible, these judgements have been based, in order of priority, on published studies, unpublished reports (grey literature) and previous experience / past knowledge based on similar cases. This information was summarised and expressed as a score of 1 – 3. When this information was not present, the judgement was based on the consensus from three marine scientists at IECS during a two-day internal workshop to generate the bioremediation options. The scores from this process were subsequently reviewed by three senior IECS ecologists (Prof Mike Elliot, Dr Rodney Forster and Dr James Strong). Collectively, the IECS senior ecologists have a high level of experience covering all forms of the species and habitats suggested for the bioremediation approaches.

This assessment, identifying the relative value of several factors considered as necessary attributes of possible bioremediation techniques, can be applied to the range of potential bioremediation approaches under consideration. Supplementary to this, the following sections consider broader factors (relating to sustainability and ecosystem services other than water quality) that can help to describe the relative value of potential bioremediation approaches. These broader factors are evaluated for each option in section 3.3.

Table 5: Scale used to rate the feasibility, performance, costs and areal requirements of the differing bioremediation approaches.

Value	Feasibility	Remediation performance	Cost	Area required
1	Low	Poor	Little or no cost	Relatively small
2	Medium	Moderate	Moderate cost	Relatively large
3	High	Good	High cost	Very large area

3.2.2 Determination of economic, social and environmental sustainability

It has been suggested (e.g. Elliott, 2002) that successful human responses to anthropogenic changes in the marine system should address three basic tenets: they should be socially desirable, environmentally and/or ecologically sustainable, and economically viable. These three tenets have long been cited in national and international strategies and reflect the three principles or dimensions of sustainability; environment, economy and society. In recent years these principles have been augmented by further considerations (for example Elliott, 2013), producing the so-called 10-tenets of sustainable management (Table 6). Where they comply with the tenets, human responses to anthropogenic changes in the marine system are likely to be sustainable, protect the environment and be pragmatic, especially where the economic imperative is paramount, and will be considered more acceptable, encouraged and visible by society.

The assessment of compliance with the ten tenets has recently been addressed through the development of a series of suggested definitions for minimal and full compliance with each of the tenets (Barnard and Elliott, 2015). These definitions (Table 6) are used within this report to assess each of the bioremediation options that have been considered. Expert judgement (based on the knowledge and experience of the project team, and outputs from reviews undertaken for this report) was used to assign a value of low, moderate or high compliance for each bioremediation option against each tenet. The results of this assessment are presented within each section; additional considerations relating to the judgements made are referenced and reported in the accompanying notes.

Table 6: Sustainability assessment using the ten tenets of sustainable management: definitions and compliance.

Tenet	Detail	Suggested definitions for minimal and full compliance of management measures
Ecologically sustainable	Where needed, management measures should ensure that ecosystem features and functioning, and both fundamental and final ecosystem services, are safeguarded; the habitat and/or resource compensation will have the desired effect	• Minimal compliance – the required measures are absent or will not ensure safeguarding ecosystem features and functioning, or fundamental and final ecosystem services • Full compliance - there is confidence that the measures will ensure ecosystem features and functioning, and fundamental and final ecosystem services, will be completely safeguarded (i.e. the natural ecology is maintained where possible) at a local (site) scale; the measures associated with the activity/project will protect the site potentially impacted by the proposed development or activity
Technologically feasible	Methods, techniques and equipment for ecosystem and society/infrastructure protection and the eco-hydrological and eco-engineering methods are available	• Minimal compliance - there is no technology or practice currently available to support the proposed measures • Full compliance - methods, techniques and equipment for ecosystem and society/infrastructure protection are available and have been demonstrated on similar projects, at a similar scale and under similar environmental circumstances
Economically viable	A cost-benefit assessment of the management measures indicates (economic) viability and sustainability; habitat and resource compensation and user compensation are affordable	• Minimal compliance - the measure is not economically viable, even in the short-term • Full compliance - cost-benefit assessment of the environmental management measures indicates, with a high degree of certainty, both full (economic) viability and subsequent long-term sustainability
Socially desirable/tolerable	Society regards the environmental management measures (including mitigation and/or compensation) as necessary or they are at least understood and tolerated by society	• Minimal compliance - society at large actively rejects any suggestion that the management measures are needed; if implemented, measures would not be tolerated • Full compliance - society at large views the management measures as an imperative; they are regarded as necessary

Ethically defensible (morally correct)	The wishes and practices of individuals are respected in decision-making	• Minimal compliance - although there may be an understanding, or even acceptance, of the underlying need for the measures, there is nevertheless the general view that the specifics of the proposal render it ethically or morally indefensible • Full compliance - the wishes and practices of individuals who are potentially affected by the project/activity have been fully respected in decision-making with no single sector or group being unduly favoured; there is general view that the measures including the future costs are acceptable on moral or ethical grounds
Culturally inclusive	Local customs and accepted practices are protected and respected	• Minimal compliance - the measures take no consideration whatsoever of local customs and practices • Full compliance - local customs and practices are fully considered with local needs embedded within the proposals – the proposed measures ensure the customs and practices of local communities are not adversely affected; where applicable, aboriginal/first-nation rights are defended
Legally permissible	There are regional, national or international agreements and/or statutes which will enable and/or force the management measures to be performed	• Minimal compliance - regional, national or international agreements and/or statutes relating to the implementation of the likely required measures are absent • Full compliance - there are regional, national and/or international agreements and/or statutes currently in place which will enable and force the likely required measures to be implemented to a full and adequate degree
Administratively achievable	Statutory bodies (such as governmental departments, environmental protection and conservation bodies) are in place and functioning to enable successful and sustainable management	• Minimal compliance - statutory (administrative) bodies (e.g. governmental departments, environmental protection and conservation bodies) required to implement (and subsequently operate) the measures are not in place • Full compliance - the requisite statutory (administrative) bodies (e.g. governmental departments, environmental protection and conservation bodies) are in place and are capable of fully enabling successful and sustainable management (critically, they have a demonstrable 'track record' in enabling such management)

Effectively communicable	Horizontal links and vertical hierarchies of governance are accommodated and decision-making is inclusive	• Minimal compliance - irrespective of the degree of public understanding of the issues surrounding the proposed measures, full and open communication is absent or problematic (e.g. full disclosure of the underlying evidence base may not be possible due to military or commercial sensitivity) • Full compliance - irrespective of their views, the consequences of adoption or rejection of the proposed measures are readily appreciated by the public; relevant stakeholder sectors are aware of the proposed measures (for example through newsletters, press articles or roadshows) and communication has been opened across horizontal links and vertical hierarchies of governance and decision-making
Politically expedient	Management approaches and philosophies are consistent with the prevailing political climate and have the support of political leaders	• Minimal compliance - underlying management approaches and philosophies are non-consistent with the prevailing political climate; the measures are at odds with prevailing policy or strategy statements • Full compliance - underlying management approaches and philosophies are fully consistent with the prevailing (national) political climate and have the explicit support of political leaders; supporting drivers for the measures are documented (for example within policy statements at the national or international level)

3.2.3 Assessment of wider ecosystem services and benefits

Nature-based solutions are a possible approach to remediating coastal water quality issues and include restoring natural habitats from existing degraded habitats or creating new habitat, with an important distinction being between active and passive techniques (Elliott *et al.*, 2007). In either case, the goal is to improve environmental quality in order to deliver a greater provision of ecosystem services and thus additional benefits for society. Ecosystem services are defined here as 'the link between ecosystems and the benefits that they provide for society' recognising that ecosystem services are different to the benefits provided by the ecosystem which are valued by society (Luisetti *et al.*, 2011). As such, they provide a useful link between natural and social sciences for identifying and valuing the benefits that humans obtain from healthy functioning coastal and marine systems (Saunders *et al.*, 2015). The potential for applying an ecosystem services approach for marine management has recently been recognised within marine policy and as such the application of an ecosystem services framework forms a key element of applying the ecosystem approach to marine management (Atkins *et al.*, 2011a) including marine planning (MMO, 2015b). Ecosystem service approaches enable the complexity of the marine system to be separated into a series of functions, which can be more readily incorporated into management and decision-making (Beaumont *et al.*, 2007).

In the UK, Defra (2007) propose a five-stage process for assessing changes in ecosystem service provision under different policy options. These five stages are outlined below and include a summary of the data requirements for each stage of the process (Annex 3). A full ecosystem service appraisal is outside the scope of the current project; however, the assessment here fulfils the first two stages of the process, by establishing the environmental baseline (Stage 1) and identifying and qualitatively assessing the provision of ecosystem services (Stage 2) under each bioremediation option. For the latter, where primary data on marine ecosystem services could not be obtained, a qualitative assessment for each ecosystem service was undertaken based on evidence drawn from the literature and databases, and on expert judgement, including that elicited through focus groups and at stakeholder meetings (Atkins *et al.*, 2013). This section outlines an appropriate coastal and marine ecosystem service framework, provides guidance and definitions for each ecosystem service, and the following sections incorporate an assessment of the impact on the provision of ecosystem services and societal benefits of a range of bioremediation measures aimed at addressing the specific water quality issues highlighted in section 2.

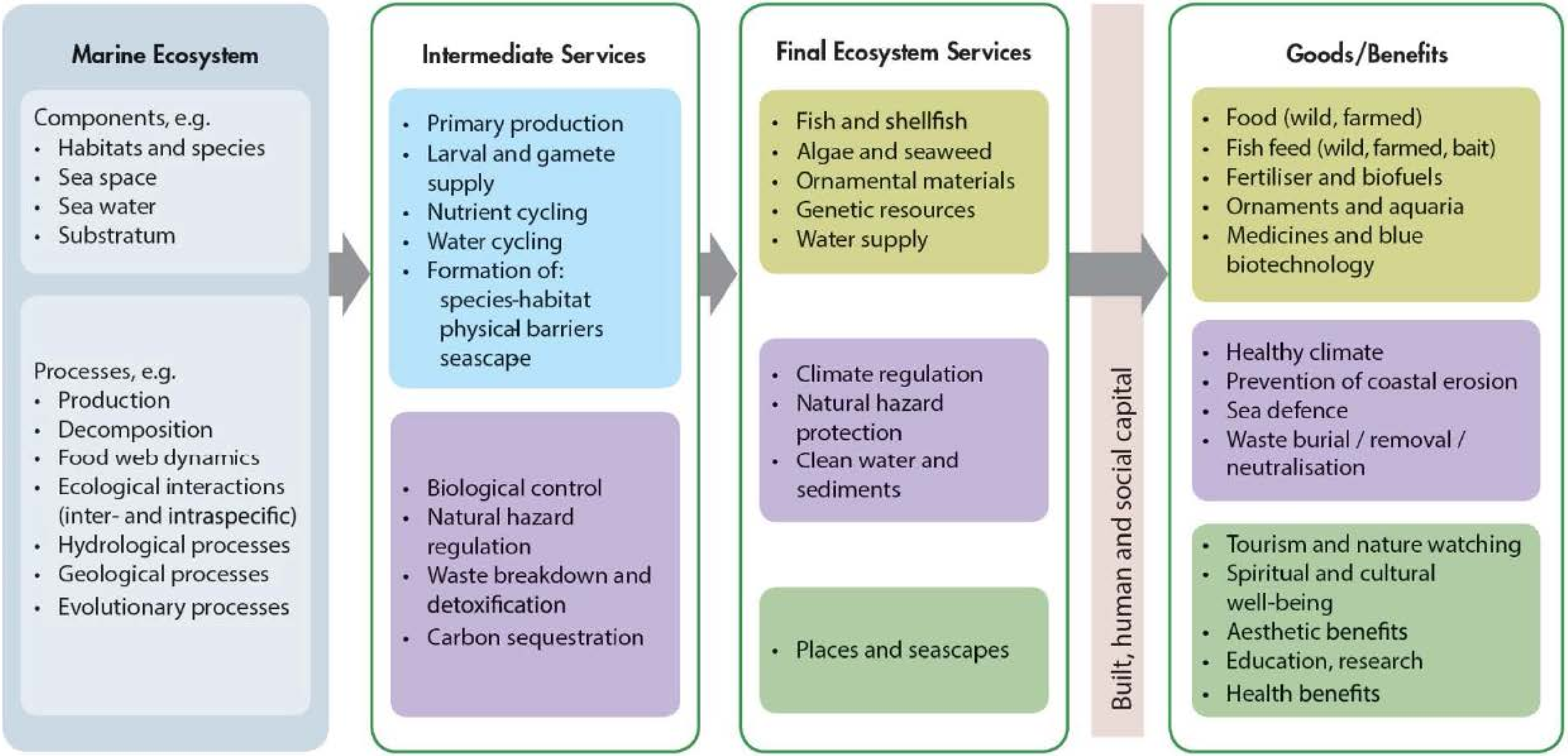
Arguably, the most widely recognised ecosystem services classification framework is that of the Millennium Ecosystem Assessment which identifies four categories (MA, 2005):

- Provisioning services - the products obtained from the ecosystem.
- Regulating services - the benefits obtained from the regulation of ecosystem processes.
- Cultural services - the nonmaterial benefits people obtain from ecosystems.
- Supporting services - those that are necessary for the production of all other ecosystem services, but do not yield direct benefits to humans.

Fisher *et al.* (2009) make a further distinction by suggesting that ecosystem processes (a service that comes from factors other than the ecosystem itself) and ecosystem functions (the result of ecosystem process) lead to a generic classification based around intermediate services associated with indirect benefits, and final services associated with direct benefits. This approach avoids any potential for double counting of benefits, where there is competition and/or complementarities between ecosystem services, which is particularly important when it comes to evaluation (Atkins *et al.*, 2011a). In the UK, this distinction has been taken forward by the UK National Ecosystem Assessment (UKNEA, 2011) which focused on the processes that link human society and well-being to the natural environment, and amongst other things, on the key role ecosystems play in delivering a diverse set of services that directly and indirectly underpin economic progress and human well-being (Atkins *et al.*, 2014). Although this generic ecosystem services framework was applied to both coastal margins and marine ecosystems, it was specifically modified for the marine environment under the NERC-funded Valuing Nature Network Coastal Management project (Potts *et al.*, 2014) and workshops within the UK National Ecosystem Assessment Follow-on Project (Turner *et al.*, 2014). The final UK National Ecosystem Assessment Follow-on Project framework is presented below (Figure 10) with definitions of each element presented in Annex 1 (Turner *et al.*, 2015).

A semi-quantitative scoring system was established whereby each ecosystem service and good/benefit for potential bioremediation options was scored against the existing baseline, for the potential significant effect (either ++ or --), potential effect (+ or -) or negligible effect (0) of each bioremediation option. Where there are gaps in current understanding these were highlighted. In order to provide an overall score, the goods/benefits values were summed for each bioremediation option and converted into a percentage score (% goods/benefits score) against a maximum score of +/- 28 (i.e. ++ or -- for all 14 categories of goods/benefits). The full results of the semi-quantitative assessment of the potential impact of bioremediation options on ecosystem service provision are presented in Annex 2. The goods/benefits scores can then be considered alongside the feasibility, cost and overall sustainability scores (section 3.5).The summary scores (Annex 2) are presented for each of the 13 biodiversity options in section 3.3. A summary of the approach to scoring is provided within section 3.5.

Figure 10: Ecosystem service classification (Turner *et al.*, 2015).



3.3 Bioremediation options to improve water quality

The following section provides details of the types of bioremediation options available. The risks and benefits of each of the 13 bioremediation approaches identified are summarised (sections 3.3.1 to 3.3.4) and the overall results are summarised (sections 3.4 to 3.6).

An overall measure of sustainability was derived for each of the bioremediation options by combining the assessment scores across all of the tenets. While this may be a simplistic approach, for example assuming equal importance of each of the tenets (i.e. no weighting factors are considered), these overall values provide a concise and indicative measure of the likely level of sustainability associated with each of the bioremediation options.

3.3.1 Filter-feeding species

Filter-feeding species play an important role in coupling the pelagic and benthic realms. Bivalves in particular can be particularly important for the removal of suspended material (detritus, sediment and phytoplankton) through their high rates of filtration, assimilation and biodeposit production. This subsequently influences nitrogen (N) dynamics both within the pelagic and benthic realms (Strong *et al.*, 2015). Additional benefits based on high rates of filtration include (i) the reduction of turbidity, (ii) the removal of suspended microbes and (iii) the adsorption of contaminants. Such is the potential of some bivalve species to influence the environment and provide physical habitat for other species, they are often referred to as naturally-occurring ecosystem engineers (i.e. species may also have a disproportionate effect on the physical environment, which can improve conditions for other species or significantly change other functional rates (Strong *et al.,* 2015)).

The main bioremediation benefit of filter feeding organisms, and especially bivalves, is the significant removal and transfer of N from the pelagic realm to the benthos through the filtration of phytoplankton (Nelson *et al.*, 2004; Piehler and Smyth, 2011; Kellogg *et al.*, 2013). Once filtered, N can be incorporated into benthic biomass, buried as biodeposits and/or be converted within the microbial loop to other available and unavailable forms of N via nitrification and denitrification processes respectively. A review of bioremediation studies by Carmichael *et al.* (2012) found that bivalves could reduce N by between 1 – 15 % of annual N loads and occasionally up to 25 % of daily N loads for reported water bodies. For all filter feeders, reductions in N are typically induced through the a number of direct and indirect mechanisms (Rose *et al.*, 2015):

- Incorporation of N into animal tissue and, to a lesser extent, the shell during growth that is subsequently removed during harvesting.
- The production and deposition of shell, faeces and pseudofaeces which become buried.
- Enhancement of denitrification in the sediment accreted under the dense patches of filter feeding species.

The importance of each mechanism varies greatly depending on several variables including the species and density of the bivalve present and numerous environmental factors (Kellogg *et al.,* 2013). Therefore, it is of note that large concentrations of filter feeders also excrete significant amounts of ammonium following the metabolism of filtered organic matter and use substantial amounts of dissolved oxygen. This suggests that although bivalves are useful for N extraction, a significant proportion of the N that is not buried or incorporated within biomass is returned to the water column in highly available forms. This process will support new phytoplankton growth and diminish the bioremediation potential. Equally, the combined metabolic activity of a filter feeding assemblage will require a substantial amount of dissolved oxygen. At very high stocking densities, the oxygen demand may induce localised hypoxia and biodiversity modification (Troell *et al.*, 2003). These issues need to be weighed against potential benefits from overall N reduction.

Any filter feeding species occurring at high densities and occupying large areas potentially is a valuable bioremediation species. However, the bioremediation potential of species has often been derived from aquaculture case studies. This is probably due to (i) the ease with which aquaculture species can be manipulated, (ii) the simplicity of working with monocultures, (iii) the established practice of harvesting these species, (iv) the prevalence of aquaculture practices globally, and (v) interest in the trading of ‘nitrogen credits’ (in North America). Hence most of the available case studies are dominated by bivalve species that are cultivated commonly, e.g. *Mytilus edulis*, *Ostrea edulis*, *Crassostrea gigas* and especially *Crassostrea virginica* (US only). Some studies have also highlighted other groups of non-bivalve species for their bioremediation value, e.g. sponges, bryozoans and ascidians (Gifford *et al.*, 2007). Sections below provide additional information on oysters, mussels, and other non-bivalve filter feeding species.

Oysters

Whilst the use of culturing mussels for bioremediation on rope-systems similar to traditional commercial aquaculture is gaining interest in Europe, in North America the use of oyster reefs (primarily of *C. virginica*) for restoration has commanded the greatest research attention. Oysters have rapid growth rates and maintain a high filtration capacity under a range of environmental conditions, e.g. 21 – 57 litres of seawater per oyster per day (*O. edulis*; Sytnik and Zolotnitskiy, 2014). Furthermore, *O. edulis* (the native or flat oyster) reefs possess biogenic engineering properties and provide valuable hard substrata for additional epifaunal species (Smyth and Roberts, 2010). Oysters, together with the other associated filter feeding species, can significantly modify the local biogeochemical cycles and environmental character of an area by removing large amounts of organic matter from the water column. The removed organic matter is metabolised for physiological maintenance or growth and the remainder excreted as faeces or pseudofaeces (filtered but undigested material). The rejected material, termed biodeposits, are either resuspended and removed by water movement, or accumulate within the sediment.

Once in the sediment, the nitrogen within these biodeposits is incorporated within the microbial loop. Microbial action either returns bioavailable N sources to the water column (nitrification) or converts fixed nitrogen to N_2 gas (denitrification) that returns to the atmosphere and therefore removes N from the marine system (Chavez-Crooker and Obreque-Contretas, 2010; Strong *et al.*, 2015). The typical aerobic environments with low light occupied by oysters are conducive to denitrification processes, which can represent a significant removal pathway for N from the system

(Newell *et al.*, 2005). Furthermore, N removal is further enhanced by the high density and diversity of infaunal species associated with the rich biodeposits. These species both directly consume the N and also bioturbate the sediment, which increases biodeposit burial and enhances microbial activity.

Through the combined mechanisms of N accumulation within biomass, biodeposit burial and enhanced denitrification processes, oysters represent an effective pathway for the large and long-term sequestration of N (Kellogg *et al.*, 2013). Furthermore, the filtration capacity of oysters has also been shown to significantly reduce the concentration of suspended sediments, detritus and chlorophyll a in the overlying water column (Nelson *et al.*, 2004), thereby significantly improving water clarity. The potential reduction in suspended solids is related to the advective rate of seston[15] supply to the bed (Newell, 1998), i.e. the greater the contact and availability of the water column to the oyster beds the greater the proportion of material removed (Nelson *et al.,* 2004). This advective rate is important for all forms of bioremediation and will, in part, determine the overall efficacy. The benthic boundary layer reduces the advection of material to the bioremediation 'surface' and therefore limits efficacy. In closed or semi-enclosed situations where the advective rate is high, e.g. the placement of oysters in small, well mixed creeks where the entire water column is available for filtration or the vertical alignment of bioremediation surfaces (e.g. mussel rope culture), this generates the greatest filtration capacity and therefore the most effective bioremediation action. For example, Roegner (1998) reported a bivalve bed inducing a >50 % reduction in seston concentration when situated in a low flow/low volume channel that maximised the availability of the water column. Nelson *et al.* (2004) also highlighted the importance of the ratio of the bioremediation layer surface area to water column volume and showed that small oyster patches in small creeks resulted in significantly improved turn-over rates and associated bioremediation activity.

Bivalve species capable of building reefs may also alter the hydrodynamic conditions at a site and thereby improve bioremediation activity. The increased bed roughness associated with these biogenic structures both increases the potential surface area to volume ratio within a habitat and the flow turbulence above the reef, thereby increasing larval retention, improving water column mixing and enhancing filtration (Nelson *et al.,* 2004). This suggests that bivalve species that are able to form biogenic structures and that are deployed in a manner that allows this, may be more effective as bioremediation agents.

Carmichael *et al.* (2012) examined the potential N removal by *C. virginica*. Nitrogen assimilation into soft tissues resulted in approximately 0.3 – 0.5 g of N being removed, per oyster, on harvesting at a marketable size. The average *C. virginica* shell contains approximately 0.2 – 0.3 g of N (which can be presumed to be removed if the shell is not returned to the environment for use as cultch[16]) (Kellogg *et al.,* 2013). Carmichael *et al.* (2012) also estimated the removal of N via denitrification to be almost 0.75 g N removed per gram of oyster dry weight per year (average

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[15] The living (plankton and nekton) and non-living (suspended detritus and sediment) matter suspended in a body of water.

[16] material (usually empty bivalve shells) laid down on oyster grounds to furnish points of attachment for the spat

harvestable dry weight is approximately 4 g). Based on these values, Carmichael *et al.* (2012) suggested that N assimilation within oyster biomass is the primary mechanism for N removal for oysters before reaching their marketable size. However, once the marketable size has been reached, denitrification then becomes the primary mechanism for N removal. Once scaled by typical oyster density, estimated N removal for *C. virginica* is approximately 12 to 158 g N m^{-2} yr^{-1} with a mean value of 58 g N m^{-2} yr^{-1} (Rose *et al.*, 2015). Kellogg *et al.* (2013) calculated the influence of the associated macrobenthic assemblage associated with mature oyster reef at a higher rate of 95 g N m^{-2} yr^{-1}. It is apparent that oysters (mostly reported for *C. virginica*) are associated with high rates of water filtration and it is therefore presumed they also contribute to the reduction of turbidity, suspended microbes and contaminants. Studies have mostly concentrated on the removal of N and the absence of information on the potential for other water quality improvements represents a significant knowledge gap.

Bioremediation potential relies both on the ability of species to generate water quality improvements and also on the capability to increase stocking densities and areas of extent to provide the size of improvements required. As both *O. edulis* and *Crassostrea gigas* (the Pacific oyster) are established aquaculture species, there are a variety of proven, high-density culture methods are available for both species. This greatly improves the ease with which oyster-based bioremediation projects could be established and expanded. Although *O. edulis* is a native North West European species and provides habitat of high conservation importance, it is generally considered to have a poor disease resistance to prevalence pathogens such as *Bonamia ostreae*. As such, *C. gigas* is more often selected for aquaculture use within the UK.

Bioremediation summary: Oysters

Positive attributes:

- Strong evidence base for high filtration, assimilation and biodeposit production
- Reductions in turbidity, suspended microbes and contaminants are also possible although the evidence base for this is currently absent
- Multiple established aquaculture practices available for *O. edulis* and *C. gigas*
- Species suitable for high density, condensed culture practices
- *O. edulis* provides additional habitat and biodiversity benefits

Negative attributes

- *C. gigas* is a non-native species (although the mainstay of the British aquaculture industry)
- Suspended oyster culture rarely used in the UK
- High and constant management requirement
- *O. edulis* has poor disease resistance

Potential oyster-based bioremediation options: the scientific evidence suggests feasible methods for addressing water quality issues include *Ostrea edulis* bottom culture, *Crassostrea gigas* bottom culture, *Ostrea edulis* bag/trestle culture, and *Crassostrea gigas* bag/trestle culture. The assigned performance, feasibility and cost efficiency scores for these four approaches are summarised in Figure 11, further information on each option summarised in Table 7 to Table 10 and the sustainability scores are summarised in Table 11.

Figure 11: Bioremediation performance, feasibility (technical and ecological) and estimated cost for oyster-based approaches.

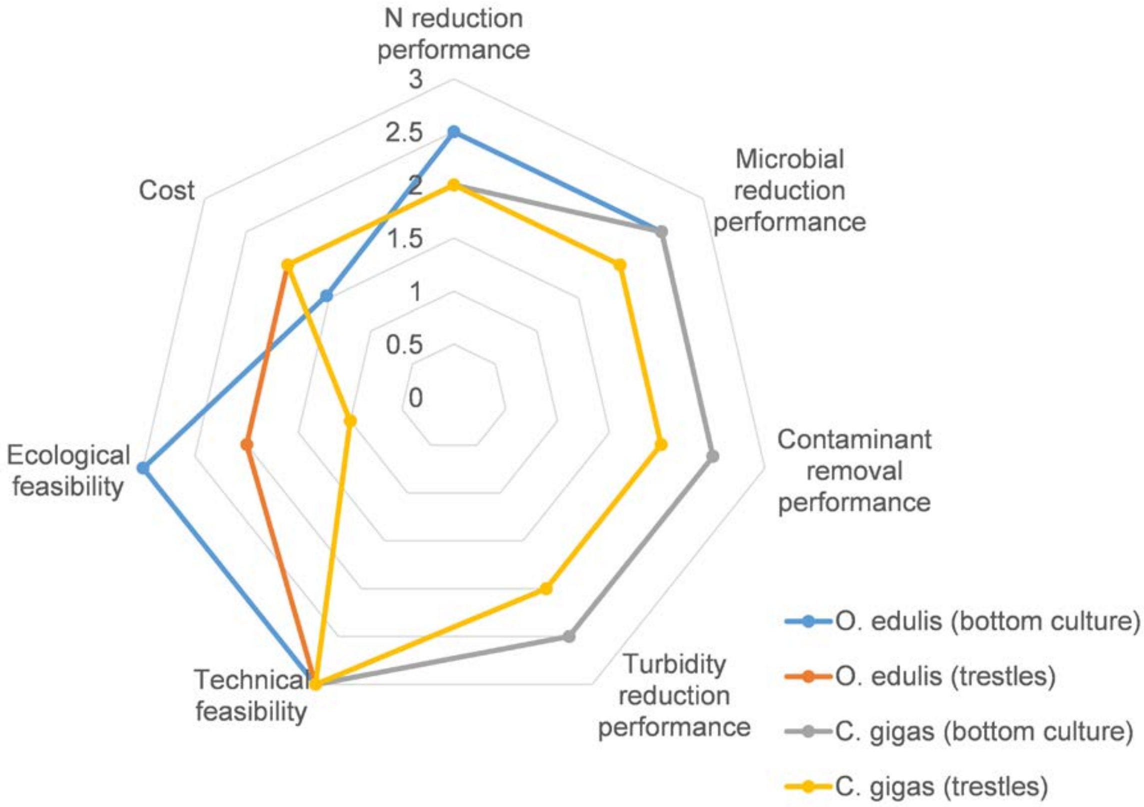

Table 7: Potential bioremediation option: *Ostrea edulis* bottom culture.

<table>
<tr><th colspan="7">Species: <i>Ostrea edulis,</i> Option: bottom culture</th></tr>
<tr><td>General description</td><td colspan="6"><i>Ostrea edulis</i> (also called the Flat or European oyster) is a UK native oyster species and is extensively used for aquaculture (although <i>Crassostrea gigas</i> is more commonly used the UK due to wider environmental tolerance and greater disease resistance). <i>Ostrea edulis</i> inhabits a wide range of substrata (sandy mud to fine gravel and bedrock) from the lower intertidal area to 30 m. Bottom culture, i.e. the laying of part-grown oysters (40 mm = 10 g) directly on to the seabed, is the normal practice for native oysters. Ongoing management may be required for thinning and predator control.</td></tr>
<tr><td>Option details</td><td colspan="3">Apparatus
• Bottom culture with oysters laid directly onto the seabed
• Established culture techniques used by the aquaculture industry
• Boating and processing infrastructure required for maintenance and harvesting</td><td colspan="2">Management
• Oyster spat required (dredged from natural populations or from hatcheries)
• Standard industrial culture techniques or a new, modified management schedule for maximum bioremediation potential.
• Moderate ongoing maintenance costs
• Implemented through direct commissioning or industrial incentivisation</td><td>Locational requirements
• Sheltered inshore locations
• Sub-tidally from 0 to 30 m
• Some substrata unsuitable for oyster cultivation
• UK-wide</td></tr>
<tr><td>Technical considerations</td><td colspan="3">Strengths
• Established industrial practice
• Easy to relocate or remove
• Surface waters free of apparatus
• Job creation
• Marketable shellfish product that may off-set costs
• Low management requirement (thinning and relaying) resulting in low overall operating costs</td><td colspan="2">Weaknesses
• Low intensity cultivation practice with high mortality rates
• Supply of required quantities of disease-free spat may potentially limit the required scaling of bioremediation operations
• Poor disease resistance
• Potential to generate contaminated, unmarketable material (via pollutants) or shellfish requiring depuration (bacteria and viruses)
• Boundary layer constraints on carrying capacity</td><td>Technical feasibility
3</td></tr>
<tr><td>Economic/spatial requirements</td><td>Initial costs
2</td><td colspan="2">Ongoing costs
2</td><td>Marketable products
2</td><td>Area
2</td><td>Overall cost
1.5</td></tr>
<tr><td>Bioremediation considerations</td><td colspan="4">Strengths
• Multiple bioremediation activities undertaken simultaneously
• Moderate evidence base available for other oyster species
• Improved biodeposit burial and denitrification potential due to direct placement of oysters onto the seabed</td><td colspan="2">Weaknesses
• Substantially reduced surface area:volume ratio/stocking density when compared with rope culture</td></tr>
<tr><td>Bioremediation performance</td><td colspan="2">N reduction
2.5</td><td colspan="2">Microbial reduction
2.5</td><td>Contaminant reduction
2.5</td><td>Turbidity reduction
2.5</td></tr>
</table>

Species: *Ostrea edulis,* Option: bottom culture			
Environmental benefits	*Ostrea edulis* addresses all four bioremediation activities simultaneously although stocking densities are comparable or less than that used for common mussels, hence the overall filtration rate is likely to be lower. This may reduce the bioremediation potential and potential improvement in water quality. Nitrogen removal will be influenced by whether oysters are harvested or left to increase the provision of reef and long-term bioremediation activity. At the site-scale, bioremediation performance, and subsequent improvement in water quality, will depend on (i) the stocking biomass, (ii) contact with the water (advective mixing into the boundary layer), (iii) the duration of contact with the water body (residence time or current speeds), (iv) concentration of the contaminant (proximity of the bioremediation site to the source of the water quality issue), (v) rate of removal mechanisms (filtration, growth rate and frequency of harvests, rate of biodeposit burial and denitrification) and (vi) rate of returning processes (excretion, mortality, resuspension and nitrification).		
Ecological considerations	**Strengths**	**Weaknesses**	**Ecological feasibility**
	• Native species • Species of conservation interest • Bioremediation site may become larval supply source population • Provision of additional habitat	• Stocking densities have the potential to reach habitat carrying capacities • Partial loss of existing benthic habitat	3
Limitations, public support and knowledge gaps	Limitations for the use of this option for bioremediation are (i) spat supply for the scaling-up of operations, (ii) required area of seabed near the source of the water quality issues and (iii) whether oysters are harvested or left to generate natural beds. As an established aquaculture practice/restoration method using a native species placed subtidally, public support for this option is estimated as very high. Knowledge gaps that contribute to the uncertainty of bioremediation performance include (i) studies documenting observed bioremediation potential for *O. edulis* for all four water quality issues, (ii) the ability to predict the biodeposit burial and denitrification loss and (iii) management scheme required for the long-term maintenance of native oyster beds.		
Potential impacts on ecosystem services and societal benefits	This option identified a number of regulating ecosystem services (biological control, natural hazard regulation, waste breakdown and detoxification) and provisioning ecosystem services (fish and shellfish) which may have potentially significant positive effects. Potential positive effects were identified for a range of goods/benefits, with waste burial / removal / neutralisation being the only positive significant effect highlighted. The overall goods/benefits score for this option is moderate (39%) with no potential negative effects identified.		
Overall assessment	Bottom culture is an established aquaculture method. Oyster filtration and growth is fast (N removal occurs via harvesting). Moderate surface area:volume ratio/stocking density with moderate pollutant adsorption and filtration capability facilitates bioremediation. Operating costs are likely to be low. The production of a marketable product can be used to offset costs or be used to incentivise the industry. Direct placement of the oysters onto the seabed may increase the potential for biodeposits to be buried and contribute to denitrification processes. Greater availability of seabed for bioremediation operations when compared with bag and trestle culture.		

Table 8: Potential bioremediation option: *Crassostrea gigas* bottom culture

<table>
<tr><th colspan="7">Species: <i>Crassostrea gigas</i>, Option: bottom culture</th></tr>
<tr><td>General description</td><td colspan="6">This option involves the deliberate establishment of wild and unmanaged <i>Crassostrea gigas</i> beds (the pacific oysters). This species is a non-native species but the mainstay of the British aquaculture industry. It is currently naturalising (Herbert <i>et al.</i>, 2012) across the UK and establishing wild populations. Unlike the native oyster, <i>C. gigas</i> is (i) highly resistant to disease, (ii) currently expanding rapidly and (iii) capable of forming dense and extensive biogenic reefs. These naturalised reefs are reported to represent a significant filtration capacity and therefore bioremediation capability. Reefs are however linked to impoverished biodiversity and reduced coastal access intertidally. No harvestable products are anticipated from this option due to the robust nature of a fully-established reef.</td></tr>
<tr><td>Option details</td><td colspan="3">Apparatus
• Not an established culture technique used by the aquaculture industry – the objective is to encourage the establishment of <i>C. gigas</i> (a disease resistant species capable of rapid expansion and generating high density reefs).</td><td colspan="2">Management
• Oyster spat required (from hatcheries)
• Spat placed onto the seabed and require no further management
• Implemented through direct commissioning</td><td>Locational requirements
• Subtidally from 0 to 40 m
• Some substrata unsuitable for oyster cultivation
• UK-wide</td></tr>
<tr><td>Technical considerations</td><td colspan="3">Strengths
• Technically simple
• Surface waters free of apparatus
• Long-term option
• Self-sustaining
• Disease resistant species</td><td colspan="2">Weaknesses
• Once placed, subsequent removal is highly unlikely
• Supply of required quantities of disease-free spat may potentially limit the necessary scaling of bioremediation operations
• Boundary layer constraints on carrying capacity</td><td>Technical feasibility
3</td></tr>
<tr><td>Economic/spatial requirements</td><td>Initial costs
2</td><td colspan="2">Ongoing costs
2</td><td>Marketable products
1</td><td>Area
2</td><td>Overall cost
2</td></tr>
<tr><td>Bioremediation considerations</td><td colspan="4">Strengths
• Multiple bioremediation activities undertaken simultaneously
• Moderate evidence base available for other oyster species
• Long-term bioremediation option
• Self-sustaining over time
• Direct placement of the oyster on the seabed may increase the transfer of biodeposits to the sediment for burial and microbial action (denitrification).
• Establish reefs capture significant amounts of biodeposit
• Oyster density is high in established reefs</td><td colspan="2">Weaknesses
• Substantially reduced surface area:volume ratio/stocking density when compared with rope culture</td></tr>
<tr><td>Bioremediation performance</td><td colspan="2">N reduction
2</td><td colspan="2">Microbial reduction
2.5</td><td>Contaminant reduction
2.5</td><td>Turbidity reduction
2.5</td></tr>
</table>

<table>
<tr><th colspan="4">Species: *Crassostrea gigas*, Option: bottom culture</th></tr>
<tr><td>Environmental benefits</td><td colspan="3">*Crassostrea gigas* addresses all four bioremediation activities simultaneously. In addition, stocking densities are likely to be greater than bottom culture of *O. edulis*, hence filtration rates are likely to be greater. However, limited mixing of the water column with the boundary layer above the reef and the loss of the N removal mechanism through shellfish harvesting will diminish the bioremediation potential and improvement in water quality. As this option results in the establishment of wild oyster reefs, it represents a long-term solution with reduced management costs (although management will be required to remove reef in undesirable locations).
At the site-scale, bioremediation performance, and subsequent improvement in water quality, will depend on (i) the stocking biomass, (ii) contact with the water (advective mixing), (iii) the duration of contact with the water body (residence time or current speeds), (iv) concentration of the contaminant (proximity of the bioremediation site to the source of the water quality issue), (v) rate of removal mechanisms (filtration, growth rate, rate of biodeposit burial and denitrification) and (vi) rate of returning processes (excretion, mortality, resuspension and nitrification).</td></tr>
<tr><td rowspan="2">Ecological considerations</td><td>**Strengths**</td><td>**Weaknesses**</td><td>**Ecological feasibility**</td></tr>
<tr><td>• *C. gigas* is a reef-building species (although associated biodiversity is low)</td><td>• Non-native species
• Larval supply will infiltrate naturalised settlement outside the bioremediation area
• Stocking densities have potential to reach habitat carrying capacities
• Loss of existing benthic habitat
• Poor experiences elsewhere in Europe with naturalised *C. gigas* reefs</td><td>1</td></tr>
<tr><td>Limitations, public support and knowledge gaps</td><td colspan="3">Limitations for the use of this option for bioremediation are (i) the inability to control the spread of *C. gigas* once established and (ii) required area of seabed near the source of the water quality issues. As an option promoting the establishment of a non-native species that can generate undesirable ecological consequences, public support for this option is estimated to be very low.
Knowledge gaps that contribute to the uncertainty of bioremediation performance include (i) the inability to control the spread of *C. gigas* and (ii) the inability to predict the biodeposit burial and denitrification loss.</td></tr>
<tr><td>Potential impacts on ecosystem services and societal benefits</td><td colspan="3">This option identified a number of regulating ecosystem services (natural hazard regulation, waste breakdown and detoxification) and provisioning ecosystem services (fish and shellfish) which may have potentially significant positive effects. The only potentially significant positive effect on goods/benefits was related to waste burial / removal / neutralisation. The overall goods/benefits score for this option is low (18%) which reflects in part the potential significant negative effects associated with the conflict between *C. gigas* beds and beach users.</td></tr>
<tr><td>Overall assessment</td><td colspan="3">This form of direct placement is not an established aquaculture practice. The purpose is to facilitate the establishment of *C. gigas* reef. Although these reefs are ecologically questionable, the likely direct bioremediation potential of this habitat is likely to be great. This option is included for completeness. It must be accepted that any form of bioremediation undertaken at a scale that significantly addresses an environmental issue will require compromises to be made.
Oyster filtration and growth is fast (N removal during harvesting). Moderate surface area:volume ratio/stocking density (moderate pollutant adsorption and filtration capability) facilitates bioremediation action. Operating costs are likely to be minimal. No marketable products are anticipated although commercial opportunities could be explored. Over time, self-sustaining reefs are likely – these will provide high bioremediation potential but may also generate new environmental issues.</td></tr>
</table>

Table 9: Potential bioremediation option: *Ostrea edulis* oyster bag/trestle culture

<table>
<tr><th colspan="8">Species: <i>Ostrea edulis.</i> Option: bag and trestle culture</th></tr>
<tr><td>General description</td><td colspan="7">The cultivation of native oysters in mesh bags placed on trestles within the intertidal and subtidal fringe is an established aquaculture method. Placement of oysters in bags (or sometimes referred to as pouches) greatly reduces mortality through predation and the location of trestle intertidally reduces management costs (e.g. boat usage).</td></tr>
<tr><td>Option details</td><td>Apparatus
• Established culture techniques used by the aquaculture industry
• Trestles required</td><td colspan="5">Management
• Oyster spat required (dredged from natural populations or from hatcheries)
• Standard industrial culture techniques or a new, modified management schedule for maximum bioremediation potential.
• Moderate ongoing maintenance costs (turning and thinning of bags)
• Implemented through direct commissioning or industrial incentivisation</td><td>Locational requirements
• Sheltered inshore locations
• Highly constrained to low intertidal and subtidal fringe (-2 – 2 m)
• UK-wide</td></tr>
<tr><td>Technical considerations</td><td>Strengths
• Established industrial practice
• Easy to relocate or remove
• Surface waters free of apparatus
• Job creation
• Marketable shellfish product that may off-set costs
• Moderate-low operating costs</td><td colspan="5">Weaknesses
• High visual impact at low tide/public resistance
• Shoreline ‘high value’ seabed – available area may limit the required scaling of operations
• Supply of required quantities of disease-free spat may potentially limit the required scaling of bioremediation operations
• Poor disease resistance
• Moderate management effort requirement (turning and thinning)
• Potential to generate contaminated, unmarketable mussels (via pollutants) or shellfish requiring depuration (bacteria and viruses)
• Supply of required quantities of oyster spat may limit required scaling of operations</td><td>Technical feasibility
3</td></tr>
<tr><td>Economic/spatial requirements</td><td>Initial costs
2</td><td>Ongoing costs
2</td><td colspan="2">Marketable products
2</td><td colspan="2">Area
3</td><td>Overall cost
2</td></tr>
<tr><td>Bioremediation considerations</td><td colspan="2">Strengths
• Multiple bioremediation activities undertaken simultaneously
• Moderate evidence base available for other oyster species</td><td colspan="5">Weaknesses
• Substantially reduced surface area:volume ratio/stocking density when compared with rope culture
• Immersion constraints on filtration time and bioremediation potential
• Use of trestles may partially reduce biodeposit burial and denitrification benefits</td></tr>
<tr><td>Bioremediation performance</td><td>N reduction
2</td><td colspan="2">Microbial reduction
2</td><td colspan="2">Contaminant reduction
2</td><td colspan="2">Turbidity reduction
2</td></tr>
<tr><td>Environmental benefits</td><td colspan="7"><i>Ostrea edulis</i> addresses all four bioremediation activities simultaneously. Stocking densities are typically greater in oyster bags than that achieved for bottom culture although the extent of the cultivation site will be substantially smaller. The use of a harvestable species</td></tr>
</table>

<table>
<tr><th colspan="4">Species: <i>Ostrea edulis</i>. Option: bag and trestle culture</th></tr>
<tr><td></td><td colspan="3">increases the potential for direct N removal although the burial of biodeposits may be less due to the use of trestles. Partial emersion will also limit filtration and growth. Due to the limited spatial scaling of this option, improvements to water quality may be modest. The typical location of oyster trestles within estuaries, and therefore near the source of common water quality issues, does increase the bioremediation potential of this option.
At the site-scale, bioremediation performance, and subsequent improvement in water quality, will depend on (i) the stocking biomass, (ii) contact with the water (tidal exposure), (iii) concentration of the contaminant (proximity of the bioremediation site to the source of the water quality issue), (iv) rate of removal mechanisms (filtration, growth rate and frequency of harvests, rate of biodeposit burial and denitrification) and (v) rate of returning processes (excretion, mortality, resuspension and nitrification).</td></tr>
<tr><td rowspan="2">Ecological considerations</td><td>Strengths</td><td>Weaknesses</td><td>Ecological feasibility</td></tr>
<tr><td>• Native species
• Species of conservation interest
• Bioremediation site may become a source population for larval supply</td><td>• Stocking densities have the potential to reach habitat carrying capacities
• Loss of existing benthic habitat
• No provision of habitat</td><td>2</td></tr>
<tr><td>Limitations, public support and knowledge gaps</td><td colspan="3">Limitations for the use of this option for bioremediation are (i) spat supply for the scaling-up of operations and (ii) required area of seabed near the source of the water quality issues. The visual impact of trestles at low tide may reduce public support for this method. Conversely, as an established aquaculture practice using a native species, public support for this option is estimated moderate to high.
Knowledge gaps that contribute to the uncertainty of bioremediation performance include (i) studies documenting observed bioremediation potential for <i>O. edulis</i> for all four water quality issues and (ii) the ability to predict the biodeposit burial and denitrification loss.</td></tr>
<tr><td>Potential impacts on ecosystem services and societal benefits</td><td colspan="3">The culture of this native bivalve on intertidal trestles resulted in only two potentially significant positive effects in relation to one regulating service (waste breakdown and detoxification) and one provisioning service (fish and shellfish). With respect to goods/benefits, potentially significant positive effects were identified for food provision and waste burial / removal / neutralisation. A number of potential negative effects were identified relating to the introduction of a man-made structure to the natural environment (e.g. a negative impact on aesthetic benefits), resulting in a low overall score (14%).</td></tr>
<tr><td>Overall assessment</td><td colspan="3">Bag and trestle culture is an established aquaculture method. Oyster filtration and growth is fast (N removal during harvesting). Moderate surface area:volume ratio/stocking density (moderate pollutant adsorption and filtration capability) facilitates bioremediation action. Operating costs are likely to be moderate although the production of marketable shellfish could be used to off-set costs. Elevation of the oysters off the seabed may reduce the potential for biodeposits to be buried and contribute to denitrification processes. Available area for trestle placement is very small and greatly limits the ability to scale up bioremediation operations.</td></tr>
</table>

Table 10: Potential bioremediation option: *Crassostrea gigas* oyster bag/trestle culture

<table>
<tr><th colspan="7">Species: *Crassostrea gigas.* Option: bag and trestle culture</th></tr>
<tr><td>General description</td><td colspan="6">The cultivation of *C. gigas* oysters in mesh bags placed on trestles within the intertidal and subtidal fringe is an established aquaculture method. Placement of oysters in bags (or sometimes referred to as pouches) greatly reduces mortality through predation and the location of trestle intertidally reduces management costs (e.g. boat usage). Although spawning may still occur, the presence of adult *C. gigas* can be more controlled than the use of this species in establishing permanent intertidal and subtidal beds.</td></tr>
<tr><td>Option details</td><td colspan="2">**Apparatus**
• Established culture techniques used by the aquaculture industry.
• Trestles required</td><td colspan="3">**Management**
• Oyster spat required (from hatcheries)
• Standard industrial culture techniques or a new, modified management schedule for maximum bioremediation potential.
• Moderate ongoing maintenance costs (turning and thinning of bags)
• Implemented through direct commissioning or industrial incentivisation</td><td>**Locational requirements**
• Sheltered inshore locations
• Highly constrained to low intertidal and subtidal fringe (-2 – 2 m)
• UK-wide</td></tr>
<tr><td>Technical considerations</td><td colspan="2">**Strengths**
• Established industrial practice
• Easy to relocate or remove
• Surface waters free of apparatus
• Job creation
• Marketable shellfish product that may off-set costs
• Disease resistant species</td><td colspan="3">**Weaknesses**
• High visual impact during low tides/public resistance
• Shoreline 'high value' seabed – available are my limit the required scaling of operations
• Supply of required quantities of disease-free spat may potentially limit the required scaling of bioremediation operations
• Poor disease resistance
• Moderate management effort requirement (turning and thinning)
• Moderate-low operating costs
• Potential to generate contaminated, unmarketable mussels (via pollutants) or shellfish requiring depuration (bacteria and viruses)</td><td>**Technical feasibility**
3</td></tr>
<tr><td>Economic/spatial requirements</td><td colspan="2">**Initial costs**
2</td><td>**Ongoing costs**
2</td><td>**Marketable products**
2</td><td>**Area**
3</td><td>**Overall cost**
2</td></tr>
<tr><td>Bioremediation considerations</td><td colspan="3">**Strengths**
• Multiple bioremediation activities undertaken simultaneously
• Moderate evidence base available for other oyster species</td><td colspan="3">**Weaknesses**
• Substantially reduced surface area:volume ratio/stocking density when compared with rope culture
• Immersion constraints on filtration time and bioremediation potential
• Use of trestles may partially reduce biodeposit burial and denitrification benefits</td></tr>
<tr><td>Bioremediation performance</td><td>**N reduction**
2</td><td colspan="2">**Microbial reduction**
2</td><td colspan="2">**Contaminant reduction**
2</td><td>**Turbidity reduction**
2</td></tr>
<tr><td>Environmental benefits</td><td colspan="6">*Crassostrea gigas* addresses all four bioremediation activities simultaneously. The use of a harvestable species increases the potential for direct N removal although the burial of biodeposits may be less due to the use of trestles. Partial emersion will also limit filtration and</td></tr>
</table>

<table>
<tr><th colspan="4">Species: <i>Crassostrea gigas</i>. Option: bag and trestle culture</th></tr>
<tr><td></td><td colspan="3">growth. Due to the limited spatial scaling of this option, improvements to water quality may be modest. The typical location of oyster trestles within estuaries, and therefore near the source of common water quality issues, does increase the bioremediation potential of this option. At the site-scale, bioremediation performance, and subsequent improvement in water quality, will depend on (i) the stocking biomass, (ii) contact with the water (tidal exposure), (iii) concentration of the contaminant (proximity of the bioremediation site to the source of the water quality issue), (iv) rate of removal mechanisms (filtration, growth rate and frequency of harvests, rate of biodeposit burial and denitrification) and (v) rate of returning processes (excretion, mortality, resuspension and nitrification).</td></tr>
<tr><td rowspan="2">Ecological considerations</td><td>Strengths</td><td>Weaknesses</td><td>Ecological feasibility</td></tr>
<tr><td>• None</td><td>• Non-native species
• Larval supply with facilitate naturalised settlement outside the bioremediation area
• Stocking densities have the potential to reach habitat carrying capacities
• Loss of existing benthic habitat and no provision of habitat</td><td>1</td></tr>
<tr><td>Limitations, public support and knowledge gaps</td><td colspan="3">Limitations for the use of this option for bioremediation are access to be required area of seabed near the source of the water quality issues to generate a significant change in water quality. Based on the visual impact of large areas of trestle on low tides, public support for this option is estimated to be moderate.

Knowledge gaps that contribute to the uncertainty of bioremediation performance include (i) studies documenting observed bioremediation potential for trestle-grown <i>C. gigas</i> for all four water quality issues and (ii) the ability to predict the biodeposit burial and denitrification loss under trestles.</td></tr>
<tr><td>Potential impacts on ecosystem services and societal benefits</td><td colspan="3">The culture of this non-native bivalve on intertidal trestles resulted in only two potentially significant positive effects in relation to one regulating ecosystem service (waste breakdown and detoxification) and one provisioning service (fish and shellfish). With respect to goods/benefits, potentially significant positive effects were identified for food provision and waste burial / removal / neutralisation. A number of potentially negative effects were identified relating to the introduction of a man-made structure and a non-native species to the natural environment, resulting in an overall low score (14%).</td></tr>
<tr><td>Overall assessment</td><td colspan="3">Bag and trestle culture is an established aquaculture method. Oyster filtration and growth is fast (N removal during harvesting). Moderate surface area:volume ratio/stocking density (moderate pollutant adsorption and filtration capability) facilitates bioremediation action. Operating costs are likely to be moderate although the production of marketable shellfish could be used to off-set costs. Elevation of the oysters off the seabed may reduce the potential for biodeposits to be buried and contribute to denitrification processes. Available area for trestle placement is very small and greatly limits the ability to scale up bioremediation operations. Although an introduced species (currently naturalising), this species is an established and valued aquaculture species</td></tr>
</table>

Table 11: Compliance of four oyster culture options for remediation with the ten tenets of sustainability and wider ecosystem services scoring (from Annex 2).

Sustainability tenet	*O. edulis* bottom	*C. gigas* bottom	*O.edulis* trestle	*C. gigas* trestle
Ecologically sustainable	H(1)	L(5)	M	L
Technologically feasible	M(2)	M(6)	H	H
Economically viable	H(3)	H(7)	H(10)	H
Socially desirable/tolerable	H	L(8)	M	M
Ethically defensible (morally correct)	H	M	H	M
Culturally inclusive	M	L(9)	M	M
Legally permissible	H(4)	M	H	H
Administratively achievable	H(4)	M	H	H
Effectively communicable	H	H	H	H
Politically expedient	H	L	H	M(11)
Overall sustainability score	H	M	H	M / H
Goods/benefits score (/28)	**11**	**5**	**4**	**4**
Relative goods/benefits score	**Moderate**	**Low**	**Low**	**Low**

H = high, M = moderate, and L = low degree of compliance with sustainability tenet

(1) More ecological functioning assumed to be associated with *Ostrea edulis*

(2) May be issues with disease resistance

(3) Assumes harvesting and sale of products to offset costs, and that costs will increase in a linear manner as the area of application increases

(4) Licensing arrangements may apply

(5) Non-native species – habitat provision is poorer; reduced biodiversity

(6) Pacific oyster (*Crassostrea*) does not require significant post-deployment management, but has no commercial product associated with it (product is not suitable for harvesting/marketing) – this is an untested methodology but is considered to be feasible

(7) Inexpensive but no commercial returns

(8) Non-native species – shells detract from recreational beach use (sharp shells make exposed or shallow subtidal beds inaccessible to recreational users)

(9) Non-native species – not likely to have been integrated into local culture

(10) Harvestable products

(11) Less potential for (undesirable) spread of species compared to open bottom culture

Mussels

Species of the *Mytilus* genus occur along many temperate coastlines worldwide and are routinely cultivated in the UK. *Mytilus edulis* is a very competitive species and able to colonise a wide range of seabed substrata at very high densities. Furthermore, the filtration rate of *M. edulis* is high, e.g. 24 to 72 L^{-1} d^{-1} seawater depending on body mass (Møhlenberg and Riisgård, 1979), and is often greater than other bivalve species such *Cerastoderma edule* (the edible cockle), *Modiolus modiolus* (horse mussel) and *Arctica islandica* (ocean quahog) (Møhlenberg and Riisgård, 1979). Cultivated *M. edulis* is also capable of rapid growth and substantial yields (Petersen *et al.*, 2014). *Mytilus* spp. (species not specified by Brzozowska *et al.*, 2012) has also been shown to be highly efficient at the removal of some heavy metals and, to a lesser degree, organic pollutants, suggesting that this genus may also be of value for the bioremediation of contaminants (Brzozowska *et al.*, 2012).

For *M. edulis*, N reduction has been demonstrated using rope culture in Sweden (Haamer, 1996; Carlsson *et al.*, 2012) and Canada (Hatcher *et al.,* 1994). Experimental analysis using chambers and flumes have also confirmed the net removal of nitrogen by this species (Kautsky and Evans, 1987; Dame *et al.*, 1991 respectively). These results typically highlight the net removal of N when mussels are harvested (Haamer, 1996; Carlsson *et al.*, 2012). Almost all of the studies documented enhanced sedimentation, hence also indicating that biodeposit burial and enhanced biochemical action may also be significant mechanisms of N removal (Kautsky and Evans, 1987; Dame *et al.*, 1991; Carlsson *et al.*, 2012). Although there is evidence that all three mechanisms of N removal do occur within *Mytilus* beds, it would appear that many biological and environmental variables determine the site-specific expression of each and hence there is no conclusive evidence about which one is of greater importance for N reduction.

As an established aquaculture practice, there is a significant knowledge-base for the cultivation of *Mytilus* sp. This information is also likely to be of great value for implementing effective and cost-efficient *Mytilus*-based bioremediation projects. However, as an aquaculture species, *Mytilus* sp. is typically cultivated for human consumption. As the end products must be marketable, this can limit the bioremediation scope and areas available for existing shellfish management practices to nutrient control rather than pollutant or bloom-forming species control. However, if the *Mytilus* sp. production is for bioremediation without human consumption, it is possible that more flexible and effective bioremediation practices can be developed. Equally, uncultivated seabed in areas failing shellfish hygiene standards may also be available for bioremediation purposes. Harvested material from these areas (or stock from unmarketable practices) could be used for used to generate fish meal and fed to other cultured animals, e.g. Lindahl *et al.* (2005) suggest that mussel flesh could be used to feed chickens. The cultivation of mussels, not as a food crop, but as a mitigation measure has been proposed for the Baltic Sea (Lindahl *et al.,* 2005), and an understanding of the costs and benefits of this measure is developing (Gren *et al.*, 2009; Petersen *et al.*, 2014).

Also in favour of *M. edulis*-based bioremediation activities is that it is a native species and shows a greater disease resistance when compared to other aquaculture species such as the native oyster *O. edulis* (Laing *et al.*, 2006).

Furthermore, the potential to use rope culture greatly increases the efficiency and flexibility of potential bioremediation approaches using this *M. edulis*. Rope culture greatly increases the surface area to volume ratio between the mussels and the target water body. This facilitates a faster turn-over of the water body and a greater clearance rate. Equally, as a surface method (although still requiring seafloor moorings), rope culture can also be deployed over larger areas compared with bottom culture.

Rope-grown mussels optimise filtration and growth, which maximises N removal by harvesting. However, N removal through the burial of biodeposits may be diminished as falling biodeposits from rope cultivation sites may be widely dispersed and occasionally resuspended on uncolonised seabeds. Observations from established *C. virginica* reefs suggest that N removal via biodeposit burial and subsequent denitrification can exceed the N loss from harvesting (Carmichael *et al.,* 2012). However, indirect enhancement of N removal via denitrification will in all cases be difficult to measure, requiring specialist techniques and modelling methods.

As stated above, other species of mussels that can occur in dense, extensive beds are also suitable bioremediation agents. Based on this, it is possible that *Modiolus modiolus* may also be a suitable bioremediation species. This species is found both infaunally and epifaunally (although typically described as semi-infaunal) in coarse, high energy environments and sheltered, soft sediment habitats (Tyler-Walters, 2007). *M. modiolus* forms aggregated reefs as it develops (Lindenbaum *et al.*, 2008). In soft sediment habitats, these aggregations are small and form distinct clumps (Maggorian and Service, 1998) whilst in higher energy environments, these aggregations can form large ridged biogenic reefs or beds, orientated perpendicular to the current. These beds can reach a thickness of 1 m on top of the underlying coarse sediment. They are also capable of high filtration rates that enable the concentration of large amounts of suspended particulates, from pelagic waters, into energy-rich faeces or pseudofaeces, which can be utilized as food by other species (Navarro and Thompson, 1997). Although a common species in UK waters (although typically distributed further north in British waters), the potential use of this species for bioremediation purposes has not been investigated. However, a number of factors make it a highly suitable candidate for used in bioremediation: the density of mussels in a reef; the filtering capacity of individual mussels (Møhlenberg and Riisgård, 1979); the ability to simultaneously undertake all four required bioremediation activities, and the abundance associated with infaunal and epifaunal assemblages. In addition, the use of *M. modiolus* would provide a self-sustaining and long-term bioremediation requiring little or no management during its lifetime.

The assigned performance, feasibility and cost efficiency scores for the mussel-based options identified as potentially suitable for bioremediation are summarised in Figure 12, further information on each option summarised in Table 12 to Table 14 and the sustainability scores are summarised in Table 15.

Bioremediation summary: *Mytilus* spp. and *Modiolus modiolus*

Positive attributes:

- Several suitable native species
- High filtration rate, growth and biodeposit production are well documented
- Reductions in turbidity, suspended microbes and contaminants are also possible although the evidence base for this is either small (contaminant removal) or absent (microbial reduction)
- Multiple established aquaculture practices available for *M. edulis*
- Species suitable for high density, condensed culture
- Potential for suspended culture that increases surface area to volume ratios and overall efficacy for *M. edulis* cultivation
- *M. modiolus* can provide long-term bioremediation and not require management after establishment
- Numerical models are available for predicting the growth rates of mussels either at the individual-scale or at the farm scale (SHELLSIM (Hawkins *et al.*, 2013) and FARM (Ferreira *et al.*, 2011, Silva *et al.*, 2011)).

Negative attributes

- High and constant management requirement for *M. edulis* cultivation
- Sites for high-performing rope culture methods are severely limited
- Wild *M. edulis* spat supplied is erratic and limited
- Cultivation and restoration potential of *M. modiolus* unproven and likely to be difficult
- As a boreal species, *M. modiolus* is rarer on the south coast and, based on climate change scenarios, may be unsuitable for long-term use further south

Figure 12: Bioremediation performance, feasibility (technical and ecological) and estimated cost for mussel-based approaches.

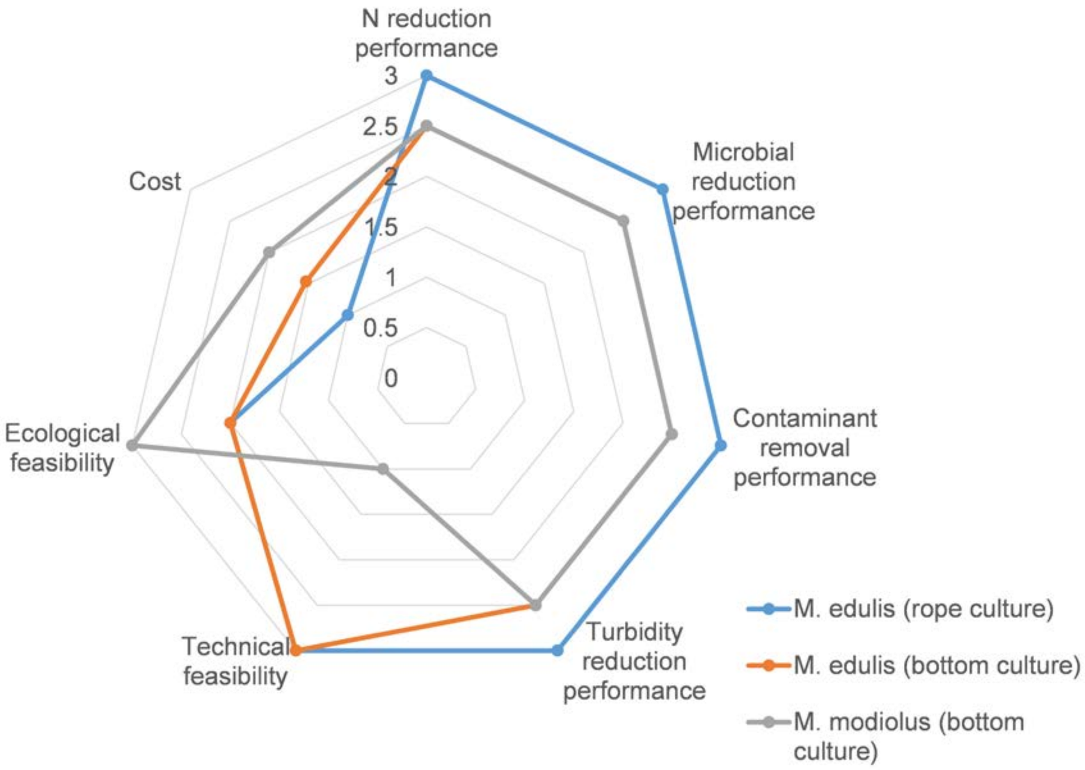

Table 12: Potential bioremediation option: *Mytilus edulis* rope culture

Species: *Mytilus edulis.* Option: rope culture			
General description	The common or blue mussel is a common marine species and is distributed widely throughout the UK. *Mytilus edulis* will settle onto almost any hard substrata. On exposed coasts, *M. edulis* occurs further up the intertidal zone but tend to be small and slow growing. The subtidal distribution and density of this species is typically controlled by intense predation from many species (Tyler-Walters 2008). Growth rates for *M. edulis* varies greatly and is mostly controlled by environmental factors. The most influential factors are (i) temperature, (ii) salinity, (iii) food availability, (iv) tidal exposure, (v) competition and (vi) parasitism. Rope culture aquaculture practices are able to eliminate issues surrounding tidal exposure and competition, and control issues, though careful positioning, of temperature, salinity and food availability. Rope cultivation refers to the practice of growing mussels on ropes suspended from either rafts or moorings. The rope culture of *Mytilus edulis* is a well-establish and wide-practiced aquaculture technique. However, as a fairly complex apparatus, rope culture is typically restricted to sheltered conditions. The world's leading producer of mussels is Spain who typically use rope culture suspended from rafts. For bioremediation purposes, management can be focused towards either the production of marketable shellfish or optimised for bioremediation purposes (e.g. greatest growth, lowest cost and disposal of products via non-human consumption).		
Option details	**Apparatus**	**Management**	**Locational requirements**
	• Rope culture apparatus requires mooring with surface, mid-water and bottom gear (standard industrial culture technique). • Boating and processing infrastructure required	• Standard industrial culture techniques or a new, modified management schedule to maximise bioremediation potential. • Droppers require cleaning, predator removal and thinning. • High initial cost and continuous management required. • Implemented through direct commissioning or industrial incentivisation	• Sheltered inshore locations with depth greater than 10 m. • Surface and seabed area required • UK-wide
Technical considerations	**Strengths**	**Weaknesses**	**Technical feasibility**
	• Established industrial practice • Easy to relocate or remove • Climate change resistant • Job creation • If correctly placed, droppers can be used for water-column interception of larvae • Marketable shellfish product that	• Very high management effort requirement • Moorings reduce surface accessibility • Overall high operating costs • Potential to generate contaminated mussels: unmarketable (pollutants) or require depuration (bacteria and viruses) • Susceptible to red tides • Carrying capacity limitation possible at high stocking densities • Wild mussel seed availability extremely limited[17]	3

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[17] The availability of wild mussel seed (recently settled *M. edulis* juveniles) is a limiting resource and is greatly in demand by all aquaculture producers. There is increasing interest in the use of mid-water spat collectors to compensate for the lack of wild seed (Jacobs *et al*., 2014). However, this is currently underdeveloped in the UK and spat supply may well limit the expansion of *M. edulis* cultivation for bioremediation purposes.

<table>
<tr><th colspan="6">Species: <i>Mytilus edulis.</i> Option: rope culture</th></tr>
<tr><td></td><td colspan="2">may off-set costs</td><td colspan="2"></td><td></td></tr>
<tr><td>Economic/spatial requirements</td><td>Initial costs
3</td><td>Ongoing costs
3</td><td>Marketable products
3</td><td>Area
1</td><td>Overall cost
1</td></tr>
<tr><td>Bioremediation considerations</td><td colspan="3">Strengths
• Multiple bioremediation activities undertaken simultaneously
• Moderate evidence base
• High surface area : volume ratio</td><td colspan="2">Weaknesses
• Biodeposits dispersed widely that might reduce burial
• Reduced burial potential may impact on denitrification loss</td></tr>
<tr><td>Bioremediation performance</td><td colspan="2">N reduction
3</td><td>Microbial reduction
3</td><td>Contaminant reduction
3</td><td>Turbidity reduction
3</td></tr>
<tr><td>Environmental benefits</td><td colspan="5">The combination of a very high stocking biomass, three-dimensional distribution of biomass within the water column and the ability to address all four bioremediation activities simultaneously suggest that this option can significantly improve water quality around and down-stream of bioremediation sites. Such is the proven filtration potential of rope-grown mussels that carrying capacity is often reached (Dame and Prins, 1998), i.e. phytoplankton and suspended solids are broadly depleted.
At the site-scale, bioremediation performance, and subsequent improvement in water quality, will depend on (i) the stocking biomass, (ii) contact with the water (surface area:volume ratio), (iii) the duration of contact with the water body (residence time or current speeds), (iv) concentration of the contaminant (proximity of the bioremediation site to the source of the water quality issue), (v) rate of removal mechanisms (filtration, growth rate and frequency of harvests, rate of biodeposit burial and denitrification) and (vi) rate of returning processes (excretion, mortality, resuspension and nitrification).</td></tr>
<tr><td>Ecological considerations</td><td colspan="2">Strengths
• Native species
• Provision of mid-water structures and habitat
• Little interference with existing benthic habitats
• Bioremediation site may become a source population for larval supply</td><td colspan="2">Weaknesses
• Stocking densities have the potential to reach habitat carrying capacities
• Potential for wide-spread organic enrichment of sediments</td><td>Ecological feasibility
2</td></tr>
<tr><td>Limitations, public support and knowledge gaps</td><td colspan="5">Limitations for the use of this option for bioremediation are (i) mussel seed supply for the scaling-up of operations, (ii) required area of seabed/surface waters near the source of the water quality issues and (iii) the management of the environmental consequences of extensive and intensive aquaculture (including, for example, associated controls on the transportation and relaying of mussels due to <i>Mytilicola</i> infestation).
This bioremediation option is an established aquaculture practice producing a marketable product and using a native species. However, farm structures are highly noticeable and restrict accessibility. As such, public support for this option is estimated to be moderate.
<i>Mytilus edulis</i> is one the most extensively studies marine organisms. There is an extensive knowledge-base on aspects of biology, ecology and cultivation. There is a substantial volume of information available on the accumulation of contaminants by <i>M. edulis</i> due to the inclusion of this species in monitoring programmes such as ‘mussel watch’ (Sericano <i>et al.</i>, 1995). Case studies demonstrating bioremediation potential are less frequent. However, remaining knowledge gaps that contribute to the uncertainty of bioremediation performance include (i) multiple studies documenting observed bioremediation potential for all four water quality issues, (ii) the ability to</td></tr>
</table>

Species: *Mytilus edulis.* Option: rope culture	
	predict the biodeposit burial and denitrification loss and (iii) management scheme required for optimum bioremediation potential (a non-established aquaculture management practice). Biodeposit burial and denitrification have been reported as being equally important mechanisms for nitrogen removal as direct removal via shellfish harvesting. The potential for biodeposit burial under rope-grown mussels will depend on site-specific variables such as depth, current speeds and the benthic assemblage present. It is not therefore possible to estimate the contribution that burial and denitrification can make to the overall bioremediation capability of a site.
Potential impacts on ecosystem services and societal benefits	This option offers potentially significant positive effects to the provision of a number of ecosystem services (nutrient cycling, biological control, fish and shellfish, clean water) and one ecosystem good/benefit (food provision). A number of potential negative effects on ecosystem services are also highlighted (formation of seascape, spiritual and cultural well-being, aesthetic benefits, tourism and nature watching) which relate to the introduction of man-made structures into the natural environment and the potential conflict this may have with both the natural seascape and some recreational interests such as boating. The overall goods/benefits score for this option is low (11%).
Overall assessment	Rope culture is an established mid-water aquaculture method. The bioremediation activity is greatly increased through high filtration rates, fast growth (mostly N removal during harvesting) and high surface area:volume ratios/stocking densities (high pollutant adsorption and filtration capability). Suspended culture may reduce N removal benefits from biodeposit burial and denitrification. Operating costs are likely to be extremely high although the potential to generate a marketable product may offset costs or allow industrial incentivisation to be used.

Table 13: Potential bioremediation option: *Mytilus edulis* bottom culture.

<table>
<tr><th colspan="4">Species: <i>Mytilus edulis.</i> Option: bottom culture</th></tr>
<tr><td>General description</td><td colspan="3">The bottom culture of <i>M. edulis</i> (common or blue mussel) involves the relaying of either dredged wild seed mussel from natural settlement areas or mid-water collection onto the seabed within designated aquaculture plots. Mussels are routinely re-dredged to grade and thin individuals. There is a significant management effort dedicated to starfish removal as predation is greater for bottom culture. For bioremediation purposes, management can be focused towards either the production of marketable shellfish or optimised for bioremediation purposes (e.g. greatest growth, lowest cost and disposal of products via non-human consumption).</td></tr>
<tr><td rowspan="2">Option details</td><td>Apparatus</td><td>Management</td><td>Locational requirements</td></tr>
<tr><td>• Bottom culture that requires no mooring structures
• Established culture techniques used by the aquaculture industry.
• Boating and processing infrastructure required for maintenance and harvesting</td><td>• Standard industrial culture techniques or a new, modified management schedule for maximum bioremediation potential.
• Seed mussel (dredged from natural settlement areas or sourced from suppliers of spat from mid-water interception of larvae).
• Moderate to high ongoing maintenance costs
• Implemented through direct commissioning or industrial incentivisation</td><td>• Sheltered inshore locations with a depth range between 2 – 20 m.
• Certain substrata are unsuitable for shellfish culture
• UK-wide</td></tr>
</table>

<table>
<tr><th colspan="10">Species: <i>Mytilus edulis.</i> Option: bottom culture</th></tr>
<tr><td rowspan="2">Technical considerations</td><td colspan="3">Strengths</td><td colspan="4">Weaknesses</td><td colspan="2">Technical feasibility</td></tr>
<tr><td colspan="3">• Established industrial practice
• Easy to relocate or remove
• Surface waters free of apparatus
• Job creation
• If correctly placed, droppers can be used for water-column interception of larvae
• Marketable shellfish product that may off-set costs</td><td colspan="4">• Moderate to high management effort requirement (starfish removal, thinning and relaying)
• Boundary layer constraints on carrying capacity (beds will require separation)
• Moderate operating costs
• Potential to generate contaminated, unmarketable mussels (via pollutants) or shellfish requiring depuration (bacteria and viruses)
• Supply of required quantities of seed mussel</td><td colspan="2">3</td></tr>
<tr><td rowspan="2">Economic/spatial requirements</td><td>Initial costs</td><td colspan="2">Ongoing costs</td><td colspan="2">Marketable products</td><td colspan="2">Area</td><td colspan="2">Overall cost</td></tr>
<tr><td>2</td><td colspan="2">2</td><td colspan="2">2</td><td colspan="2">2</td><td colspan="2">1.5</td></tr>
<tr><td rowspan="2">Bioremediation considerations</td><td colspan="5">Strengths</td><td colspan="4">Weaknesses</td></tr>
<tr><td colspan="5">• Multiple bioremediation activities undertaken simultaneously
• Moderate evidence base
• Potential for improved N removal through biodeposit burial and denitrification processes</td><td colspan="4">• Substantially reduced surface area:volume ratio/stocking density when compared with rope culture
• Bottom culture can be inefficient (1 tonne of spat is required for the production of 1 tonne of adult mussels</td></tr>
<tr><td rowspan="2">Bioremediation performance</td><td colspan="2">N reduction</td><td colspan="3">Microbial reduction</td><td>Contaminant reduction</td><td colspan="3">Turbidity reduction</td></tr>
<tr><td colspan="2">2.5</td><td colspan="3">2.5</td><td>2.5</td><td colspan="3">2.5</td></tr>
<tr><td>Environmental benefits</td><td colspan="9">The combination of a high stocking biomass, three-dimensional distribution of biomass within the water column and the ability address all four bioremediation activities simultaneously suggest that this option can improve water quality around and down-stream of bioremediation sites. At the site-scale, bioremediation performance, and subsequent improvement in water quality, will depend on (i) the stocking biomass, (ii) contact with the water (surface area:volume ratio or advective mixing into the boundary layer), (iii) the duration of contact with the water body (residence time or current speeds), (iv) concentration of the contaminant (proximity of the bioremediation site to the source of the water quality issue), (v) rate of removal mechanisms (filtration, growth rate and frequency of harvests, rate of biodeposit burial and denitrification) and (vi) rate of returning processes (excretion, mortality, resuspension and nitrification).</td></tr>
<tr><td rowspan="2">Ecological considerations</td><td colspan="4">Strengths</td><td colspan="4">Weaknesses</td><td>Ecological feasibility</td></tr>
<tr><td colspan="4">• Native species
• Provision of benthic habitat
• Bioremediation site may become a source population for larval supply</td><td colspan="4">• Stocking densities have the potential to reach habitat carrying capacities within the boundary layer
• Loss of existing benthic habitat</td><td>2</td></tr>
</table>

Species: *Mytilus edulis.* Option: bottom culture	
Limitations, public support and knowledge gaps	Limitations for the use of this option for bioremediation are (i) mussel seed supply for the scaling-up of operations, (ii) inefficient biomass conversion ratios[18], (iii) required area of seabed near the source of the water quality issues and (iv) the management of the environmental consequences of extensive and intensive aquaculture (including, for example, associated controls on the transportation and relaying of mussels due to *Mytilicola* infestation). As an established aquaculture practice producing a marketable product and using a native species placed subtidally, public support for this option is estimated to be high. Knowledge gaps that contribute to the uncertainty of bioremediation performance include (i) multiple studies documenting observed bioremediation potential for all four water quality issues, (ii) the ability to predict the biodeposit burial and denitrification loss and (iii) management scheme required for optimum bioremediation potential (a non-established aquaculture management practice).
Potential impacts on ecosystem services and societal benefits	This option offers potentially significant positive effects on a number of supporting (formation of species habitat, formation of seascape), regulating (biological control, natural hazard regulation and waste breakdown and detoxification), provisioning (fish and shellfish) and cultural (places and seascapes) ecosystem services. With respect to the provision of goods/benefits, this option only offers potentially significant positive effects in relation to waste burial / removal / neutralisation. The overall goods/benefits score for this option is moderate (39%) with no potential negative effects identified.
Overall assessment	Bottom culture is an established aquaculture method that allows moderate - high production rates (N removal during harvesting), moderate surface area/stocking density (moderate pollutant adsorption and filtration capability) and also potentially generates a marketable product that can be used to off-set costs or allow industrial incentivisation to be used. Operating costs are likely to be moderate to high as although moorings are not required, predator control is labour intensive. The close proximity of the mussels to the seabed may increase the potential for biodeposits to be buried and not be resuspended. Stocking density / surface area:volume ratio poor when compared with rope culture.

Table 14: Potential bioremediation option: *Modiolus modiolus* bottom culture

Species: *Modiolus modiolus.* Option: bottom culture	
General description	*Modiolus modiolus* is a native bivalve that can occur in dense and extensive biogenic reefs. The reef also provides a substratum for additional epifaunal species, thereby increasing the filtration and biodeposit production rates. This option requires the placement of 'cultch' (dead shell used to enhance the seabed surface) and either allow the natural settlement of *M. modiolus* or translocate individuals from elsewhere. Although suggested as a bioremediation method here, it has only been trialled as a restoration method elsewhere (trailed by the *M. modiolus* Restoration Group in Strangford Lough, NI). As a long-lived species, this is a long-term bioremediation option with additional ecological benefits.

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[18] Currently, approximately 1 tonne of seed is required for 1 tonne of adult biomass (Seafish, 2002). If the main bioremediation mechanism for N removal is the harvesting of biomass, then it is clear that the cultivation phase of the bioremediation process adds little to this mechanism and merely delays the removal. However, based on the demand for seed, it would not be possible to directly remove this biomass.

<table>
<tr><th colspan="8">Species: <i>Modiolus modiolus</i>. Option: bottom culture</th></tr>
<tr><td>Option details</td><td>Apparatus
• Initial cultch layer
• Translocated adults from wild beds or natural settlement</td><td colspan="4">Management
• Once placed, no further management is anticipated although predator control during the establishment of the reef may reduce mortalities.
• Implemented through direct commissioning</td><td colspan="2">Locational requirements
• Sheltered and moderately exposed inshore locations
• Moderate current speeds required
• Subtidally from 0 to 40 m (limited by practical considerations)
• Better suited to more northerly locations</td></tr>
<tr><td>Technical considerations</td><td>Strengths
• Surface waters free of apparatus
• No management requirement after establishment
• Long-term option
• Self-sustaining
• Disease resistant species</td><td colspan="5">Weaknesses
• Although previously trialled, this cultivation technique remains unproven
• Reduced initial benefit for both the translocation of adults (overall filtering capacity the same although better positioned) or natural recruitment (although juvenile growth is rapid, adult growth is slow)
• Supply of adults for translocation may diminish ecosystem services elsewhere
• Settlement slow and unpredictable
• Boundary layer constraints on carrying capacity
• High initial cost</td><td>Technical feasibility
1</td></tr>
<tr><td>Economic/spatial requirements</td><td>Initial costs
3</td><td colspan="2">Ongoing costs
1</td><td colspan="2">Marketable products
1</td><td>Area
2</td><td>Overall cost
2</td></tr>
<tr><td>Bioremediation considerations</td><td colspan="6">Strengths
• Multiple bioremediation activities undertaken simultaneously
• High density reefs
• Reef elevation increases mixing and seston availability
• Abundant infauna and epifauna enhance filtration, burial and denitrification
• Improved biodeposit burial and denitrification potential due to direct placement of mussels onto the seabed</td><td>Weaknesses
• Substantially reduced surface area:volume ratio/stocking density when compared with rope culture
• Slow adult growth
• Evidence base absent</td></tr>
<tr><td>Bioremediation performance</td><td colspan="2">N reduction
2.5</td><td colspan="2">Microbial reduction
2.5</td><td colspan="2">Contaminant reduction
2.5</td><td>Turbidity reduction
2.5</td></tr>
<tr><td>Environmental benefits</td><td colspan="7"><i>Modiolus modiolus</i> addresses all four bioremediation activities simultaneously and biogenic reef densities are typically high suggesting that the overall bioremediation, and subsequent improvement in water quality, is high. Although there is no N removal through shellfish harvesting, the potential for biodeposit burial and N removal via denitrification is significant. At the site-scale, bioremediation performance, and subsequent improvement in water quality, will depend on (i) the stocking biomass, (ii) contact with the water (advective mixing into the boundary layer), (iii) the duration of contact with the water body (residence time or current speeds), (iv) concentration of the contaminant (proximity of the bioremediation site to the source of the water quality issue), (v) rate of removal mechanisms (filtration, growth rate, rate of biodeposit burial and denitrification) and (vi) rate of returning processes (excretion, mortality, resuspension and</td></tr>
</table>

Species: *Modiolus modiolus.* Option: bottom culture			
	nitrification).		
Ecological considerations	**Strengths** • Native species • Species of conservation interest • Bioremediation site may become a source population for larval supply • Provision of additional high value biogenic reef habitat	**Weaknesses** • Required stocking densities have the potential to reach habitat carrying capacities • Partial loss of existing benthic habitat • Damage to existing *M. modiolus* beds if adults are translocated	**Ecological feasibility** 3
Limitations, public support and knowledge gaps	Limitations for the use of this option for bioremediation are (i) generating a successful reef generation method, (ii) the supply of settling larvae or translocated individuals, (iii) the required area of seabed near the source of the water quality issues and (iv) growth and reef expansion rates. As a native species that generates high-value biogenic reef, public support for this option is estimated to be very high. Knowledge gaps that contribute to the uncertainty of bioremediation performance include (i) proven reef establishment methods, (ii) documented bioremediation potential for *M. modiolus* for all four water quality issues, (iii) the ability to predict the biodeposit burial and denitrification loss and (iv) management scheme required for the long-term maintenance of *M. modiolus* reefs.		
Potential impacts on ecosystem services and societal benefits	This option identified one supporting ecosystem service (formation of species habitat), three regulating services (biological control, natural hazard regulation, waste breakdown and detoxification), one provisioning service (fish and shellfish) and one cultural service (places and seascape) which may have potentially significant positive effects. With respect to goods/benefits, potential significant positive effects were identified for waste burial / removal / neutralisation and tourism and nature watching (in relation to diving), resulting in a moderate overall score (39%) with no negative effects on goods/benefits identified.		
Overall assessment	This option relies on a novel deployment method of a native species. Although simple to implement, this habitat creation method is untested. Equally, the value of *M. modiolus* specifically has not been documented. However, established biogenic reefs of this species have the required characteristics for high-value bioremediation potential. This method will generate lower N removal as it is not anticipated that individuals will be harvested. However, biodeposit production and burial will be high and as such, denitrification processes could be significantly enhanced. The high density of mussels combined with the abundant epifaunal community suggests the filtration capacity of this option could be high and therefore the capacity to reduce suspended microbes, contaminants and turbidity may also be high. Operating costs are likely to be very low. The long-term development of raise biogenic reef will increase the potential burial of biodeposits over time. Over time, self-sustaining reefs are likely.		

Table 15: Compliance of mussel culture options for bioremediation with the ten tenets of sustainability and wider ecosystem services scoring (from Annex 2).

Sustainability tenet	*M. edulis* rope	*M. edulis* bottom	*M. modiolus* bottom
Ecologically sustainable	M	M(4)	H(7)
Technologically feasible	H	H	L(8)
Economically viable	H(1)	H(5)	H(9)
Socially desirable/tolerable	L	M	H
Ethically defensible (morally correct)	H	H	H
Culturally inclusive	L(2)	M	M
Legally permissible	H(3)	H(6)	H
Administratively achievable	H(3)	H(6)	H
Effectively communicable	H	H	H
Politically expedient	H	H	H
Overall sustainability score	M / H	H	H
Goods/benefits score (/28)	**3**	**11**	**11**
Relative goods/benefits score	**Low**	**Moderate**	**Moderate**

H = high, M = moderate, and L = low degree of compliance

(1) Assumes harvesting and sale of products to offset costs, and that costs will increase in a linear manner as the area of application increases

(2) Assumes reduced access to local groups (such as local fishers)

(3) Licensing arrangements may apply

(4) Requires dredged spat for use as an inoculum and may need a hard surface to be prepared (e.g. by dredging) prior to seeding – both of which may limit ecological sustainability

(5) Assumes harvesting and sale of products to offset costs, and that costs will increase in a linear manner as the area of application increases

(6) Licensing arrangements may apply

(7) Biogenic reef-forming; generally improves local biodiversity

(8) Only single published study identified – results are uncertain as studies are ongoing

(9) High initial cost – no potential for returns from harvesting but resultant reef likely to increase local biodiversity

Other filter feeding species

Other filter feeding species that occur in large extents and also exist at high densities are also potential bioremediation mediators. Many species of sponge, bryozoan and ascidian are also therefore suitable candidates. The value of these non-bivalve species is further enhanced as many are of interest to pharmaceutical industry for novel secondary metabolites, e.g. many sponge metabolites are in global demand and have high market values. Despite their potential value both within bioremediation and bioprospecting, there is a significant knowledge gap demonstrating the outputs and practicalities of scales bioremediation with these species. Documented filtration rates are typically high and compared well with bivalve species. For example, Fiala-Médioni (1978) reported filtration rates between 22 – 97 L of seawater per individual per day for three common ascidian species (*Ciona intestinalis*, *Phallusia mammillata* and *Styela plicata*). Likewise, Riisgård *et al.* (1993) reported filtrations between 2 – 20 L of seawater per gram of sponge for *Halichondria panicea*.

Within regard to the potential for the accumulation of contaminants, Perez *et al.* (2003) reported that the 'bath sponge' *Spongia officinalis* was able to concentrate many organic contaminants, including polychlorinated biphenols, and estimated a bioconcentration factor (the ratio of concentration with the organism to the exposure concentration) of approximately 10^5, which is much greater than factors observed in bivalves. Olesen and Weeks (1994) observed a bioconcentration factor of 42200 for cadmium in the common sponge *H. panicea*. There is a substantial evidence base documenting high bioconcentration values for many common filter-feeding species. These studies demonstrate the bioremediation potential of specific filter-feeding species for removing contaminant loadings in seawater. However, there is no information on the bioremediation capabilities of the majority of the common species found in British waters. Equally, there is no information on the technical considerations for generating scaled-up and effective bioremediation apparatus using these species. Overall, there are significant knowledge gaps on proven bioremediation capability and culture methods for common UK species.

The cultivation of sponges and ascidians is widely practiced in Asia but not currently undertaken within the UK or with species native to UK waters. It is probable that the suspended rope and mesh bag culture methods used in Asia could be transferred to the UK. However, the absence of an established cultivation industry in the UK is a significant limitation for the development of non-bivalve based bioremediation methods.

Bioremediation summary: other filter feeding species (non-bivalve)

Positive attributes:

- High filtration rates are documented for several common filter feeding species, suggesting that nitrogen, microbial and turbidity reductions should be significant.
- There is evidence for high bioconcentration factors associated with many common filter feeding species. These factors for organic contaminants may be greater than in bivalve species.
- Cultured products can have a high market value
- There are established sponge and ascidian cultivation practices that could be transferred to the UK

Negative attributes

- Overall, there are significant knowledge gaps on proven bioremediation capability and culture methods for common UK species

3.3.2 Seaweed

Although not as widely used in European aquaculture as bivalves, brown, red and green macroalgae (seaweeds) are cultivated at a small-scale and have a number of existing uses in bioremediation. In areas with limiting freshwater supplies, land-based tank systems containing seaweeds can be effective at capturing nutrients from point sources such as fin-fish aquaculture or sewage treatment facilities (Lüning and Pang, 2003). The ability of seaweeds to capture inorganic nutrients from the water depends upon the growth rate, which is largely determined by the availability of light (day-length, turbidity, position of algae in the water column) and temperature. However, certain large brown algae such as *Laminaria hyperborea* have evolved mechanisms to take up and store nitrogen during the winter months in order to compete with phytoplankton and other seaweeds during the following spring. Due to their restriction to the photic zone (either close to the surface for suspended culture or in shallow water when attached to the seabed), and a light-limited growth season, the annual nutrient-accumulating efficiency of seaweeds per unit of area of sea surface is lower than that of bivalves. Hence, relatively large areas of seaweed cultivation would be required to achieve equivalent bioremediation results. For the full removal of the excess nitrogen associated with a commercial fish farm, one hectare of seaweed was estimated for each ton of fish standing stock (Troell *et al.*, 1997).

Without the capacity of filter-feeders to clear the water column of particles, a seaweed farm site would have limited effectiveness in reducing microbial contamination. The turbulence of water passing through a large farm would be reduced however, and this could be expected to cause settlement of sediments, hence reducing turbidity in the vicinity. Seaweed biomass, either in the form of living fronds or dried material, does, however, have a high or very high binding capacity for heavy metals (e.g. mercury, arsenic, lead) and radioisotopes (Villares *et al.*, 2001).

Seaweed cultivation is well-established in Asia, where the material is grown for human consumption and for high-value colloids such as carrageenan and agar. In northern China, the cultivation of *Laminaria japonica* has been encouraged to balance the negative environmental effects of very large scale bivalve cultivation. Bivalves have a high efficiency for obtaining particulate nitrogen in the form of phytoplankton, however some of the N is processed during metabolism and excreted. At high stocking densities of bivalves, this can lead to locally-elevated seawater concentrations of ammonium which may then be controlled by seaweed cultivation.

Recently, there has been an increased European interest in the large-scale cultivation of seaweeds for the conversion into biofuels and bioenergy and for high-value commodity chemicals. Much work has been done in Ireland and Scotland to develop mass cultivation of seaweeds, particularly in combination with salmon aquaculture. Expertise in seaweed biotechnology has been developed at the Scottish Association for Marine Sciences with projects such as BIOMARA[19] and SUPERGEN[20]. The Crown Estate and the Centre for Environment, Fisheries and Aquaculture Science (Cefas) have recently explored the ecological impacts of seaweed farming using a modelling approach to calculate the theoretical impact of a 20 km^2 kelp farm on the nitrogen cycle (Aldridge *et al.*, 2012). Funding continues for this work with a recent Innovate_UK project[21]. Combining the estimates for nitrogen removal from recent studies shows a potential sink in the range of 25 to 250 tonnes nitrogen per km^2 of farm yr^{-1} (Sanderson *et al.*, 2008, Aldridge *et al.*, 2012). The underlying physiological performance data on nutrient consumption by species native to the south marine plan areas such as *Ulva lactuca* and *Laminaria digitata* is largely known at the individual level. Scaling-up estimates from the single algal blade depends on the farming method selected. Algal spores can be settled onto ropes, nets or horizontal sheets, or small algae may be fastened onto lines in a hatchery before transplanting to the sea. The final biomass produced, and hence nutrient or chemical removal potential will depend upon the packing density of the farm system. Smale *et al.* (2013) cautioned against the use of large-scale seaweed farming either as part of an integrated multi-trophic aquaculture system or for biofuel, stating that the ecosystem-wide impacts of these approaches are not sufficiently understood. A further discussion of the legislation and governance of the emerging European seaweed industry is given by Benson *et al.* (2014).

The proposed use of macroalgae for bioremediation should also be viewed in the context of the overall trend for European seaweed populations, which shows for some locations well-documented examples of local seaweed species declines as a result of anthropogenic pressure (e.g. eutrophication, trampling, habitat modification, and invasive species and overgrazing) and regional seawater warming and other changes (Brodie *et al.*, 2014, Mineur *et al.*, 2014). The relationship between stocks of natural seaweeds and the ecosystem services that they provide is not well understood. Even the large, canopy-forming brown seaweeds, which represent the largest standing stock of biomass and support a high level of biodiversity, have not been systematically studied in the UK, as highlighted by a recent report to the Joint Nature Conservation Committee (Burrows *et al.*, 2014). A synopsis of kelp habitats in the English Channel indicated a declining trend (Yesson *et al.*, 2015), in common with the kelp habitat in neighbouring Brittany (Davoult *et al.*, 2011). Range projections for the kelp *Laminaria digitata* under a warming climate over the next

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[19] http://www.biomara.org/ accessed 27/4/15

[20] http://www.supergen-bioenergy.net/ accessed 27/4/15

[21] http://www.bbsrc.ac.uk/news/industrial-biotechnology/2015/150327-pr-biotechnology-funding-boost-for-uk-projects/ accessed 11/05/2015

century suggest a strong northwards shift of this important species and a possible loss to the south marine plan areas *(*Raybaud *et al.*, 2013).

As shown in section 2.3.3 there are areas in which the over-abundance of opportunistically-growing green seaweeds are a major problem. Thus, in addition to seaweed farming, the collection of opportunistic algae (mainly green seaweed which grows prolifically with high levels of nutrients) can also be viewed as a bioremediation solution to be considered in policy. Areas with severe eutrophication problems such as Venice Lagoon and the northern bays of Brittany have implemented harvesting measures to remove the unwanted algal biomass, and with the biomass, a substantial amount of nitrogen. At its peak, 40,000 tonnes of green algae per year were removed from Venice Lagoon before nutrient reduction eutrophication measures were introduced to control the problem at source. Similarly, Troell *et al.* (2005) showed the potential of using algae to remove nutrients from the Swedish west coast as a response to controlling the symptoms of eutrophication. The LIFE project ALGAE[22] (1997-2001) tested technologies for removing floating macroalgae and its use in fertiliser, biogas, paper and cellulose production. While the results were described as meagre, the techniques were shown to have potential as a remediation tool. The project concluded that the techniques were required when on-land nutrient reduction methods have reached their limit.

The Environment Agency commissioned research into methods for collecting the algal mats from areas such as Poole Harbour as a means of removing this highly visible visual indicator of eutrophication (Capuzzo and Forster, 2014). It was estimated that 15-30 tonnes of nitrogen could be removed from the harbour by harvesting green algae during the summer growth season. If a viable beneficial use could be found for the harvested material, e.g. to produce biogas or animal feedstock, then this removal mechanism could be trialled at sites within the south marine plan areas with similar green algal problems. Harvesting of eutrophication-induced green algal mats on a much larger scale is practised elsewhere by a variety of means such as purpose-built seaweed harvesters or using tractors at low tide (discussed in Capuzzo and Forster, 2014). Even if the amount of nitrogen which could be permanently removed in this manner is small relative to the requirement for a total reduction of more than 400 tonnes annually, a potential benefit of this type of bioremediation would be to restore the natural denitrification function (by the sediment microbial community) of intertidal areas by removing the smothering algal mats under which conditions are completely anoxic.

A further type of seaweed-based bioremediation would be to increase the availability of suitable substrata for seaweed growth within the photic zone. This could be done by modifying the design of artificial structures such as coastal defences and wind turbines so that the maximum ecological benefit in terms of water quality is obtained (Airoldi *et al.,* 2005). 'Bio-blocks' developed by the URBANE project[23] could allow additional seaweed biomass to develop in this way.

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[22] http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=1399&docType=pdf accessed 15/5/15

[23] http://urbaneproject.org/project, accessed 11/05/2015

Bioremediation summary: Farmed macroalgae (e.g. *Laminaria*, *Palmaria*)

Positive attributes:

- Moderate nutrient (nitrogen, phosphorus) assimilation capacity
- High removal capacity for heavy metals and other chemical pollutants
- Aquaculture practices beginning in the UK
- Local species are available
- Potential for medium to high-value products from seaweed processing
- Structure of seaweed farm provides additional habitat and biodiversity benefits
- Local employment

Negative attributes

- Seaweed farming requires more space than bivalve aquaculture
- High and constant management requirement
- Declining local seaweed stocks suggests an unfavourable environment
- Dedicated seeding facility on land required

Bioremediation summary: mechanised collection of opportunistically-growing macroalgae e.g. *Ulva*

Positive attributes:

- Measurable removal of nitrogen from known problem areas
- High removal capacity for heavy metals and other chemical pollutants
- Existing technology available or can be converted from marine litter harvesters
- Immediate improvement in local environmental conditions
- Potential for low to medium-value products from seaweed processing
- Local employment

Negative attributes

- Need sorting facilities to receive harvested material
- Disturbance of birds by collection activities

Bioremediation summary: provision of additional seaweed habitat

Positive attributes:

- Low level nutrient and hazardous chemical removal during seaweed growth season
- Moderate improvement in local environmental conditions
- Potential for recreational sea angling and diving around new structures
- Local employment

Negative attributes

- Difficult to quantify the nitrogen storage
- Expensive
- Limited spatial scale
- Unknown outcomes of competition on artificial surfaces (e.g. seaweeds versus barnacles versus mussels)
- Possible stepping stone for non-native species

The assigned performance, feasibility and cost efficiency scores for three seaweed-based bioremediation options identified as potentially suitable for bioremediation are summarised in Figure 13, further information on each option summarised in Table 16 to Table 18 and the sustainability scores are summarised in Table 19.

Figure 13: Bioremediation performance, feasibility (technical and ecological) and estimated cost for macroalgal-based approaches.

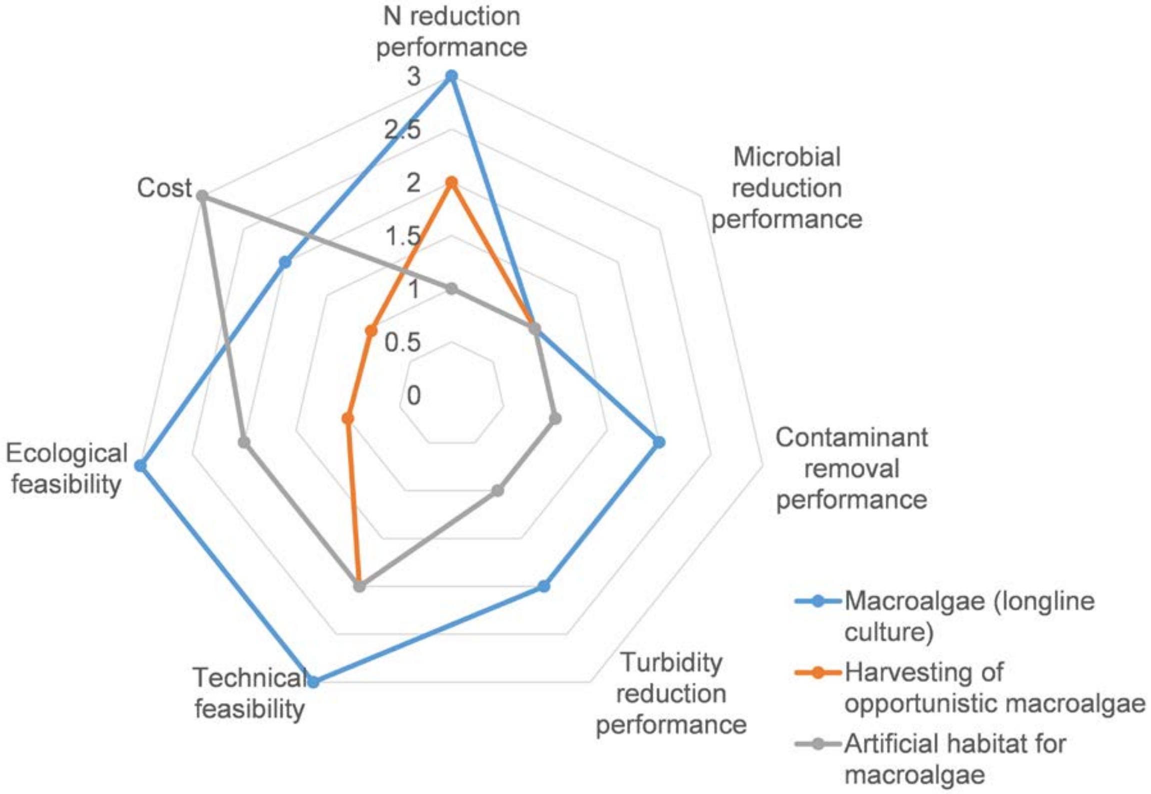

Table 16: Potential bioremediation option: macroalgal rope cultivation.

<table>
<tr><th colspan="6">Species: Native macroalgae. Option: rope culture</th></tr>
<tr><td>General description</td><td colspan="5">Macroalgal culture using long-lines is an established aquaculture method but not widely practiced in the UK. Long-line culture requires surface floats and seabed moorings. Strings or droppers, coated in propagules, are suspended from the long-lines. Macroalgal biomass is routinely harvested and either used for food additives or biofuel production. Native macroalgae such as *Gracilaria* spp. and *Palmaria* spp. are all suitable species for food/food additive production. *Laminaria* spp. and *Ulva* spp. are suitable for biofuel production (biogas or alcohol-based fuels).</td></tr>
<tr><td>Option details</td><td>**Apparatus**
• Surface long-lines with moorings
• Boating and processing infrastructure required</td><td colspan="3">**Management**
• Inputs: lines coated in spores (hatchery-sourced)
• Established aquaculture management practices exist for some species, e.g. *Gracilaria* spp. and *Palmaria palmata*
• Moderate to high level of management required through culture period
• Direct commissioning or industrial incentivisation</td><td>**Locational requirements**
• Very sheltered inshore locations with depth greater than 10 m.
• Surface and seabed area required
• UK-wide</td></tr>
<tr><td>Technical considerations</td><td colspan="2">**Strengths**
• Greater access to larger areas
• Algal long-line culture well established (although not practiced much in the UK)
• Easy to relocate or remove
• Job creation
• Climate change resistant
• Disease resistant species
• Marketable products for consumption or use as a biofuel</td><td colspan="2">**Weaknesses**
• Significant management required throughout/overall high operating costs
• Long-lines reduce site access, i.e. navigational restrictions
• Hatchery facilities to produce ‘seeded’ strings may be limiting</td><td>**Technical feasibility**
3</td></tr>
<tr><td>Economic/spatial requirements</td><td>**Initial costs**
3</td><td>**Ongoing costs**
3</td><td>**Marketable products**
3</td><td>**Area**
2</td><td>**Overall cost**
2</td></tr>
<tr><td>Bioremediation considerations</td><td colspan="2">**Strengths**
• Moderate nutrient and high contaminant removal via harvesting
• Moderate-large evidence base on nutrient uptake and growth rates
• Greater potential for spatial scaling</td><td colspan="3">**Weaknesses**
• Harvesting of biomass is the only mechanism of nutrient removal
• Microbial bioremediation poor
• Turbidity reduction through water baffling only</td></tr>
<tr><td>Bioremediation performance</td><td>**N reduction**
3</td><td>**Microbial reduction**
1</td><td colspan="2">**Contaminant reduction**
2</td><td>**Turbidity reduction**
2</td></tr>
</table>

<table>
<tr><th colspan="4">Species: Native macroalgae. Option: rope culture</th></tr>
<tr><td>Environmental benefits</td><td colspan="3">The combination of a very high stocking biomass, three-dimensional distribution of biomass within the water column (although within the photic zone) and the absence of excreted products suggest that this option can significantly improve nutrient-related, and to a lesser extent contaminant-related, water quality issues around and down-stream of bioremediation sites. The removal of inorganic N is likely to be high due to the combination of high stocking biomass throughout the water column in the photic zone and high growth rates. The absence of biodeposits reduces the potential for N removal by burial and denitrification but also reduces the impact of localised organic enrichment of sediments. Macroalgal growth will remove nutrients used by phytoplankton, thereby reducing the potential for eutrophication and partially improving water clarity. Reduced turbidity will increase light penetration that may indirectly increase microbial reduction. Contaminant removal is related to the surface area:volume ratio as no active filtration is undertaken.
At the site-scale, bioremediation performance, and subsequent improvement in water quality, will depend on (i) the stocking biomass, (ii) contact with the water column (surface area:volume ratio), (iii) the duration of contact with the water body (residence time or current speeds), (iv) concentration of the contaminant (proximity of the bioremediation site to the source of the water quality issue), (v) rate of removal mechanisms (filtration, growth rate and frequency of harvests, rate of biodeposit burial and denitrification) and (vi) rate of returning processes (excretion, mortality, resuspension and nitrification).</td></tr>
<tr><td rowspan="2">Ecological considerations</td><td>Strengths</td><td>Weaknesses</td><td>Ecological feasibility</td></tr>
<tr><td>• Native species
• Long-line structures may provide mid-water habitat
• Seabed impact minimal</td><td>• Loss of existing benthic habitat within the footprint of the moorings</td><td>3</td></tr>
<tr><td>Limitations, public support and knowledge gaps</td><td colspan="3">Limitations for the use of this option for bioremediation are related to (i) the high initial costs for long-line moorings, (ii) access to a sufficient area of sheltered waters near the source of the water quality issue and (iii) the high on-going maintenance effort/costs to clean and harvest material. Based on the visual impact of large areas of long-lines and impact of navigation, public support for this option is estimated to be moderate.
Knowledge gaps that contribute to the uncertainty of bioremediation performance include (i) studies documenting observed bioremediation potential for macroalgae grown on ropes and (ii) estimated area and costs for tackling specific loadings of nutrients.</td></tr>
<tr><td>Potential impacts on ecosystem services and societal benefits</td><td colspan="3">Rope cultivation of macroalgae results in a significant potential positive effect on two intermediate supporting ecosystem services (primary production and nutrient cycling) and two final ecosystem services in relation to one provisioning service (algae and seaweed) and one regulating service (clean water). No potential significant positive effects on ecosystem goods/benefits were identified, with 6 positive effects and 2 negative effects identified, resulting in a low overall score (14%).</td></tr>
<tr><td>Overall assessment</td><td colspan="3">This option relies on established long-line cultivation methods for macroalgae. Nutrient removal is via frequent harvesting of material only. Some harvested algal material has a high market value and may have potential for biogas, cellulose and fertiliser production. This bioremediation option is unsuitable for turbidity and microbial reductions. It is relatively benign ecologically but requires a very high management effort to maintain the long-lines. Availability of sheltered locations may also be limiting.</td></tr>
</table>

Table 17: Potential bioremediation option: harvesting of opportunistic macroalgae.

<table>
<tr><th colspan="8">Species: Opportunistic macroalgae. Option: harvesting</th></tr>
<tr><td>General description</td><td colspan="7">Certain species of native macroalgae (e.g. <i>Enteromorpha</i> spp.) bloom rapidly in high nutrient conditions. In some areas, this results in the accumulation of large quantities of biomass termed ‘Green Tides’. The macroalgal biomass can accumulate on beaches or as large floating rafts. Hypoxia and excessive organic enrichment can occur within the footprint of these accumulations, thereby having an impact on established benthic communities. The large quantities of decomposing biomass also impacts on public use and perception of intertidal areas. This bioremediation option suggests the harvesting of macroalgal biomass following a green tide. The removal of biomass harvests nutrients that would potentially be returned to the system following decomposition and reduces the impact of hypoxia, enrichment and/or decomposition.</td></tr>
<tr><td>Option details</td><td colspan="2">Apparatus
• Specialist mechanical removal equipment
• Facilities to process biomass</td><td colspan="4">Management
• Rapid response to the appearance of a green tide
• New methods potentially required for the careful collection and disposal of material
• Direct commissioning
• Biomass can be processed into biofuels or used for anaerobic digesters</td><td>Locational requirements
• Location and volume determined by green tide
• UK-wide</td></tr>
<tr><td>Technical considerations</td><td colspan="2">Strengths
• Green tide removal valued by public
• Process of biomass removal fairly straight-forward
• No ongoing management requirement between removal bouts
• Marketable products for consumption or use as a biofuel</td><td colspan="4">Weaknesses
• Volume of green tide biomass dictates bioremediation potential
• Efficiency of extraction depends on accessibility (access or substrata type) and how concentrated the green tide biomass at a site
• Specialist machinery might be required to reduce physical disturbance</td><td>Technical feasibility
2</td></tr>
<tr><td>Economic/spatial requirements</td><td>Initial costs
1</td><td>Ongoing costs
2</td><td colspan="2">Marketable products
2</td><td colspan="2">Area
2</td><td>Overall cost
1</td></tr>
<tr><td>Bioremediation considerations</td><td colspan="2">Strengths
• Bulk biomass removal provides a clear and tangible extraction of nutrients</td><td colspan="5">Weaknesses
• Remediation of extreme consequences of poor water quality
• Sporadic events
• Harvesting of biomass is the only mechanism of nutrient removal
• No suspended microbial bioremediation
• No turbidity reduction – in fact, operations may briefly increase local turbidity
• Evidence base for option small</td></tr>
<tr><td>Bioremediation performance</td><td colspan="2">N reduction
2</td><td>Microbial reduction
1</td><td colspan="2">Contaminant reduction
1</td><td colspan="2">Turbidity reduction
1</td></tr>
</table>

<table>
<tr><th colspan="4">Species: Opportunistic macroalgae. Option: harvesting</th></tr>
<tr><td>Environmental benefits</td><td colspan="3">The accumulation of large quantities of harvestable biomass provides an easy bulk removal of nutrients from marine ecosystems. The harvesting both remediates the *in situ* impact of green tides and removes nutrients that could sustain eutrophication following the localised decomposition. However, this option targets the extreme manifestations of water quality issues and only partially addresses source issues. Contaminant removal is related to the surface area:volume ratio as no active filtration is undertaken.
At the site-scale, bioremediation performance, and subsequent improvement in water quality, will depend on (i) the quantity of biomass removed, (ii) the impact of the removal operation and (iii) the location and hence localised concentration of contaminants.</td></tr>
<tr><td>Ecological considerations</td><td>**Strengths**
• Rapid removal of biomass will reduce the impact of green tides</td><td>**Weaknesses**
• Machinery required for biomass removal may impact existing habitats</td><td>**Ecological feasibility**
1</td></tr>
<tr><td>Limitations, public support and knowledge gaps</td><td colspan="3">Limitations for the use of this option for bioremediation are related to (i) the access and ability to extract green tide biomass, (ii) the ability to respond quickly to green tide events and (iii) balancing the physical impacts of the removal process with the benefits of nutrient removal. Based on the visual impact of green tides and the impact on the underlying seabed, public support for this option is estimated to be high.
Knowledge gaps that contribute to the uncertainty of bioremediation performance include (i) studies documenting observed bioremediation potential for the harvesting of green tide biomass and (ii) estimates of biomass removal, and associated costs, required to significantly reduce nutrient loads.</td></tr>
<tr><td>Potential impacts on ecosystem services and societal benefits</td><td colspan="3">With respect to ecosystem service provision, harvesting opportunistic macroalgae resulted in two potential significant positive effects in relation to biological control and the provision of algae and seaweed. A number of significant positive effects on ecosystem goods/benefits were identified including the provision of fertiliser and biofuels, waste burial / removal / neutralisation, tourism and nature watching, aesthetic benefits and health benefits, resulting in an overall high goods/benefits score (50%). The only potential negative effects identified were in relation to supporting intermediate ecosystem services (primary production, larval and gamete supply, and nutrient cycling) as this bioremediation options actively removes biological material from the system.</td></tr>
<tr><td>Overall assessment</td><td colspan="3">This option targets the consequences of poor water quality. However, bulk removal of macroalgal biomass represents a tangible removal of nutrients that may otherwise remain in the marine environment. There is the potential for commercial products such as biogas or fertiliser production although the feasibility of this will depend on the ability of machinery to easily extract large volumes of biomass without a significant impact on the underlying habitat.</td></tr>
</table>

Table 18: Potential bioremediation option: provision of artificial habitat for macroalgae.

<table>
<tr><th colspan="7">Species: Native macroalgae Option: substrata augmentation</th></tr>
<tr><td>General description</td><td colspan="6">This option builds on established macroalgal cultivation methods to enhance the availability of hard substrata for colonisation and growth. The enhancement provision of hard substrata for macroalgal growth is the basis for the production of <i>Laminaria</i> spp. in many countries.</td></tr>
<tr><td>Option details</td><td colspan="3">Apparatus
• Artificial substrata placed within the photic zone</td><td colspan="2">Management
• Methods will draw upon the artificial reef literature
• Little ongoing management required after placement
• Direct commissioning of projects</td><td>Locational requirements
• Sheltered inshore locations
• Photic zone
• Soft sediment substrata
• UK-wide</td></tr>
<tr><td>Technical considerations</td><td colspan="3">Strengths
• Extension of existing work on artificial reefs
• No management requirement after establishment
• Long-term and self-sustaining option</td><td colspan="2">Weaknesses
• Spatially constrained to the area of seabed within the photic zone
• Requires sheltered areas to favour macroalgae
• Very high initial cost</td><td>Technical feasibility
2</td></tr>
<tr><td>Economic/spatial requirements</td><td>Initial costs
3</td><td colspan="2">Ongoing costs
1</td><td>Marketable products
1</td><td>Area
3</td><td>Overall cost
3</td></tr>
<tr><td>Bioremediation considerations</td><td colspan="2">Strengths
• Moderate-large evidence base on nutrient uptake, growth and trophic transfer</td><td colspan="4">Weaknesses
• Absence of harvesting reduces nutrient removal
• Biomass consumption in situ may return a large component of the nutrients to the water column
• Microbial bioremediation poor
• Turbidity reduction through water baffling only</td></tr>
<tr><td>Bioremediation performance</td><td colspan="2">N reduction
1</td><td colspan="2">Microbial reduction
1</td><td>Contaminant reduction
1</td><td>Turbidity reduction
1</td></tr>
<tr><td>Environmental benefits</td><td colspan="6">Additional macroalgal biomass will absorb inorganic sources of N that would otherwise be available for phytoplankton production. However, without harvesting, N is merely retained within biomass. Physical erosion, grazing and mortality will return some of the stored N to the system, although some of this will be buried or converted to secondary biomass.
Macroalgal growth will remove nutrients used by phytoplankton, thereby reducing the potential for eutrophication and partially improving water clarity. Reduced turbidity will increase light penetration that may indirectly increase microbial reduction. Contaminant removal is related to the surface area:volume ratio as no active filtration is undertaken.
At the site-scale, bioremediation performance, and subsequent improvement in water quality, will depend on (i) substrata cover/stocking biomass, (ii) contact with the water (surface area:volume ratio), (iii) the duration of contact with the water body (residence time or current speeds), (iv) concentration of the contaminant (proximity of the bioremediation site to the source of the water quality issue) and (v) rate of returning processes (mortality, grazing and physical erosion).</td></tr>
</table>

Species: Native macroalgae Option: substrata augmentation			
Ecological considerations	**Strengths**	**Weaknesses**	**Ecological feasibility**
	• Native species • High value habitat provision • Trophic stimulation • Ecologically benign	• Loss of existing benthic habitat within the footprint of the substratum structures	2
Limitations, public support and knowledge gaps	Limitations for the use of this option for bioremediation are related to (i) the high initial costs for substratum placement, (ii) access to a sufficient area of sheltered seabed within the photic zone and (iii) intensity of processes returning pooled N and contaminants to the environment. Based on this option being subtidal and being perceived as an augmentation of a natural and valued habitat, public support for this option is estimated to be high. Knowledge gaps that contribute to the uncertainty of bioremediation performance include (i) studies documenting observed bioremediation potential for macroalgae grown on artificial substrata and (ii) estimated area and costs for generating the required biomass pool of nutrients to make a significant impact on water quality.		
Potential impacts on ecosystem services and societal benefits	Positive significant effects on ecosystem services were identified for a number of supporting intermediate services (primary production, nutrient cycling, formation of species habitat, formation of seascape) and one regulating intermediate services (biological control). Potential significant positive effects were also identified for provisioning final services (fish and shellfish, algae and seaweed) and one final cultural ecosystem service (places and seascapes). Potential positive effects were highlighted for 12 out of 14 goods/benefits, resulting in a high overall score of 43%, although none of these were considered to be significant effects.		
Overall assessment	This option relies on the augmentation of natural stands of macroalgae. Although material can be harvested by specialised seaweed-harvesting vessels, it is anticipated the biomass will not be cropped. Although this reduces the N removal potential, it greatly reduces operating costs. Bioremediation potential for (i) suspended microbe reduction, (ii) turbidity reduction and (iii) contaminant reduction is generally low. The placement of substratum structures is limited to the available seabed within the photic zone – this may significantly limit the potential scaling bioremediation operations to the required level.		

Table 19: Compliance of three macroalgae culture and harvesting options for bioremediation with the ten tenets of sustainability and wider ecosystem services scoring (from Annex 2).

Sustainability tenet	Macroalgae rope culture	Macroalgae harvesting	Macroalgae habitat augmentation
Ecologically sustainable	M(1)	L	H
Technologically feasible	H	M(4)	H
Economically viable	H(2)	M(5)	H(7)
Socially desirable/tolerable	M	H	H
Ethically defensible (morally correct)	H	H	H
Culturally inclusive	L(3)	H(6)	M(8)
Legally permissible	H	H	H
Administratively achievable	H	H	H
Effectively communicable	H	H	H
Politically expedient	H	H	H
Overall sustainability score	H	H	H
Goods/benefits score (/28)	**4**	**11**	**12**
Relative goods/benefits score	**Low**	**Moderate**	**Moderate**

H = high, M = moderate, and L = low degree of compliance

(1) May potentially score higher but new habitat is lost as seaweed is cropped/harvested

(2) Products are marketable

(3) Assumes reduced access to local groups (such as local fishers)

(4) Some areas may be inaccessible

(5) Likely to be site-specific (due, for example, to issues of access – such as the need to get heavy plant over dune systems)

(6) Product (collected macro-algae) may have commercial value, such as for use as biofuel

(7) No commercial products

(8) Assessment based on potential change in existing habitat (e.g. a change from a sandy substrate to artificial reef/seaweed bed may have consequent impacts on local fisheries

3.3.3 Seagrasses

There is a growing research and management interest in seagrasses due to their important role as long-term storage sites for fixed carbon. In addition, and due to their sensitivity to environmental degradation, seagrasses are important water quality indicators. The ‘blue carbon’ ecosystem service of seagrass beds is well-documented, but this habitat can also function as an important sink for nitrogen (Welsh *et al.*, 2000). Seagrasses can take up nutrients from the water column and additionally from sediment pore-water via their root system. It is not clear whether rates of denitrification in the root-sediment matrix of seagrass meadows is significant compared to the direct uptake of N (Risgaard-Petersen *et al.*, 1998). Measurements and modelling of bivalve populations, macroalgae and seagrass meadows which co-occurred in a shallow bay indicated that considerable amounts of N were biologically removed by the combined natural sinks (Kohata *et al.*, 2003).

Due to the reduction in turbulence caused by the three-dimensional structure of a dense seagrass meadow, there is considerable capacity for sediment trapping and turbidity reduction. Transplantation experiments in the eastern Wadden Sea showed increased sediment deposition rates in intertidal *Zostera marina* plots. The local sub-species used had an annual growth form, and the deposited sediments were lost when plants died back during the winter. Subtidal *Z. marina* plants survive for many years and would form more stable sites of sediment accumulation.

Seagrass blade material has a strong affinity for certain toxic substances. Dead blades of *Zostera* were found to have an adsorbent capacity for arsenic of similar strength to activated carbon (Pennesi *et al.*, 2012). Living seagrass meadows were also found to have considerable potential for the remediation of sediments contaminated with aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) (Huesemann *et al.*, 2009).

The first consideration for using re-constructed seagrass beds in a bioremediation is that the three seagrass species in the UK are considered to be scarce, with populations stable but not recovering after many years of decline (Jackson *et al.*, 2013). Of the three UK species, dwarf eelgrass *Zostera noltii* is a perennial plant found highest on the shore, often adjacent to lower saltmarsh communities, *Z. marina* is a large perennial with the greatest bioremediation potential, found from the low water mark to a depth of 5 m. The narrow-leaved eelgrass *Zostera marina* var. *angustifolia* is an annual species occurring on the mid to lower shore (Jackson *et al.,* 2013). The lower limit of *Z. marina* corresponds to a depth at which irradiance is reduced to approximately 10% of its surface value. Seagrass beds develop in intertidal and shallow subtidal areas on sands and muds. Marine inlets and bays are the main locations but beds are also present in other areas, such as lagoons and channels, which are sheltered from significant wave action. Although individual seagrass species are not protected, seagrass beds are a Biodiversity Action Plan priority habitat.

The Environment Agency’s South East RBMP (Environment Agency, 2009b) lists Pagham, Chichester, Langstone and Portsmouth Harbours as sites where various *Zostera* species are found. The Poole Harbour management plan lists all three species of eelgrass as present, with *Z. marina* only found in two main areas in the Whitley Lake area, although it is believed there may have been other areas previously colonised (PHSG, 2006). Other sites of extensive seagrass coverage include The Fleet Lagoon, the Exe Estuary, and intertidal areas of The Solent on the north coast of the Isle of Wight.

A more recent Natural England report provides a thorough description of *Zostera* distribution, ecology and management (Jackson *et al.*, 2013). To obtain an estimate of the total seagrass area in the south marine plan areas it is possible to use the OSPAR Habitats spatial dataset released in 2013[24]. The OSPAR layer for *Zostera* has inputs from UK data providers such as the JNCC, Devon Wildlife Trust, Natural England, Torbay Coast and Countryside Trust (TCCT) and contains all of the sites referred to above. The total extent of the seagrass polygons within the south marine plan areas is 1,657 ha which may represent 34% of the total UK seagrass coverage (4,887 ha; Luisetti *et al.*, 2013). The largest single seagrass site, at nearly 1,000 ha, is the subtidal *Z. marina* bed to the south of the Exe estuary recorded by Devon Wildlife Trust / JNCC (Figure 5).

There are signs that the status of seagrass habitats in the UK are starting to improve[25], or at least stabilise after decades of loss (Jackson *et al.,* 2013). However, without further sustained improvements in water clarity and nutrient reductions (Boström *et al.*, 2014), and in the presence of continued direct pressures such as anchoring and propeller scarring, the passive recovery process may be complex and difficult to predict (Soissons *et al.*, 2014). To date, most attempts to actively restore *Zostera* meadows have failed (van Katwijk *et al.*, 2009). For example, none of the European seagrass restoration programs developed by participants of the European Seagrass Restoration Workshop over the last 10 years had been successful. The research field remains active due to the importance of aquatic vegetation in coastal protection *(*Ondiviela *et al.*, 2014), and the focus of seagrass management has switched from active restoration to conservation of remaining areas (Cunha *et al.*, 2012). The experience in North America is somewhat better and enough seagrass restoration studies have been successful to allow an analysis of costings for different plantation methods (Busch *et al.*, 2008).

More research is needed into seagrass ecology and pathology in the UK and specifically in the south marine plan areas before investment can be considered in this habitat for bioremediation purposes. There are still concerns regarding the prevalence and controls of wasting disease, with a suggestion that wasting disease is more prevalent during the positive phase of the Atlantic Multidecadal Oscillation, and the relationship to fishing pressure via top-down control and over-abundance of small fish (Baden *et al.*, 2012).

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[24] Information contained here has been derived from data that is made available under the European Marine Observation Data Network (EMODnet) Seabed Habitats project (*www.emodnet-seabedhabitats.eu*), funded by the European Commission’s Directorate-General for Maritime Affairs and Fisheries (DG MARE).

[25] http://helfordmarineconservation.co.uk/publications/newsletters/eelgrass-the-latest/ accessed 11/5/15

Bioremediation summary: *Zostera marina* restoration

Positive attributes:

- Moderate nutrient (nitrogen, phosphorus) assimilation capacity
- Settlement of suspended sediments reduces turbidity
- Documented removal capacity for heavy metals and other pollutants
- Local species are available
- Restoration of a high-value habitat

Negative attributes

- Many failed restoration attempts in Europe
- Expensive, with hand-planting of seeds or seedlings
- High and constant management requirement
- Moderate status of local stocks suggests an unfavourable environment
- Locations are limited and would need protection from physical abrasion pressure

The assigned performance, feasibility and cost efficiency scores for seagrass-based bioremediation options are provided in Figure 14 with other angiosperm-based approaches. Further details for seagrass options are summarised in Table 20 and the sustainability scores are summarised in Table 21).

Table 20: Potential bioremediation option: *Zostera marina* restoration.

<table>
<tr><th colspan="7">Species: <i>Zostera marina.</i> Option: restoration</th></tr>
<tr><td>General description</td><td colspan="6">Seagrass restoration techniques have been extensively trialled throughout the world. Most restoration methods are only able to provide modest areas of restoration. The translocation of seagrass vegetation has been presumed to be the primary method for this bioremediation option.</td></tr>
<tr><td>Option details</td><td>Apparatus
• Translocated seagrass</td><td colspan="3">Management
• Once placed, no further management is anticipated although site production will be required until the seagrass beds become established.
• Implemented through direct commissioning</td><td colspan="2">Locational requirements
• Probably constrained to historical range (sheltered, soft sediment substrata in the shallow subtidal, i.e. 0 – 5 m)
• UK wide</td></tr>
<tr><td>Technical considerations</td><td>Strengths
• Surface waters free of apparatus
• No management requirement after establishment
• Long-term option
• Self-sustaining
• Disease resistant species</td><td colspan="3">Weaknesses
• Although previously trialled, seagrass restoration methods are unreliable and currently only appropriate for smaller, site-scale restoration – spatial scaling may be problematic
• Success dependent on high levels of existing water quality, i.e. this option only becomes suitable following other bioremediation methods
• The supply of material for transplantation may also limit the spatial extent of bioremediation activity
• Supply of adults for translocation may diminish ecosystem services elsewhere
• Boundary layer constraints on mixing with the entire water column
• High initial cost</td><td colspan="2">Technical feasibility
1</td></tr>
<tr><td>Economic/spatial requirements</td><td>Initial costs
3</td><td>Ongoing costs
1</td><td>Marketable products
1</td><td>Area
3</td><td colspan="2">Overall cost
3</td></tr>
<tr><td>Bioremediation considerations</td><td colspan="2">Strengths
• High nutrient and contaminant removal and storage (burial within the sediment)
• High carbon capture potential
• Rhizomes and abundance of infaunal community may increase denitrification potential
• Moderate evidence base</td><td colspan="4">Weaknesses
• Microbial bioremediation poor
• Turbidity reduction through water baffling only
• Success dependent on high levels of existing water quality, i.e. this option only becomes suitable following other bioremediation methods
• Dynamic patchiness of seagrass beds (cycles of accumulation and subsequent erosion) may diminish some bioremediation mechanisms.</td></tr>
<tr><td>Bioremediation performance</td><td>N reduction
2.5</td><td colspan="2">Microbial reduction
1</td><td colspan="2">Contaminant reduction
2</td><td>Turbidity reduction
2</td></tr>
</table>

<table>
<tr><th colspan="4">Species: <i>Zostera marina.</i> Option: restoration</th></tr>
<tr><td>Environmental benefits</td><td colspan="3">Additional seagrass biomass will absorb inorganic sources of N from the sediment that would otherwise be returned to the water column. The reduction of the flux of nutrients for the sediment to the water column will reduce phytoplankton production and potential turbidity. The baffling of water motion also induces the settlement of suspended particles and reduces resuspension. However, without harvesting, N is merely pooled within seagrass/epiphyte biomass. Physical erosion, grazing and mortality will return some of the pooled N back to the system, although some of this will be buried or converted to secondary biomass. It is likely that the accumulation and burial of detrital material will be the primary route of N removal.

Contaminant removal is related to the surface area:volume ratio as no active filtration is undertaken.

At the site-scale, bioremediation performance, and subsequent improvement in water quality, will depend on (i) standing biomass/extent, (ii) contact with the water (SA:volume ratio), (iii) the duration of contact with the water body (residence time or current speeds), (iv) concentration of the contaminant (proximity of the bioremediation site to the source of the water quality issue) and (v) rate of returning processes (mortality, grazing and physical erosion).</td></tr>
<tr><td>Ecological considerations</td><td>Strengths
• Native species
• Species of conservation interest
• Provision of additional high value biogenic habitat
• Other ecosystem services provided</td><td>Weaknesses
• Habitat condition susceptible to fluctuations in water quality
• Habitat sensitive to physical damage
• Loss of existing benthic habitats
• Damage of existing <i>Z. marina</i> beds if material has to be translocated</td><td>Ecological feasibility
3</td></tr>
<tr><td>Limitations, public support and knowledge gaps</td><td colspan="3">Limitations for the use of this option for bioremediation are related to (i) the high initial costs for translocation and establishment, (ii) the supply of seagrass material from donor sites, (iii) the poor level of translocation success and (iv) intensity of processes returning pooled N and contaminants to the environment.

Based on this option being subtidal and being perceived as an augmentation of a natural and valued habitat, public support for this option is estimated to be very high.

Knowledge gaps that contribute to the uncertainty of bioremediation performance include (i) the presence of a reliable and successful seagrass translocation method and (ii) estimated area and costs for generating the required biomass pool of nutrients to make a significant impact on water quality.</td></tr>
<tr><td>Potential impacts on ecosystem services and societal benefits</td><td colspan="3">This bioremediation option offers a number of potentially significant effects (++) in relation to four intermediate supporting services (primary production, nutrient cycling, formation of species habitat, formation of seascape), two intermediate regulating services (biological control, carbon sequestration), two final provisioning services (fish and shellfish, algae and seaweed) and one final cultural service (places and seascapes). With respect to goods/benefits, potential significant positive effects (++) have been identified for tourism and nature watching and aesthetic benefits, resulting in a moderate overall score (39%).</td></tr>
<tr><td>Overall assessment</td><td colspan="3">Seagrass restoration could only occur once certain water quality issues have been resolved. Documented seagrass restoration projects have a high failure rate. Nutrient and pollutant removal capacity is great although much reduced for microbial and turbidity reduction. The habitat generated has a high ecological value. This bioremediation option, once established, is a long-term, self-sustaining option.</td></tr>
</table>

Table 21: Compliance of creation of seagrass beds for bioremediation with the ten tenets of sustainability and wider ecosystem services scoring (from Annex 2).

Sustainability tenet	Compliance
Ecologically sustainable	H
Technologically feasible	L(1)
Economically viable	L(2)
Socially desirable/tolerable	H
Ethically defensible (morally correct)	H
Culturally inclusive	M(3)
Legally permissible	H
Administratively achievable	H
Effectively communicable	H
Politically expedient	H
Overall sustainability score	M / H
Goods/benefits score (out of 28)	**10**
Relative goods/benefits score	**Moderate**

H = high, M = moderate, and L = low degree of compliance

1) Not good as an initial measure; likely to require additional water quality improvements to have brought about positive changes before it could be successfully deployed

(2) Labour intensive and (spatially) extensive programmes needed; areas where the method may be successfully deployed may also be limited (e.g. by suitable substrate; water clarity through the photic zone)

(3) Establishment of seagrass beds may restrict future provision of anchorage sites – impacting on commercial or recreational use (e.g. potting) or recreation (e.g. yacht anchorage)

3.3.4 Managed realignment (saltmarsh) and *Phragmites* reedbeds

The Environment Agency currently predict an increase in sea level rise e.g. in the Exe Estuary (Environment Agency, 2013) of up to 0.75 m by 2060, and up to 1 m by 2110. This will significantly increase the risk of flooding in coastal areas and the role of coastal defences will become increasingly important.

In areas where large-scale land claim has historically occurred for urban development, coastal defence is particularly important as a way of protecting the residents and reducing the need for necessary financial compensation from relocation costs and rebuilding fees. In recent decades, there has been a significant change in the way coastal defence is undertaken. Artificial defences are now being replaced by more cost effective and sustainable methods, such as managed realignment (Garbutt *et al.*, 2006; Doody, 2012).

Managed realignment aims to develop and establish various habitats such as mudflat and saltmarsh, in a bid to stabilise sediments and reduce the rate of coastal erosion (French, 2006). The existing artificial sea wall is removed and rebuilt further in-land, and the area of land that was previously protected by the old sea wall is allowed to permanently flood. Over time this develops into areas of saltmarsh, mudflat, reed bed and grassland, creating a new area of intertidal wetland habitat. It is a widely accepted concept that coastal wetlands, and saltmarshes in particular, absorb considerable wave energy thus preventing water travelling too far inland, and alleviating the effect of eroding wave action on hard coastal defence structures (Doody, 2012; Möller *et al.*, 2001; Morris, 2012; Pethick, 1992). Managed realignment schemes in the UK and elsewhere have shown that relatively little pre- or post- breach management, allowing land to flood will quickly produce intertidal mudflats that are colonised by saltmarsh plants (French *et al.*, 2000; Wolters *et al.*, 2005). Although coastal defence may be the driving mechanism behind most managed realignment schemes, the subsequent habitats created can have an important role to play in the remediation of aquatic pollutants.

Response and recovery of marshes to negative human influences such as dredging, the discharge of wastes and the spillage of oils or other toxic chemicals is generally slow under natural unaltered conditions, and remediation can be accelerated by the addition of vegetated habitat (Broome *et al.*, 1988). Remediation primarily involves reducing soil erosion and sedimentation, and therefore reducing turbidity in the water column, and sequestration of pollutants (retention of diffuse nutrient and faecal pollutants into accumulating sediments) though nutrient and carbon storage (Burden *et al.*, 2013). In addition, at a global scale, wetlands provide the largest terrestrial carbon store, and therefore provide an important mechanism for the remediation of excess carbon and nutrients in the system. Restored saltmarshes have the potential to contribute more to carbon sequestration per unit area than the much researched restoration of degraded peatlands (Burden *et al.*, 2013).

As a result of increasing population and increasing human activities, saltmarshes and other coastal habitats have been subjected to increasing nitrogen loading, often leading to eutrophication (Lillebø *et al.*, 2005). Therefore, nutrient cycling by saltmarshes is important to the ecological functioning of wetland ecosystems (Sousa *et al.*, 2008). However, it is necessary to determine whether this constitutes short or long term storage depending on the relative build-up of plant material and the subsequent release of nutrients following degradation of the organic matter.

Carbon (C) and N sequestration rates in the cord grass *Spartina maritima* in the Odiel marshes nature reserve, near Seville, Spain have been assessed as support for habitat restoration strategies that may offset negative aspects of eutrophication in wetland ecosystems (Curado *et al.*, 2013). In a restored saltmarsh area which borders the main channel of the Huelva estuary, Andalucia, the sediment carbon content was approximately 13 mg C g^{-1} and sediment N content was approximately 1.8 mg N g^{-1}. The highest carbon content for *S. maritima* was recorded in leaves and stems (approximately 420 mg C g^{-1}) and the lowest in roots (361± 4 mg C g^{-1}). *S. maritima* also concentrated more N in its leaves (31±1 mg N g^{-1}) than in other parts of the plant (Curado *et al.*, 2013). In addition, 2.5 years after habitat restoration, *S. maritima* was capturing nitrogen and therefore potentially reducing eutrophication. The concentrations of carbon and N contents in sediments, and the relative coverage of the cordgrass (62%), as well as low below-ground biomass, suggest restored marshes can sequester more carbon and N than is presented here. This would be based on *S. maritima* plantations in low marshes replacing either bare sediments, or even invasive populations of *Spartina densiflora* and therefore increasing the carbon and N sequestration capacity of the marsh by increasing biomass production and accumulation (Curado *et al.*, 2013).

In addition, studies have highlighted the potential of phytoremediation, the use of vegetation for the *in situ* treatment of soil and sediment contaminated by petroleum hydrocarbons (Lin and Mendelssohn, 1996, 1998; White *et al.*, 2006). For example, the potential for the rush species *Juncus roemerianus* as a tool for remediation of diesel contamination was discussed by Lin and Mendelssohn (2009). Here, *J. roemerianus* was transplanted into saltmarsh sediment contaminated with diesel fuel at concentrations between 0 and 640 mg diesel g^{-1} dry sediment. Plant tolerance was estimated between 160 and 320 mg g-1, but at 40 mg g^{-1}, *J. roemerianus* enhanced oil degradation, as concentrations of residual total petroleum hydrocarbons, polycyclic aromatic hydrocarbons and n-alkanes in the sediments planted with *J. roemerianus* were significantly lower than total petroleum hydrocarbons, polycyclic aromatic hydrocarbons and n-alkanes concentrations in sediments containing no plants after 1 year (Lin and Mendelssohn, 2009).

Phytoremediation is also well documented in relation to reed beds. One of the most well documented instances of this is in relation to the Wheal Jane coal and metal mine, which accidentally released large quantities of highly acidic, metal-rich mine waters into the Carnon River and Fal Estuary, South West England in 1992 (Younger *et al.*, 2004). Although there had been instances of pollution occurring from abandoned coal and metal mines previously, this was on a much larger scale, and heightened awareness of problems associated with acid mine drainage (Whitehead *et al.*, 2005).

As part of an overall strategy to determine a long-term treatment option for acid mine drainage, a passive treatment plant was constructed with a remediation scheme employed to counter the effects of this pollutant (Whitehead and Prior, 2004). The plant consists of three separate systems, each containing artificial wetland cells consisting of aerobic reed beds designed to remove iron and arsenic, an anaerobic cell and rock filters; this represents the largest European experimental facility of its kind. Since construction of the treatment plant in 1994, extensive data have been collated on water quality, geochemical and biological parameters, in order to improve understanding and inform future bioremediation initiatives (Whitehead *et al.*, 2005).

As part of the passive treatment component, the aerobic system was designed to remove iron as ferric hydroxide/oxyhydroxide, with arsenic removal by co-precipitation and adsorption onto the iron precipitate (Whitehead *et al.*, 2005). The key parameters in the aerobic cell design were oxygen availability and pH maintenance, with sufficient oxygen for the oxidation of ferrous iron obtained via diffusion from the atmosphere. This is achieved by maintaining a water depth <300 mm within the aerobic system, so oxygen can be transported via the reeds to the rooting zone (Whitehead *et al.*, 2005). By using reedbed as a key stage of the passive treatment system, monthly samples showed that on average, the removal rate of iron is 4 g m^{-2} day^{-1}, which although less than half the slowest rate encountered commonly in aerobic wetlands receiving neutralised ferruginous mine waters (Younger *et al.*, 2004), this still contributes to >90% of iron removal from the polluted mine water inflow (Whitehead *et al.*, 2005).

Phytoremediation using saltmarsh vegetation has the potential to be particularly useful in wetland environments, as it provides a less intrusive clean-up method in comparison to conventionally mechanical approaches, which tend to re-suspend sediments and disturb nutrient or carbon sinks. An important question about the creation of saltmarsh habitat is the expected lifetime of the restored or newly-created site, and this requires an understanding of natural saltmarsh dynamics.

The tidal common cord-grass *Spartina anglica* is a notable component of saltmarshes. As *S. anglica* can occur under a broad range of abiotic conditions, it generally out-competes other common saltmarsh species, and is now dominant throughout European saltmarsh habitats (Nehring and Hesse, 2008). Therefore, it can be a good indication of whether saltmarsh habitat is developing.

Poole Harbour appears to have the best-documented recording showing the evolution of *S. anglica*. It has also been the source of plants to many other national and overseas areas for land-claim and coastal defence purposes. The plant began to spread around the harbour during the 1890s and by 1924 it had covered 800 ha (63% of coverage in this period). Currently the species only covers 400 ha (Raybould, 1997). According to Oliver (1925; in Raybould, 1997) once the plant was established in the area, it spread several feet per year but only formed sward extensions in the upper reaches of the harbour from Fitzworth Point to Hamworthy. After reaching its maximum extent in 1924 erosion commenced in the following years at the edges of the marshes. Between 1924 and 1952 *Spartina* spp. decreased at some sites but continued to increase in others although in general, there was a recession in sward extent in most areas. Between 1981 and 1994 marshes were lost because of land-claim for the Holes Bay road (Raybould, 1997; Gray *et al.*, 1991).

Spartina spp. has not only died-back in the fringes of the marsh but also in the main body of the sward, a condition not very well understood but which seems to be associated with badly drained, highly anaerobic soils with high concentrations of sulphide ions. The latter, together with the lack of oxygen, are toxic to the *Spartina* spp. rhizomes (Gray *et al.*, 1992, and Raybould, 1997). Moreover, such a chemical environment can also increase the potential sequestration of pollutants given that, for example, insoluble metal sulphides will be retained in the reduced (anaerobic) conditions (McLusky and Elliott, 2004).

Another potential reason for the decrease in *Spartina* spp. extent is the invasion/colonisation by other species from the landward edge, e.g. *Phragmites communis*, *Bolboschoenus maritimus*, *Elytrigia atherica*, *Agrostis stolonifera*, *Festuca rubra*, *Puccinellia maritima*, and *Atriplex portulacoides*. It could be therefore inferred that *Spartina* spp. could be creating conditions leading to a succession to higher marsh.

Although saltmarsh creation and restoration are frequently used to replace ecological attributes and values lost when natural wetlands are degraded or destroyed, many sites have shown that ecological functions such as secondary production, species diversity and wetland soil characteristics are slow to develop, and even though macrophyte communities are often quick to colonise, functions in relation to pollutant remediation are generally low within the first decade of creation in comparison to well established saltmarshes (Craft *et al.*, 1999). In addition, it was suggested by Garbutt and Walters (2008) that although saltmarsh plants will colonise formerly re-claimed land quickly upon the renewed tidal regime, saltmarshes differ in species richness, composition and structure from reference communities even 100 years after regeneration. However, in relation to remediation of physical stressors such as sedimentation and associated turbidity, sediment dynamics have been shown to depend on plant cover more than elevation, with extensive saltmarsh plantations behaving in a similar way to natural preserved marshes within 2 years (Curado *et al.*, 2012). Therefore, in terms of remediation of turbidity and sedimentation, saltmarsh provides a reliable solution and rapid results. However, it should not be relied upon for remediation of pollutants within a similar time frame.

Bioremediation summary: Managed Realignment

Positive attributes:

- Productive cycling of carbon and nitrogen.
- Saltmarsh plant colonisation leads to increased sediment stability, and therefore reduction in erosion and sedimentation, and reduced turbidity.
- Benefits associated with saltmarsh plant colonisation known to occur within 2 years.
- Bioremediation performance likely to increase with time.
- Not as destructive as other techniques for removing metals etc.
- More than one aspect of bioremediation addressed.
- Multiple ecosystem services provided by managed realignment site, including cultural services.
- Low management requirements post breach.

Negative attributes

- Unlikely to be as productive as naturally occurring saltmarsh wetland habitats.
- Uncertainties about the implications for the wider estuary/coastal area when

Bioremediation summary: Managed Realignment

disturbing land so close to the shore.

- Not as effective as more ecologically damaging techniques for removing metals and other chemical contaminants.
- Requires loss of terrestrial land, which has associated compensation costs for land owners
- Very little control over how the saltmarsh develops once the site has been breached, other than manually planting species.
- Constraints on where managed realignment can be implemented based on the geography of the coastline.

The assigned performance, feasibility and cost efficiency scores for saltmarsh-based bioremediation options are summarised in, further information on each option summarised in Table 22 and Table 23 and the sustainability scores are summarised in Table 24.

Figure 14: Bioremediation performance, feasibility (technical and ecological) and estimated cost for angiosperm-based approaches.

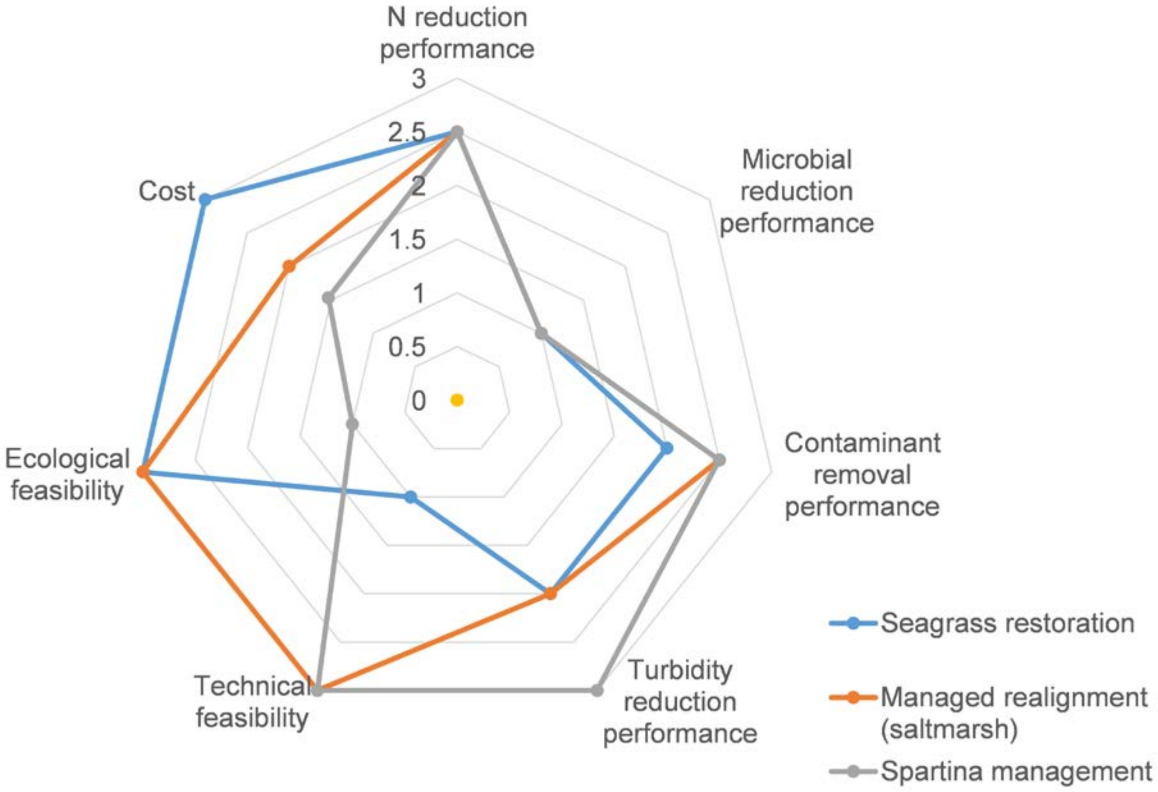

Table 22: Potential bioremediation option: managed realignment.

Species: Native saltmarsh. Option: managed realignment					
General description	This option aims to create areas of mudflat and saltmarsh (*Spartina, Salicornia, Juncus, Phragmites, Scirpus* etc.), usually in order to stabilise sediments and reduce the rate of coastal erosion. This is typically achieved by the removal of the existing artificial sea wall is removed or lowered and rebuilt further in-land. The area of land that was previously protected by the old sea wall is allowed to permanently flood, and over time develops into areas of saltmarsh, mudflat, reed bed and grassland, creating a new area of intertidal habitat for wetland species.				
Option details	**Apparatus**	**Management**			**Locational requirements**
	• Modification of existing sea defences • New sea defences inland	• Established construction and management of realignment sites • Little ongoing management required after placement - once the site is breached, periodic condition assessments of the vegetation species/extents is suggested • Direct commissioning of projects			• Shallow intertidal area to allow flooding to occur naturally • UK-wide
Technical considerations	**Strengths**	**Weaknesses**			**Technical feasibility**
	• Relatively low cost after the initial process • Long-term and self-sustaining option	• Constraints on where managed realignment can be implemented based on geography of coastline. • Management of the area is required post breach (*Spartina*, *Phragmites* etc.) • Requires loss of land, leading to compensation for previous land owner. • Initial costs associated with relocation of hard coastal defences.			3
Economic/spatial requirements	**Initial costs**	**Ongoing costs**	**Marketable products**	**Area**	**Overall cost**
	3	1	1	2	2
Bioremediation considerations	**Strengths**			**Weaknesses**	
	• Reduction in soil erosion and sedimentation, and therefore reduced turbidity • Attenuation of nutrient and carbon enrichment • Little chance of decline in bioremediation performance over time • Strong empirical evidence base on several aspects of saltmarsh acting as a source for bioremediation (although much of it laboratory based) • More than one aspect of bioremediation addressed			• Saltmarsh occurring on managed realignment sites can be slow to develop, and mudflat habitats (which develop first) have lower bioremediation potential • Absence of harvesting reduces nutrient removal • Microbial bioremediation poor	
Bioremediation performance	**N reduction**	**Microbial reduction**		**Contaminant reduction**	**Turbidity reduction**
	2.5	1		2.5	2
Environmental benefits	The use of managed realignment will result both in the removal of N and the accretion and burial of contaminants. As vegetation is not harvested, the main mechanism for N removal is also via burial and denitrification processes. The baffling of water motion also induces the settlement of suspended particles and reduces resuspension. Physical erosion, grazing and mortality will return some of the pooled N back to the system, although some of this will be buried, transported to land or converted to secondary biomass.				

Species: Native saltmarsh. Option: managed realignment			
	At the site-scale, bioremediation performance, and subsequent improvement in water quality, will depend on (i) realignment extent/volume, (ii) contact with the water (surface area:volume ratio), (iii) the duration of contact with the water body (residence time or current speeds), (iv) concentration of the contaminant (proximity of the bioremediation site to the source of the water quality issue) and (v) rate of returning processes (mortality, grazing and physical erosion).		
Ecological considerations	**Strengths** • Creation of habitat for wildfowl and waders (potentially species of conservation interest) • Reduction in coastal erosion • Mitigation of coastal squeeze	**Weaknesses** • Loss of existing terrestrial habitat • Uncertainties about the implications for the wider estuary/coastal area when disturbing land so close to the shore • Very little control over how the saltmarsh develops once the site has been breached	**Ecological feasibility** 3
Limitations, public support and knowledge gaps	Limitations for the use of this option for bioremediation are related to (i) the high initial costs to establish realignment sites, (ii) the availability of suitable terrestrial land for conversion and (iii) intensity of processes returning pooled N and contaminants to the environment. Based on this option generating valued habitat, public support for this option is estimated to be high. Knowledge gaps that contribute to the uncertainty of bioremediation performance include (i) uncertainties about the implications for the wider estuary/coastal area when disturbing land so close to the shore and (ii) estimated area and costs for generating the required biomass pool of nutrients to make a significant impact on water quality.		
Potential impacts on ecosystem services and societal benefits	This option provides the greatest potential for additional ecosystem services and goods/benefits. Potentially significant positive effects have been highlighted for four intermediate supporting ecosystem services (primary production, nutrient cycling, formation of species habitat, formation of seascape), four intermediate regulating ecosystem services (biological control, natural hazard regulation, waste breakdown and detoxification, carbon sequestration), one final provisioning ecosystem service (fish and shellfish), three final regulating ecosystem services (climate regulation, natural hazard protection, clean water) and one final cultural ecosystem service (places and seascapes). This bioremediation option offers potentially significant positive effects on seven goods/benefits (healthy climate, prevention of coastal erosion, sea defence, waste burial / removal / neutralisation, tourism and nature watching, aesthetic benefits, health benefits) resulting in the highest overall score (64%).		
Overall assessment	In a suitable area, managed realignment and the subsequent development of saltmarsh leads to habitats which have a high bioremediation performance and provide numerous ecosystem services including coastal defence. However, initial costs can be high (depending on the extent of the realignment area), and the process has been known to be met with negative views from policy makers and the public, who focus on loss of land (particularly when in use for agriculture), and the short term disturbance caused by the relocation of the defence structure.		

Table 23: Potential bioremediation option: modified *Spartina anglica* management.

<table>
<tr><th colspan="8">Species: <i>Spartina anglica.</i> Option: modified management</th></tr>
<tr><td>General description</td><td colspan="7">This option suggests the modified management of <i>S. anglica</i> to allow greater habitat occupation and duration at a site before bulk removal. The objective is to allow a greater accretion of buried organic matter and silt to occur before the bulk removal of vegetation and underlying deposits. However, as an undesirable (non-native) species, management must be balanced against conservation objectives.</td></tr>
<tr><td>Option details</td><td>Apparatus
• None</td><td colspan="5">Management
• Requires new management practices to balance the competing needs of biological control and bioremediation
• New methods potentially required for the careful collection and disposal of material
• Direct commissioning of projects</td><td>Locational requirements
• Any area with significant quantities of <i>S. anglica</i>
• UK-wide</td></tr>
<tr><td>Technical considerations</td><td>Strengths
• Modification of existing management plans
• Long-term and self-sustaining option</td><td colspan="5">Weaknesses
• Novel and untested management schedule required
• Limited spatial coverage
• Spatial constraints
• Allowable footprint of <i>S. anglica</i> partially dictates bioremediation efficacy
• Volume/frequency of <i>S. anglica</i>/sediment also determines bioremediation potential
• Efficiency of extraction depends on accessibility (access or substrata type) at a site
• Specialist machinery might be required to reduce physical disturbance</td><td>Technical feasibility
3</td></tr>
<tr><td>Economic/spatial requirements</td><td>Initial costs
1</td><td colspan="2">Ongoing costs
2</td><td colspan="2">Marketable products
1</td><td>Area
2</td><td>Overall cost
1.5</td></tr>
<tr><td>Bioremediation considerations</td><td colspan="5">Strengths
• Attenuation of nutrient and carbon enrichment
• Reduced turbidity also increases light penetration and will indirectly induce microbial suppression
• Extremely high potential for silt accumulation and burial
• High denitrification potential
• Strong empirical evidence base on several aspects of saltmarsh acting as a source for bioremediation (although much of it laboratory based)
• More than one aspect of bioremediation addressed</td><td colspan="2">Weaknesses
• Bulk removal of vegetation and accumulated silt will retard bioremediation mechanisms, e.g. denitrification.
• Conservation objections will limit spatial extent and hence bioremediation potential</td></tr>
<tr><td>Bioremediation performance</td><td colspan="2">N reduction
2.5</td><td colspan="2">Microbial reduction
1</td><td>Contaminant reduction
2.5</td><td colspan="2">Turbidity reduction
3</td></tr>
<tr><td>Environmental benefits</td><td colspan="7">The modification of <i>S. anglica</i> management for bioremediation purposes provides a significant removal of N when the vegetation and underlying sediments are removed. Contaminants are also likely to accumulate within the underlying sediments and will also be removed</td></tr>
</table>

<table>
<tr><th colspan="4">Species: <i>Spartina anglica.</i> Option: modified management</th></tr>
<tr><td></td><td colspan="3">during bouts of management. The baffling of water motion also induces the settlement of suspended particles and reduces resuspension. Physical erosion, grazing and mortality will return some of the pooled N back to the system, although some of this will be buried, transported to land or converted to secondary biomass.
At the site-scale, bioremediation performance, and subsequent improvement in water quality will depend on (i) the allowable footprint of <i>S. anglica</i>, (ii) contact with the water (surface area:volume ratio), (iii) the duration of contact with the water body (residence time or current speeds), (iv) concentration of the contaminant (proximity of the bioremediation site to the source of the water quality issue) and (v) rate of returning processes (mortality, grazing and physical erosion).</td></tr>
<tr><td>Ecological considerations</td><td>Strengths
• <i>S. anglica</i> habitat favoured by some species</td><td>Weaknesses
• Displacement of native marsh species
• Intermittent removal of <i>S. anglica</i> and accumulated silt may potentially damaging surrounding habitats</td><td>Ecological feasibility
1</td></tr>
<tr><td>Limitations, public support and knowledge gaps</td><td colspan="3">Limitations for the use of this option for bioremediation are related to (i) conflicts with conservation objectives, (ii) the availability of suitable areas for <i>S. anglica</i> expansion and (iii) intensity of processes returning pooled N and contaminants to the environment. Based on the use of an invasive and undesirable species as well as the disruption of bulk removal of vegetation and sediment, public support for this option is estimated to be low.
Knowledge gaps that contribute to the uncertainty of bioremediation performance include (i) uncertainties about the implications for the wider estuary/coastal area when allowing <i>S. anglica</i> to occupy a larger area and (ii) estimated area and costs for generating the required biomass pool of nutrients to make a significant impact on water quality.</td></tr>
<tr><td>Potential impacts on ecosystem services and societal benefits</td><td colspan="3">This bioremediation option does not offer the potential for any significant positive effects on ecosystem service provision, although nine intermediate and six final ecosystem services have been identified as providing potentially positive effects. With respect to ecosystem goods/benefits, only one significant positive effects has been identified for waste burial / removal / neutralisation, with eight potential positive effects and two potential negative effects being identified, resulting in a moderate ecosystem goods/benefits score (29%).</td></tr>
<tr><td>Overall assessment</td><td colspan="3">Although likely to be a contentious option, <i>S. anglica</i> is vigorous and accumulates significant amounts of silt within the marsh. Management should aim to allow the <i>S. anglica</i> to build up significant amounts of silt before both the silt and vegetation are removed. The bioremediation potential of this method is related to the allowable area of coverage – this is likely to generate conflicts with broader environmental objectives.</td></tr>
</table>

Table 24: Compliance of managed realignment for bioremediation with the ten tenets of sustainability and wider ecosystem services scoring (from Annex 2).

Sustainability tenet	Saltmarsh realignment	*Spartina* management
Ecologically sustainable	H(1)	L(4)
Technologically feasible	H	M(5)
Economically viable	H	H
Socially desirable/tolerable	H	L
Ethically defensible (morally correct)	H	M(6)
Culturally inclusive	M(2)	M(7)
Legally permissible	H	M
Administratively achievable	M(3)	M
Effectively communicable	H	H
Politically expedient	H	M(8)
Overall sustainability score	H	M
Goods/benefits score (out of 28)	**18**	**8**
Relative goods/benefits score	**High**	**Moderate**

H = high, M = moderate, and L = low degree of compliance

(1) Assumes undertaken in correct location/habitat
(2) Associated drawbacks may include (for example) the loss of established farming land
(3) Requires coordination of land purchase from (potentially) a number of separate landowners
(4) Highly invasive non-native with potential to disrupt native ecosystems if not managed correctly
(5) Feasible, but not documented
(6) Not fully defensible as is allowing a non-native species to spread
(7) Changes in habitats type are likely to impact upon established local activities
(8) Non-native species

3.4 Summary of remediation approaches

3.4.1 Issues of scale

The primary objective is to provide a significant improvement in water quality over an extensive area. This requires two factors to be addressed by bioremediation. Firstly, that the capacity of an option is capable of significant improvements in water quality. This capacity is generated by the combination of rapid process rates and high stocking densities /biomass: the ability of each option to achieve this capability is demonstrated in sections 3.3.1 to 3.3.4. The second requirement is that the spatial extent of the reduction is sufficiently large to be environmentally significant. This can be met by (i) distributing the bioremediation widely and/or (ii) intercepting the substance responsible for the water quality issue before it disperses widely. The ability to intercept substances contributing to poor water quality partially reduces the required extent of a remediation option. Unfortunately, it is likely that these last two factors pose the greatest challenge for practical applications of bioremediation.

The ability to dedicate large areas to bioremediation is likely to be limited by (i) competition with other marine users for large enough sea areas, (ii) the initial investment required for apparatus (e.g. long-line area) and infrastructure (e.g. boats and processing facilities), (iii) the supply of propagules, juveniles or adults for translocation and/or use, (iv) ongoing maintenance and management costs and (v) acceptability of the extent of any undesirable environmental consequences of the bioremediation process. For the bioremediation options based on aquaculture techniques, it is assumed that the aquaculture industry would have expanded further (and to a point where is provides a *de facto* significant and extensive bioremediation option) had it been possible and profitable to do so. Therefore, to enable the aquaculture industry to deliver the required scale of bioremediation activity, enabling mechanisms may be required such as subsidy, assisted development or incentivisation (e.g. implementing a nitrogen credit scheme that increases aquaculture uptake and profitability). For non-aquaculture options, significant amounts of funding will be required for the direct commissioning of bioremediation over large areas.

Many of the water quality issues occur in tributaries and estuaries and bioremediation areas are best placed, and have greatest likely success, as close to the source of the water quality issues as possible. It is suggested that bioremediation in semi-enclosed area will have a greater effect, than in more open areas, given the retention of the pollutant close to the agents capable of removing it. This allows the bioremediation site to address the greatest concentrations of undesirable substances, which may subsequently reduce both the area required for bioremediation and the footprint of the area impacted by the substances before removal. However, these areas typically contain the greatest number of marine activities and interest, and therefore pose the greatest difficulty for siting bioremediation projects. There may, therefore, be considerable difficulty in aligning marine planning priorities and ensuring compliance with policies to achieve placement of bioremediation sites within these areas.

Without the commitment to dedicate the required area for bioremediation activity and to site these areas effectively (i.e. near the source of the water quality issues), then it is probable that the bioremediation options considered in this report will be unable to generate significant and extensive improvement in water quality. As such, the commissioning or either direct or indirect enabling action is therefore likely to be expensive, and for many options, long-term. However, comparisons with other water quality remediation techniques still suggest that the 13 options considered here are cost-effective.

3.4.2 Wider benefits through additional ecosystem services

A number of bioremediation options have been identified above based on available literature and expert judgement and a semi-quantitative assessment of the impact of each bioremediation option on each intermediate ecosystem service, final ecosystem service and good/benefit has also been undertaken. This assessment used UK and other North West European information such that its findings are relevant to all UK coastal and marine waters.

It is clear that each bioremediation option has the potential to provide a wide range of additional ecosystem services and benefits for society, with the ecosystem services and goods/benefits directly associated with bioremediation (such as 'waste breakdown and detoxification', 'clean water' and 'Waste burial / removal / neutralisation') scoring most highly. Potential gains in ecosystem services and societal benefits are highest for newly created habitats, such as saltmarsh in managed realignment sites which previously did not provide such services. In comparison, for *Spartina anglica* management options the habitat is already present but is allowed to increase in area, thus there are only smaller gains in ecosystem service provision, as the baseline is much higher. In addition, this assessment has also identified other ecosystem services and goods/benefits which may not be directly related to bioremediation, but from which society can gain significant increases in benefit (such as 'Food' and 'Tourism and nature watching'). The latter being particularly relevant, given the potential for bioremediation to improve some forms of tourism and nature watching, particularly those associated with improvements in biodiversity such as wildlife watching and diving, whereas other recreational activities may be negatively impacted by bioremediation options, such as potential restrictions on boating in relation to long-line bioremediation options.

With respect to the potential increase in societal benefits, managed realignment offers the greatest potential to provide additional benefits (goods/benefits score of 64%), then harvesting opportunistic macroalgae (goods/benefits score of 50%), artificial substrata for macroalgae (goods/benefits score of 43%) and bottom culture of numerous bivalve species (goods/benefits score of 39%). From an ecosystem service assessment perspective, the bioremediation options associated with the placement of man-made structures into the natural environment (such as trestles) or the introduction of non-native species (such as *Crassostrea gigas*) both score lower when compared to the re-establishment of natural habitats and native species.

Therefore this assessment identifies the key ecosystem services and goods/benefits which may be gained from each bioremediation option, and thus identifies the areas of focus for future ecosystem service assessments. At this stage of the assessment, these findings must be interpreted with caution as they represent an initial attempt to identify and semi-quantify additional ecosystem services and societal benefits, mainly based on the literature review (presented in section 3 above) and expert judgement. This assessment has been undertaken at the generic UK-level and therefore the findings can be applied to any UK coastal and marine location. Despite the limitations in this approach, it is especially important that the potential additional benefits are included in any assessment of bioremediation options, even if only semi-quantitatively. Where site-specific data are available, a quantitative assessment of changes in key ecosystem service provision should be undertaken, in addition to an assessment of change in human welfare and economic valuation of such change (Annex 3).

3.4.3 Ecosystem-scale consequences of eco-engineering

Once a suitable method has been identified following the selection criteria described here, then a detailed characterisation of the site itself and its hydrodynamic conditions is required. It is important to understand water movements in and around the site of interest in order to calculate how much of the unwanted element could be intercepted by a bioremediation facility. This may include modelling of biogeochemical flows in and around the site in order to identify any unwanted effects on the wider ecosystem. Bioremediation, or ecosystem engineering at a large scale can influence the outcomes of competition between different species or functional types or cause existing resources to become limiting (Aldridge *et al.*, 2012). The water filtration efficiency of bivalve-dominated ecosystems can be considerable, as demonstrated by the following unintended experiment in The Netherlands.

Pacific oysters, *C. gigas*, were introduced to the eastern Scheldt estuary in 1964 and have since expanded rapidly. *C. gigas* is a long-lived, reef-forming species that can colonise hard and soft substrata. Over 7% of the intertidal area of the estuary is now covered by *C. gigas* reef (~8 km^2). Subtidal areas are more difficult to map but a large area is also believed to have been colonised (Smaal *et al.*, 2009). As a result of the increasing introduced oyster population, together with intensive aquaculture of mussels and a natural standing stock of cockles (and invasive razor-fish, *Ensis americanus*, and other filter-feeders associated with oyster reefs), the eastern Scheldt estuary is thought to have reached its carrying capacity for filter feeders (Smaal *et al.*, 2013) i.e. there is no longer sufficient phytoplankton food. The bivalve capacity is such that the water of the entire estuary is filtered within one week; chlorophyll and suspended sediment concentrations are low compared to other North Sea estuaries and water transparency is high. As a result, the flesh content (quality) of harvested mussels has declined in recent years and in the phytoplankton the proportion of picoplankton, which are too small to be grazed, has increased to 30% (Smaal *et al.,* 2013). The picoplankton fraction would normally be less than 20% in nutrient-rich coastal waters.

Biogeochemical models such as ERSEM[26] and food-web tools such as ECOPATH[27] could be deployed to continue the suitability assessment process. Following this, assuming that no unwanted effects were detectable by modelling, the next step would be to search for suitable locations. The environmental factors which influence the site of a bioremediation facility include depth, sediment type, current speed and direction of transport, distance from source of pollution, degree of shelter from

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[26] In development by NERC/Cefas/MetOffice http://www.shelfseasmodelling.org/index-en accessed 11/5/2015

[27] http://www.ecopath.org/ accessed 11/5/2015

waves, distance of location from access points or possible markets and processing facilities, co-location of activities/zonation (e.g. using co-location matrices developed in MMO, 2013d), disturbance of views, presence of protected features or military/privately-owned shore or seabed. These layers would be interrogated in order to obtain the optimal location. An example of the type of layer selection and GIS process for the selection of potential seaweed-farming sites in the North Sea is given by Capuzzo *et al.,* (2014)

3.4.4 Associated costs

Other than for oil spill remediation, the reduction of N has typically been the primary objective for most bioremediation activity to date. As such, it has only been possible to gather costings for traditional and bioremediation-based methods of N reduction. The ability of some bioremediation options to address multiple water quality issues must therefore be seen as additional, but currently unquantifiable, economic benefits.

Nitrogen removal costs for mussels and oyster (although based on *C. virginica*) are broadly similar across the range of anticipated costs (Table 25). Due to the greater management required, shellfish produced for human consumption increases the overall cost of N removal (Gren *et al.*, 2009). On average, shellfish costs for N removal appears to be significantly cheaper when compared with waste water treatment plants and storm-surge reduction solutions. The N removal costs associated with catchment management and agricultural approaches are either slightly cheaper or comparable to the use of shellfish (Hasler *et al.*, 2012). However, many land based measures are mostly already in use and therefore have a reduced potential for additional capacity. Therefore, the marginal expansion of catchment–based measures is likely to require the use of sub-optimum areas or relatively more expensive measures, hence improving the relative cost-efficiency of the use of shellfish for the same purpose.

Shellfish can provide several ecosystem services in addition to N removal, such as reducing turbidity, suspended microbial removal and habitat provision. By reducing turbidity levels and subsequently increasing the depth of the photic zone, shellfish beds can also facilitate the full habitat occupation by macroalgae and the restoration of seagrass beds, which themselves also provide additional N removal benefits. Overall, when the cost and efficiency (i.e. N removal per unit area) are taken into account, it is clear that shellfish compare more favourable as management practices for non-point sources of nitrogen (i.e. rather than point source such as waste water treatment (Rose *et al.*, 2014). Furthermore, several of the bioremediation solutions suggested are self-sustaining over time and have diminishing operational costs over time, e.g. seagrass restoration and *M. modiolus* reef creation.

As a profitable branch of the aquaculture industry, shellfish production need not always represent a net overall cost. Based on this and the value of shellfish for N removal (and other ecosystem benefits), several coastal and estuarine management schemes have aimed to directly promote the expansion of shellfish via the aquaculture industry. Expansion and profitability has been promoted through both the implementation of nitrogen trading and direct subsidies. Nitrogen offsets are currently traded as ‘nitrogen credits’ in several states along the eastern United States (Piehler and Smyth, 2011).

Table 25: Estimated minimum and maximum costs (£ per kg) associated with various point-source and non-point source nitrogen reduction measures.

N reduction	Estimated cost for N removal		Source and notes
	Minimum	Maximum	
Mussels (*Mytilus* spp.)	11.7	16.7	Petersen *et al.* (2014) Does not include potential income from selling mussels. Longline culture in Skive Fjord, Denmark Converted to £ using an average 2014 € exchange rate.
Mussel farming (*Mytilus* spp.)	22.7	42.0	Gren *et al.* (2009) For human consumption Baltic Sea Converted to £ using an average 2009 € exchange rate.
Mussel farming (*Mytilus* spp.)	11.2	18.6	Gren *et al.* (2009) Not for human consumption Baltic Sea Converted to £ using an average 2009 € exchange rate.
Oyster farming (*C. virginica*)	10.2	10.2	Jones (2010) Chesapeake Bay, United States
Fertiliser use below optimum	6.8	26.8	Studies collated in Petersen *et al.* (2014) Converted to £ using a 2014 € exchange rate.
Increased use of manure	9.5	10.7	Studies collated in Petersen *et al.* (2014) Converted to £ using a 2014 € exchange rate.
Energy crops	9.1	20.9	Studies collated in Petersen *et al.* (2014) Converted to £ using a 2014 € exchange rate.
Agriculture (various options)	0.1	616.8	Studies collated in Rose *et al.* (2015) Converted from US pounds and from $ using a December 2014 $ exchange rate.
Urban storm-water	39.4	4,762.3	Studies collated in Rose *et al.* (2015) Converted from US pounds and from $ using a December 2014 $ exchange rate.

N reduction	Estimated cost for N removal		Source and notes
	Minimum	Maximum	
Waste water treatment	15.7	48.6	Rose *et al.* (2014) Converted from US pounds and from $ using a December 2014 $ exchange rate.
Waste water treatment upgrades	0.7	9,986.5	Studies collated in Rose *et al.* (2015) Converted from US pounds and from $ using a December 2014 $ exchange rate.
Wetlands	0.8	280.8	Studies collated in Rose *et al.* (2015) Converted from US pounds and from $ using a December 2014 $ exchange rate.
Constructing buffer and wetland	9.1	20.9	Studies collated in Petersen *et al.* (2014) Converted to £ using a 2014 € exchange rate.

3.4.5 Appetite among users for bioremediation

Public opinion expresses the overall level of acceptance for a project from across a broad spectrum of stakeholders with potentially conflicting requirements – the relative demands of stakeholder groups is likely to vary between geographic areas and bioremediation options. Opinions can also be influenced by topically or emotive issues specific to certain stakeholder groups, hence a direct and balanced analysis of the costs and benefits may not necessarily indicate overall public opinion. The key issue is the level of perceived need and benefit for a project by the public.

The term ‘appetite’ may be regarded as being defined as a socially desirable or tolerable attribute amongst stakeholders, as indicated in the 10-tenets analysis above (and see Barnard and Elliott, 2015). It may also encompass the result of remediation measures being required under governance requirements and constraints by statutory bodies. However, whereas the latter will have legal or policy enforcement, the former (especially actions which are socially desirable) implies societal choice which is then tempered by other consideration such as the economic viability or conflicts between users. For example, the wider society may have an appetite for greater waste-water treatment until faced with greater sewerage charges. Similarly, local residents may have to choose between eutrophication symptoms and the presence of mussel rafts aimed at removing nutrients.

The statutory bodies such as the Local Authority Environmental Health Departments, the Environment Agency, the Inshore Fisheries and Conservation Agencies and the statutory nature conservation bodies will have an ‘appetite’ for bioremediation of pollutant problems which is governed by their statutory remits and policy drivers. The regional water companies and industries discharging waste will have an appetite governed by both fulfilling the conditions of their licences, consents, authorisations and permits and by their duty of care and public relations.

Improvements to water quality are the primary objectives for the bioremediation options considered within this project. The question therefore is whether there is a sufficient public interest and concern about water quality as a current issue to tolerate potential impacts such as limited marine access, reduced aesthetic quality of seascapes and the modification of natural benthic habitats. The public understanding of water quality probably relates to bathing water quality, shellfish hygiene, aesthetic considerations (water colour and clarity) and general concepts of water pollution. It is possible that some of these issues are not as emotive and important for the public when compared, for example, with sea defences, the loss of charismatic species (habitat loss), fisheries and visual impacts (tourism). As such, the wide-scale implementation of bioremediation, especially the transitional water bodies, may generate lower public support when compared with other management activities.

Although outwith the current project, full evaluation of the appetite for remediation measures requires assessment via a detailed stakeholder analysis of views and perceptions. Such stakeholders, both statutory and non-statutory, would need to be included in a cost-benefit and willingness-to-pay analysis which also includes an attitudes and user-conflict analysis. For example, Atkins and Burdon (2006) examined the benefits and costs of reduced eutrophication of the Randers Fjord in Denmark, with a primary focus on assessing individual preferences for water quality improvements, using a contingent valuation survey approach. The findings of their study offered support for funding an action plan to improve the ecological status of the Randers Fjord. Hence such a dedicated attitude survey will need to include both the costs and benefits of remediation techniques and approaches. While the above analysis gives a semi-quantitative description of these, a further study is required.

Clearly, the enhancement of aquaculture for bioremediation purposes is likely to be widely supported by the aquaculture industry (if implemented without impacting on existing aquaculture activity). Equally, the use of habitat creation, especially of high value biogenic habitats, for bioremediation is also likely to be engender support from the conservation organisations. These spin-off benefits, relating to economic development, sustainable food production and habitat conservation, although not the primary objective of bioremediation, are likely to be influential factors improving public support for these projects. It is even possible that these secondary benefits would be perceived to be of greater value by the public than the water quality issues primarily targeted by bioremediation.

3.5 Summary of bioremediation options scoring

A summary of the overall performance scores for each potential bioremediation option (assessed independently relative to its application with regard to: nutrient loading, microbial contamination, chemical contamination and increased turbidity) is presented in Table 26. In each case, scoring is presented on a scale from ‘low’ to ‘high’ (equivalent to scores of 1 to 3 in section 3.3).

Together with the performance scores, overall sustainability scores are presented together with a relative goods and benefits score indicating the level of additional societal benefits that may accrue from each bioremediation option. Both the overall sustainability scores and the additional goods and benefits score are provided as the percentage of the theoretical maximum scores attainable (Annex 2). Hence, for overall sustainability, scores are presented as a percentage of 30 (a maximum score of three, i.e. ‘high’, for each of the ten tenets considered). Similarly, for additional goods and benefits, scores are presented as a percentage of 28 (a maximum score of two from a range of -2 to 2, for each of 14 independent goods and benefits). Scores are summarised as low (<20%), moderate (20-40%), and high (>40%) in Table 26.

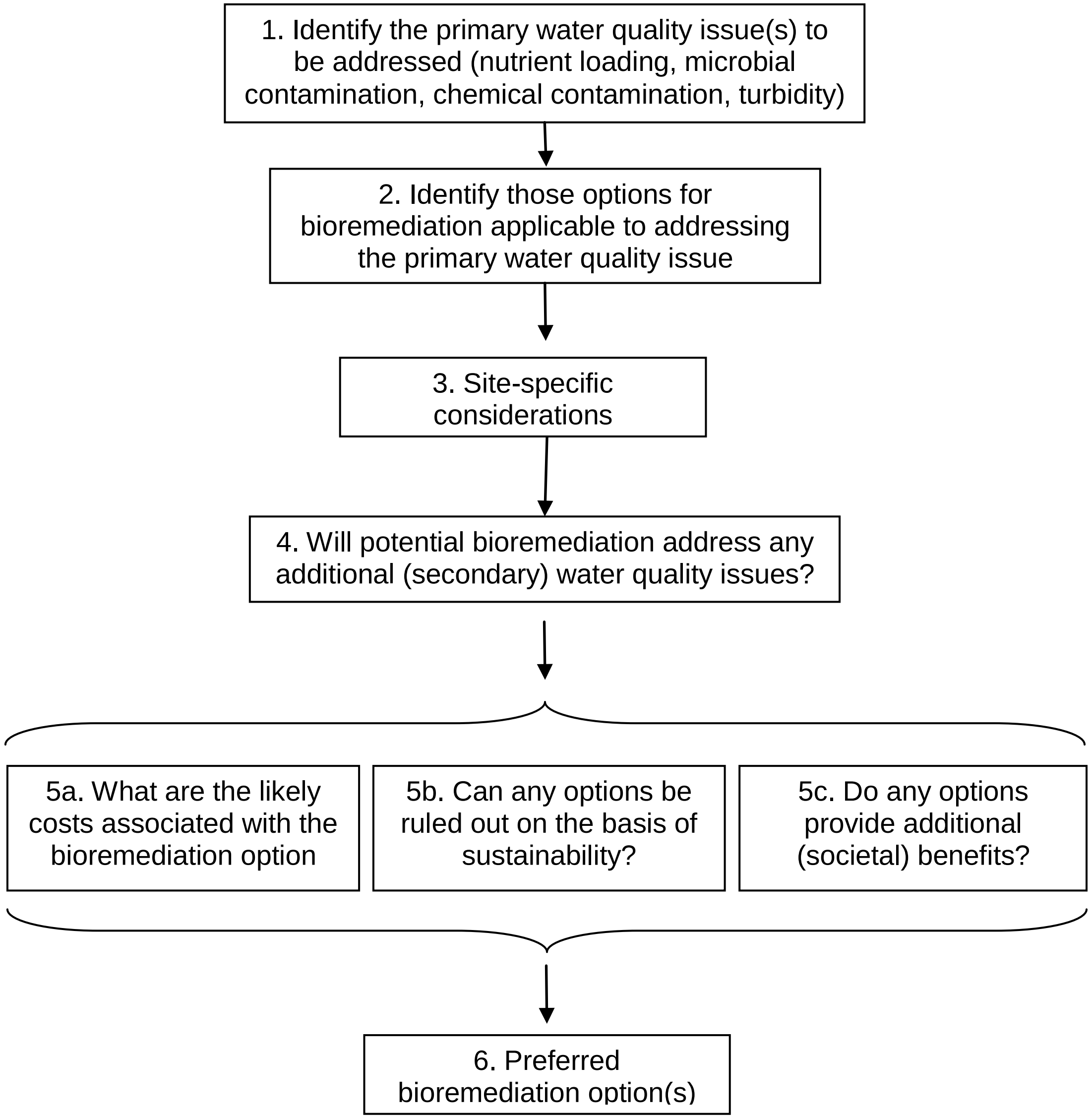
It should be recognised that the expert judgements that have been used as the basis for these assessments have been based on a consideration of their use at the UK level rather than on specific examples of the use of each option. This has the associated advantage that the assessments are potentially transferable between marine plan areas.

It is not intended that the values presented in Table 26 be summed (or otherwise integrated) across the parameters for each potential bioremediation option to derive a single option score. Rather, it is anticipated that decisions on method applicability will be informed by each of the parameters independently. For example, initial selection could be based on likely performance allied to cost information. Subsequently, the final selection might be obtained by considering the relative degree of overall sustainability associated with an option, and/or the potential for accruing additional goods and benefits in a wider ecosystem context. A flow chart outlining how these decisions may be made is given in Figure 15.

Table 26: Overall assessment scores for potential bioremediation options.

Bioremediation option	Performance of potential bioremediation option relative to:				Indicative cost	Overall sustainability score	Relative goods/ benefits score
	Nutrient loading	Microbial contamination	Chemical contamination	Increased turbidity			
Rope culture – *Mytilus*	H	H	H	H	L	M/H	L
Bottom culture – *Mytilus*	M/H	M/H	M/H	M/H	L/M	H	M
Bottom culture – *Ostrea*	M/H	M/H	M/H	M/H	L/M	H	M
Bottom culture – *Crassostrea*	M	M/H	M/H	M/H	M	M	L
Bottom culture – *Modiolus*	M/H	M/H	M/H	M/H	M	H	M
Trestle culture – *Ostrea*	M	M	M	M	M	H	L
Trestle culture- *Crassostrea*	M	M	M	M	M	M/H	L
Rope culture – seaweed	H	L	M	M	M	H	L
Nuisance seaweed harvesting	M	L	L	L	L	H	H
Artificial habitat for seaweed	L	L	L	L	H	H	H
Seagrass bed	M/H	L	M	M	H	M/H	M
Managed realignment	M/H	L	M/H	M	M	H	H
Spartina management	M/H	L	M/H	H	L/M	M	M

Figure 15: Flow chart outlining process for identifying optimum bioremediation option(s)



See review of water quality baseline (site specific) (section 2)

See columns 2, 3 and 4 of Table 26

See columns 2, 3, and 4 of Table 26

See columns 5, 6 and 7 of Table 26

3.6 Confidence summary

Confidence ratings for this summary were derived as described in section 2.7.

The overall confidence rating for data within section 3 is MEDIUM. There are a sufficiently large number of high-quality peer-reviewed publications to enable the bioremediation performance (e.g. filtration rates, nitrogen content) to be extracted at the individual level for selected species of interest. Thus, confidence in the findings of this report is high at the level of individual algal, plant or animal species, growing for periods of up to one year. The performance of bioremediation at the larger scale (e.g. rope-grown mussel or seaweed farm, intact saltmarsh) is more site specific and thus by nature difficult to assess, and confidence is lower. For example, bioremediation of nutrient excess using macroalgal culture would be more effective in a lagoon with restricted water exchange than in open estuaries.

This report has low confidence in the scale of bioremediation treatment required (section 3.4.1), medium confidence in the wider ecosystem services benefits (section 3.4.2), low confidence in ecosystem-scale consequences (section 3.4.3), medium confidence in costs (section 3.4.4), and medium confidence for user appetite for such measures (section 3.4.5). However, as yet, the appetite of users for bioremediation methods has not yet been explored rigorously or quantitatively. This would require willingness-to-pay and attitude surveys amongst the groups of stakeholders. For example, the methodology adopted by the Defra 2011 'Survey of public attitudes and behaviours towards the environment' would be beneficial in this case.

4. Remediation option feasibility for the south marine plan area

4.1 The suitability of water bodies for bioremediation options

Table 27 scores the suitability of bioremediation options for water bodies with Water Quality (WQ) codes 4 –9 (see Table 1) in terms of the physical environmental conditions prevalent within the bodies and the presence of existing habitat. The suitability of each bioremediation option was assessed using expert judgment and guided by a number of rules:

- Transitional waterbodies provide sheltered conditions and increase suitability for most bioremediation options.
- Water body areas between 0 – 10 km2 = reduced suitability, 10 – 100 km2 = neutral suitability and greater than 10 km2 = increased suitability.
- Mean water depth less than 5 m = reduced suitability, 5 – 10 m = neutral suitability and greater than 10 m = increased suitability (inverted for artificial habitat for macroalgae).
- Reduced suitability of long-line/suspended culture options in areas of high marine traffic density (MMO, 2014b)[28.]
- The suitability of intertidal options - intertidal percentage less than 50 % = reduced suitability, 50 – 75 % = neutral suitability and greater than 75 % = increased suitability.
- Extensive intertidal structures in transitional waterbodies could create a high aesthetic impact that may reduce suitability.
- Seagrass suitability is based on the whether the area has existing seagrass and if it is subtidal. Similarly, *Spartina anglica* management requires established stands of vegetation and whether areas have a conservation designation (reducing suitability).
- Suitability for managed realignment has been assessed broadly on (i) elevation, (ii) the presence of existing sea defences, (iii) the presence of existing saltmarsh and (iv) availability of adjoining land for development.
- The suitability according to whether an area is closed, semi-enclosed or open has not yet been investigated given the poor understanding of such hydrophysical structure and dynamics in relation to the ability of species to bioremediate.

Many of the larger and deeper transitional water bodies have the greatest suitability for various bioremediation options (Table 27). This is typically due to the increased feasibility of operating in sheltered conditions and the space available for scaled-up bioremediation projects. Shallow mean water depths reduced the suitability of some of these sites for long-line/suspended culture options but generally did not influence bottom culture. The use of transitional water bodies also provides the most effective positioning for bioremediation near the source of water quality issues. Trestle-based options were most suitable in transitional water bodies with large areas available and

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[28] The presence of high marine traffic density has been estimated using AIS (Automatic Identification System) composite plots and expert judgement.

a high proportion of intertidal area, thereby allowing the required area to be occupied to enable effective bioremediation rates.

Overall, areas such as Chichester Harbour, Poole Harbour, the Exe, Pagham Harbour and Langstone Harbour had high overall levels of suitability of the greatest number of bioremediation options – this was most driven by available space (including intertidal area) and the naturally-occurring presence of species such as *Z. marina* and *S. anglica*. It is also noteworthy that many of these areas are associated with low water quality values and thus will benefit the most from the use of bioremediation.

Table 27: Suitability of possible bioremediation options for each water quality area within the south marine plan areas.

Water body	WQ index	Area (km^2)	Mean depth (m)	Area intertidal (%)	Flushing time (d)	High marine traffic density[29]	*M. edulis* rope culture	*M. edulis* bottom culture	*O. edulis* bottom culture	*C. gigas* bottom culture	*M. modiolus* bottom culture	*O. edulis trestle culture*	*C. gigas* trestle culture	Macroalgae rope culture	Harvesting opportunistic algae	Artificial habitat for macroalgae	Seagress bed restoration	Managed realignment (saltmarsh)	*S. anglica* management
Exe (T)	4	18	5	59%	6	No	*	***	***	*	NA	**	*	*	***	***	***	**	**
Dart (T)	5	8.3	10	36%	11	No	*	**	**	*	NA	**	*	*	**	**	NA	NA	NA
Southampton Water (T)	5	31	12	35%	14	No	***	***	***	*	NA	NA	NA	***	**	***	*	**	**
Portsmouth Harbour (T)	5	16	5	61%	6	Yes	*	***	***	*	NA	NA	NA	*	***	***	***	NA	**
Teign (T)	6	3.5	5	59%	6	No	*	**	**	*	NA	**	*	*	**	**	NA	NA	**
Poole Harbour (T)	6	33	2	54%	4	No	**	***	***	*	NA	**	*	**	***	***	***	**	**
The Solent (C)	6	260	NK	NK	NK	Yes	*	NA	*	*	NA	NA	NA	*		**	**	**	**
Chichester Harbour (T)	6	30	3	79%	4	No	*	***	***	*	NA	***	**	*	***	***	***	**	**
Sussex East (C)	6	131	NK	NK	NK	Yes	*	NA	NA	*	NA	NA	NA	*	NA	**	*	**	*
Lyme Bay West (C)	7	137	NK	NA	NK	No	**	NA	NA	NA	NA	NA	NA	**	NA	**	**	NA	NA
Torbay (C)	7	24	NK	NA	NK	No	*	NA	NA	NA	NA	NA	NA	*	NA	*	**	NA	NA
Lyme Bay East (C)	7	118	NK	NA	NK	No	**	NA	NA	NA	NA	NA	NA	**	NA	**	**	NA	NA
Fleet Lagoon (T)	7	4.9	2	0%	1-40	No	*	*	*	*	NA	NA	NA	*	*	**	***	NA	NA

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[29] Estimated using data from MMO (2014b)

Water body	**WQ index**	**Area (km^2)**	**Mean depth (m)**	**Area intertidal (%)**	**Flushing time (d)**	**High marine traffic density[29]**	***M. edulis* rope culture**	***M. edulis* bottom culture**	***O. edulis* bottom culture**	***C. gigas* bottom culture**	***M. modiolus* bottom culture**	***O. edulis trestle culture***	***C. gigas* trestle culture**	**Macroalgae rope culture**	**Harvesting opportunistic algae**	**Artificial habitat for macroalgae**	**Seagress bed restoration**	**Managed realignment (saltmarsh)**	***S. anglica* management**
Lymington (T)	7	2.5	2	79%	3	No	*	*	*	*	NA	**	*	*	**	**	NA	NA	NA
Medina (T)	7	1.6	7	46%	9	No	**	**	**	*	NA	*	*	**	**	*	NA	NA	NA
Newtown River (T)	7	1.9	1	89%	2	No	*	*	*	*	NA	**	*	*	**	**	*	**	NA
Sussex (C)	7	191	NK	NA	NK	Yes	**	NA	NA	NA	NA	NA	NA	**	NA	**	NA	**	*
Kent South (C)	7	248	NK	NA	NK	Yes	**	NA	NA	NA	NA	NA	NA	**	NA	**	NA	**	*
Pagham Harbour (T)	7	2.6	3	92%	3	No	*	*	*	*	NA	**	*	*	**	**	**	**	**
Portland Harbour (C)	8	10	NK	NA	NK	Yes	*	NA	NA	NA	NA	NA	NA	*	NA	*	**	NA	NA
Beaulieu River (T)	8	3.1	3	76%	4	No	*	*	*	*	NA	**	*	*	**	**	NA	NA	**
Langstone Harbour (T)	8	19	3	79%	4	No	*	*	*	*	NA	***	*	*	***	***	*	NA	**
Isle of Wight East (C)	8	264	NK	NA	NK	Yes	*	NA	NA	NA	NA	NA	NA	*	NA	**	*	NA	*
Devon South (C)	9	76	NK	NA	NK	Yes	*	NA	NA	NA	NA	NA	NA	*	NA	*	*	NA	*
Weymouth Bay (C)	9	7.9	NK	NA	NK	Yes	*	NA	NA	NA	NA	NA	NA	*	NA	*	*	NA	NA
Dorset/Hampshire (C)	9	513	NK	NA	NK	No	**	NA	NA	NA	NA	NA	NA	**	NA	**	*	NA	*

T = transitional water body, C = coastal water body

NK =not known, NA = not applicable

* = reduced suitability, ** = neutral suitability, *** = increased suitability

Note: The southern limit of the distribution of *M. modiolus* does not cover the English Channel hence it is not appropriate for the sites considered

4.2 Worked examples

4.2.1 The Exe Estuary

The process of selecting a bioremediation option following the steps outlined in Figure 15 will be demonstrated here using the example of the Exe Estuary. This estuary has multiple water quality issues (Table 1, section 2.3.2). The catchment area is a Nitrate Vulnerable Zone, and although not a designated eutrophication sensitive area, inorganic nutrient concentrations are too high at present to allow a good status classification under the WFD. A rapidly increasing human population in the catchment could further increase nutrient inputs in the next 20 years. The Exe estuary has a well-documented problem with microbial contamination of shellfish, and also fails WFD on its chemical status.

Maintaining or increasing the area and health of the existing intertidal and subtidal seagrass populations may require turbidity as well as nutrient concentrations to be regulated if elevated turbidity is the result of anthropogenic rather than natural characteristics. However, it is of note that turbidity may be a limiting factor on the use of the nutrients by the phytoplankton and reducing it may increase the sensitivity of the waters to further eutrophic symptoms. Water quality managers have to be aware of such issues so that solving one problem does not increase another.

Step 1

The Exe requires bioremediation for all of the main water quality issues, but the primary issue of concern is judged to be microbial contamination due to the economic value of the shellfish industry at this location. Limiting factors in the Exe estuary for remediation techniques are the lack of available space (< 20 km^2) and multiple uses by other sectors such as recreation (Exe Estuary Management Partnership, 2014b). However, paradoxically the remediation of the microbial contamination would increase that recreation use. Identification of microbial contamination input sources followed by hydrodynamic modelling would be necessary to identify the best possible locations for a bioremediation facility to be installed.

Step 2

Draft south marine plan policies (section 5) give clear guidance that proposals or activities which can deliver an improvement to estuarine water quality (policy S-WQ-3b) will be supported by marine planning. Policy S-BIO-7c is more specific and indicates that water filtration, nutrient reduction and chemical sequestration ecosystem service will be supported. Following this direction, the local estuarine management partnership and all relevant agencies would review the most suitable bioremediation technology. The most effective reduction in microbial loading is via bio-filtration, with rope-grown mussels having the highest efficiency (and therefore requiring least area).

Step 3

Rope-grown mussels would also have the secondary effect of reducing the nutrient load of the Exe Estuary and surrounding waters (noting that locally, in the vicinity of the farm, that metabolically-released ammonia may cause seawater concentrations to be elevated to levels above ambient). It is possible that the chemicals in breach of EQS, fluoranthene and tributyltin, may also be removed by bioaccumulation in mussel tissue; this would require further research and modelling of contaminant sources with respect to water flows. Turbidity would probably be reduced in the vicinity of the farm due to phytoplankton consumption and trapping of sediment particles in pseudofaeces. However, rope-grown systems require a water depth of more than 10 m, and this condition severely limits the number of suitable locations in the Exe itself (Table 27). The next most suitable bioremediation option could be the bottom culture of *M. edulis, O. edulis or C. gigas*, which although less efficient than a rope-grown system, would still have significant biofiltration capacity. All three benthic bivalve species scored well in the key areas of technical feasibility, cost marketable products and area required (Table 26).

Step 4

The suitability of establishing bottom cultures of bivalves can then be compared with the other drivers: cost, sustainability, societal benefits and conflicts with other marine policies. Draft marine policies have been proposed to regulate the interaction of static objects in the water with recreational boating (S-TR-2c), and to avoid adversely influencing tourism or recreational activities (S-TR-2d). The relative weighting of each driver would become apparent during, for example, stakeholder consultation meetings. For example, costs of establishing bioremediation may become less important under the threat of extremely damaging infraction proceedings from the European Commission for breach of a particular Directive. Bottom cultivation of all three species is rated as low-to-moderately expensive, with *Ostrea* cultivation scoring high for sustainability, and equal with *Mytilus* for additional societal benefits. In this case, the selection of a bioremediation option which, after GIS mapping of constraints in the estuary, could offer a sustainable solution and a wide range of additional benefits to society (e.g. reef-forming habitat, fish nursery function and waste burial).

4.2.2 Poole Harbour

Step 1

Poole Harbour has a ‘moderate’ WFD status (macroalgae and dissolved inorganic nitrogen). It has also consistently failed WFD chemical standards (although mostly driven just by the concentration of tributyltin compounds). A variety of extensive shellfish fisheries and aquaculture areas in Poole Harbour are categorised as either class B-LT and class C and a large seagrass bed within the harbour. The main bioremediation requirements for this area, in order of priority, are:

- nitrogen reduction
- contaminant reduction
- suspended microbial reduction
- turbidity reduction.

Step 2 and 3

If draft plan policies are taken forward, there would be clear guidance from the South Inshore Marine Plan that proposals or activities which can deliver an improvement to estuarine water quality (policy S-WQ-3b) will be supported by marine planning, and that bioremediation technologies should be used if appropriate to Poole Harbour.

There should also be consideration of the local Poole Harbour Management Plan, and investigation of the use of bioremediation options should be made in detail. Seven bioremediation approaches are capable of addressing all four issues simultaneously at a moderate to high level of performance. All seven are bivalve-based bioremediation approaches. Poole Harbour is at the very southern edge of the distribution of *Modiolus modiolus* and therefore expert judgement has been used to exclude this approach for this location. Based on overall performance, feasibility and cost for the remaining bivalve approaches, it is apparent that the most promising bioremediation approaches, in order of merit, are (Table 26 and Table 27):

1. *Mytilus edulis* (rope culture)
2. *Mytilus edulis* or *Ostrea edulis* (bottom culture)
3. *Crassostrea gigas* (bottom culture)
4. *Ostrea edulis* and *Crassostrea gigas* (trestle culture)

The order of the approaches reflects the value in terms of bioremediation potential of particular culture methods, although *O. edulis* consistently out-performs *C. gigas* based only on it being a native species and having a greater ecological feasibility. Rope culture allows the greatest stock density to be achieved in a volume of seawater. This in turn increases the surface area to volume ratio and overall clearance rate. The absolute filtration rate dictates the efficacy of removal of phytoplankton (N reduction), microbes (microbial reduction), contaminants (contaminant removal via ingesting and absorption) and suspended solids (turbidity reduction).

Step 4

As with all remediation approaches, bioremediation sites in Poole Harbour should be placed as closed to the pollutant sources as feasible. This reduces the impact of dilution on bioremediation efficient and also minimises the area impacted by the pollutant before reaching the bioremediation site. Additional benefits for the use of bivalve culture, and especially rope culture, in Poole Harbour are:

- the bioremediation site is as concentrated as possible, thereby reducing conflicts with other activities within the harbour (e.g. fisheries and habitats of conservation importance)
- the reduced turbidity will benefit the seagrass beds within the harbour
- industrial incentivisation is possible as Poole Harbour has an established aquaculture presence
- the sheltered conditions within the harbour are conducive for rope culture.

However, as a busy harbour, bioremediation approaches with surface gear may be incompatible with existing activities in the area. If this is the case, bottom culture may provide a more suitable option in high traffic areas. Based on the N removal values of Petersen *et al.* (2014) and the predicted need to remove 400 tonnes of N per year (see section 2.3.3) then it is estimated that between 1920-2880 ha are required for rope cultivation. Based on the area of the harbour, this would require an approximate coverage of between 11 – 18 % to achieve the required reduction in N concentration (harvest N only – burial and denitrification contributions not included). This is a feasible but significant area and highlights the need for (i) realistic bioremediation targets, (ii) concentrated bioremediation footprints, (iii) implementing a diversity of bioremediation approaches and (iv) the positioning of the bioremediation as close to the source of the problem as possible (thereby improving the removal of N – see Nelson *et al.* (2004).

4.3 Confidence summary

Confidence ratings for this summary were derived as described in section 2.7.

The overall confidence rating for data within section 4 is MEDIUM. Sufficient evidence has been gathered in this report to enable the outputs of sections 2 and 3 to be combined, and a first approximation to be made of which types of bioremediation technique would be suitable for which water quality problem area.

Co-location of multiple bioremediation options within the same space could be beneficial, and could offer returns higher than the sum of the parts. However, a recent review of the subject (MMO, 2013d) indicates a lack of primary evidence for relevant examples of co-location of the types of marine activities within the scope of this report. As confidence in this would therefore be low at present, co-location of bioremediation was not considered within this report.

5. Recommendations for environmental remediation in the south marine plan areas

5.1 Use of report outputs to inform draft south marine plans

The final section of this report considers how the evidence gathered on water quality issues, bioremediation options and implementation could inform the draft inshore and offshore marine plans for the South coast of England. A high quality of the natural marine environment including the quality of the water was identified early in the planning process by the South Plans Analytical Report as an undoubted attraction of the region. The updated water quality evidence presented in this report complements the South Plan Analytical Report conclusions that, whilst there has been a steady improvement in bathing water quality across the South coast, sensitive areas for eutrophication exist, and certain parts of the region have moderate rather than good ecological status. Chemical contamination also causes water quality to fail European legislation at certain sites. The protection of the natural marine environment, including improvement of water quality, was then recognised as a core issue in the following step of the planning process (drafting of a Vision and Objectives). High-level objectives for the South marine plan areas have been written to support progress towards a vision by 2036 of sustainable use of the South Inshore and South Offshore Marine Plan Areas. The relevant high-level objectives with respect to water quality in the area are:

- Activities within and adjacent to the south marine plan areas must take account of the achievement or maintenance of Good Environmental Status and Good Ecological Status under the MSFD and WFD respectively

- To safeguard space for the natural marine environment to enable continued provision of ecosystem goods and services

- Cumulative impacts affecting estuarine water quality within the South Inshore Plan Area should be addressed through strategic management addressing terrestrial and marine drivers

During the next stage of the planning process, policy variants or options were proposed which sit under the high level objectives. The original policy options shared under consultation differed in strength from a ‘flexible’ set of policies, through ‘balanced’, to more ‘prescriptive’ ones. Stakeholder feedback to these options showed that a more prescriptive approach (Option 3) for water quality issues was preferred[30]. The MMO is now at the stage of refining its draft south marine plan, and the following section examines the possible role of bioremediation in each of the draft policies, using versions received at the end of April 2015, when this report was underway. The MMO emphasised that these draft policies were still subject to revision and were to be treated as such; the analysis here has been aware of the need to revise many of these draft policies but takes the view that they are sufficient to test the proposed methodology. The aim here is to identify if the project outputs

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[30] https://marinedevelopments.blog.gov.uk/2015/03/25/south-marine-plan-areas-options-consultation-summary/ accessed 12/5/2015

support the specific policies (or not), and identify if the evidence presented in this report could allow or requires more specificity within the policy, as well as listing gaps or issues that need addressing before the policy could be refined and taken further.

The full set of 58 draft south marine plan policies (in April 2015) were screened to see if proposals involving bioremediation would be consistent with the objectives of the policy (Annex 3). A potential negative interaction was detected for 12 of the policies: bioremediation would act against the policy S-TR-2c (static objects); S-TR-2d (tourism or recreation); S-TR-3c (public access); S-CAB-1b (cable landfall sites); S-TIDE-1b (tidal energy); S-DD-2b (dredging/disposal); S-GOV-1b (displacement); S-AGG-3c (aggregates); S-PS-2b (static infrastructure); S-PS-3b (navigation routes), and S-PS-4g (ports expansion). Competition for space on the seafloor or at the sea surface is the cause of potential conflict in most of these cases.

There is a further sub-set of thirteen draft policies for which a direct or indirect role of bioremediation was identified as broadly supportive of the policy. These draft policies are reviewed here, exploring the justification for linking bioremediation to the policy, which bioremediation options might be feasible, any additional system benefits, the monitoring required, how to measure success, conclusions and gaps in knowledge.

5.1.1 Draft south marine plans policies: water quality

S-WQ-1c
Draft policy: Where the re-suspension of sediments may have an adverse impact on water quality, proposals will be required to demonstrate (in order or preference):

(a) how adverse impacts will be avoided;
(b) if they cannot be avoided, how adverse impacts will be minimised; or
(c) if they cannot be minimised, how they will be mitigated.

Justification for bioremediation

- Evidence supports that proposals for bioremediation options will not have an adverse impact on water quality.
- There is a sound evidence base to support the use of bivalve-based. bioremediation as a mitigation option for the reduction of suspended solids through filtration and biodeposit production.

Suitable bioremediation options

- All bivalve-based rope and bottom culture options (*M. edulis* rope culture, *M. edulis* bottom culture, *O. edulis* bottom culture, *C. gigas* bottom, *M. modiolus* bottom culture, *O. edulis* trestle culture, and *C. gigas* trestle culture).

Additional system benefits

- High N removal, microbial reduction and contaminant reduction.
- Low to moderate costs.
- Moderate to high sustainability.
- Low to moderate goods/benefits.

Potential monitoring approaches

- Standard water quality sampling for suspended solids against baseline values
- Satellite estimates of suspended solids
- Citizen science measurements of water clarity[31]
- SCUBA diver observations.

Measure of success

- Proposal does not have an adverse impact on water quality
- Improved water quality as a result of mitigation measures to decrease re-suspended solids

Conclusion

- Proposals for bioremediation activity are anticipated to be consistent with this policy
- Consideration should be given to bioremediation as a suitable mitigation option for achieving this policy objective

Gaps in knowledge

- Conflicts between bioremediation options and existing/proposed activities
- Scaling-up to effective operational levels
    - Access to the appropriate sites
    - Adverse consequences of bioremediation waste products

S-WQ-2b
Draft policy: Proposals which have an adverse impact upon estuarine water quality, individually or cumulatively should demonstrate (in order or preference):

(a) how the impacts will be avoided
(b) how if there are adverse impacts they will be minimised; or
(c) how if the adverse impacts cannot be minimised how they will be mitigated
(d) the case for proceeding if mitigation is not possible.

Justification for bioremediation

- Evidence supports that proposals for bioremediation options will not have an adverse impact on water quality
- Evidence supports the use of bioremediation options discussed in this report as a mitigation option to offset the impacts on water quality from adverse proposals

Suitable bioremediation options

- All bioremediation options discussed in this report.

Additional system benefits

- These will be dependent on the option selected and its location

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[31] http://www.secchidisk.org/

Potential monitoring approaches

- Standard water quality sampling against baseline values

Measure of success

- Proposal does not have an adverse impact on water quality
- Improved water quality as a result of mitigation by bioremediation options

Conclusion

- Proposals for bioremediation activity are anticipated to be consistent with this policy
- Bioremediation options could also be used as mitigation measures for other proposals that fail to satisfy the policy objective

Gaps in knowledge

- Conflicts between bioremediation options and existing/proposed activities
- Scaling-up to effective operational levels
  - Access to the appropriate sites
  - Adverse consequences of bioremediation waste products

S-WQ-3b

Draft policy: Activities that can deliver an improvement to estuarine water quality should be supported wherever practical.

Justification for bioremediation

- Evidence supports the value of bioremediation proposals (including those identified as potential mitigation measures) for the delivery of improvements to water quality.

Suitable bioremediation options

- All bioremediation options discussed in this report.

Additional system benefits

- These will be dependent on the option selected and its location

Potential monitoring approaches

- Standard water quality sampling against baseline values

Measure of success:

- Improved water quality through the use of bioremediation options

Conclusion

- Proposals for bioremediation are consistent with this policy and should be supported
- Where used as a mitigation measure bioremediation satisfy this policy and should be supported

Gaps in knowledge

- Conflicts between bioremediation options and existing/proposed activities
- Scaling-up to effective operational levels

- Access to the appropriate sites
- Adverse consequences of bioremediation waste products

5.1.2 Draft south marine plan policies: biodiversity

S-BIO-1c

Draft policy: Proposals that may have adverse impacts on habitats that provide a flood defence or carbon sequestration service must demonstrate, in order or preference:

(a) that there are no adverse impacts on these ecosystem service(s);
(b) how if there are adverse impacts they will be minimised; or
(c) how if the adverse impacts cannot be minimised they will be mitigated to ensure the continuation of the ecosystem service(s).

Justification for bioremediation

- It is evident that bioremediation proposals must be appropriately sited in order to avoid substituting or depleting areas of habitat that would otherwise provide flood defence and/or carbon sequestration services
- The literature supports the use of saltmarsh creation and seagrass restoration as mitigation measures for promoting carbon sequestration, and the use of saltmarsh as a natural form of flood defence; the use of these bioremediation options as a means of providing a wide range of ecosystem services

Suitable bioremediation options

- *Zostera anglica* bed restoration, managed realignment of saltmarsh and modified management of *Spartina*.

Additional system benefits

- Moderate to high N removal, microbial reduction, contaminant reduction, and turbidity reduction
- Moderate to high sustainability
- Moderate to high goods/benefits

Potential monitoring approaches

- Habitat mapping: standard metrics of habitat extent for the relevant habitats against baseline values

Measure of success

- No net loss of habitats that provide flood defence or carbon sequestration services
- Mitigation measures based on bioremediation for water quality issues provide a net increase in flood defence and/or carbon sequestration services

Conclusion

- The adoption of proposals based on these bioremediation options is not anticipated to impact negatively on flood defence or carbon sequestration

- The adoption of these bioremediation options as mitigation measures for water quality issues is likely to provide flood defence and/or carbon sequestration as wider secondary benefits

Gaps in knowledge

- Conflicts between bioremediation options and existing/proposed activities
- Potential impact of seagrass translocation

S-BIO-2c

Draft policy: Proposals must take appropriate action to avoid and minimise adverse effects on the marine area through the transport and introduction of non-indigenous species, particularly when moving equipment, boats or live stock (e.g. fish and shellfish) from one water body to another or introducing structures suitable for settlement of non-indigenous species. Proposals in areas where invasive non-indigenous species are known to exist must include mitigation measures or a contingency plan approved by decision-makers that seeks to minimise the risk of spreading the invasive non-indigenous species or identifies ways to eradicate the organisms and set up a scheme to prevent reintroduction.

Justification: Several of the bioremediation options are well-documented vectors for the introduction of non-indigenous species. For example, evidence has linked the movement of seed mussel to the spread of *Crepidula fornicata* within the UK and provision of additional habitat for macroalgae could potentially act as a stepping stone for non-indigenous species. Consequently, given that three potential remediation options also directly involve the use of non-indigenous species (*Crassostrea gigas* bottom and trestle culture and modified management of *Spartina anglica*), certain options presented within this report may not satisfy this policy; this policy objective must be considered when selecting appropriate bioremediation. The bioremediation options reviewed in this report are not designed to mitigate against the spread or impact of non-indigenous species.

S-BIO-3c

Draft policy: Public authorities must ensure adequate, year round provision for and removal of beach and marine litter, on prioritised beaches.

Justification: This policy objective must be considered when undertaking bioremediation as the activity itself, if not appropriately managed, may provide a source of marine litter. The bioremediation options reviewed in this report are not designed to mitigate against the introduction and removal of beach and marine litter.

S-BIO-4c

Draft policy: Activities that help reduce marine litter will be supported.

Justification: This policy objective must be considered when undertaking bioremediation as the activity itself, if not appropriately managed, may provide a source of marine litter. The bioremediation options reviewed here for water quality improvement are not designed to reduce marine litter.

S-BIO-5c
Proposals that may have adverse impacts on natural habitat and species adaptation, migration and connectivity must demonstrate, in order of preference:

(a) How such impacts will be avoided;
(b) If they cannot be avoided, how they will be minimised;
(c) If they cannot be minimised, how they will be mitigated.

Justification for bioremediation

- It is evident that, by instigating certain forms of bioremediation (either as a proposal or as a mitigation measure), the overall availability of natural habitat, species presence and overall connectivity will be enhanced and supported.

Suitable bioremediation options

- All native species bioremediation options (i.e. all options within this report excluding *C. gigas* bottom and trestle culture, and opportunistic macroalgae harvesting).

Additional system benefits

- These will be dependent on the option selected and its location

Potential monitoring approaches

- Mapping the distribution of natural species and habitats, testing standard metrics of habitat extent and species distribution against baseline values

Measure of success

- Bioremediation options should maintain the potential for natural species and habitat presence, migration and ecological connectivity
- Where used as mitigation measures, bioremediation should enhance, maintain or facilitate natural habitat and species adaptation, migration and connectivity

Conclusion

- Bioremediation options should not be located where they may impact on existing natural habitats or areas used for species migration and which are important for connectivity
- Bioremediation options which encourage the increased connectivity of natural habitats and species should be supported

Gaps in knowledge

- Conflicts between bioremediation options and existing/proposed activities

S-BIO-6c
Proposals that incorporate features that enhance, maintain or facilitate natural habitat and species adaptation, migration and connectivity will be supported. Proposals must take account of the space required for coastal habitats where important in their own right and/or for ecosystem functioning and provision of services. Proposals must (in order of preference):

(a) Avoid net loss of habitat.

(b) Minimise net loss of habitat extent.
(c) Mitigate for net loss in extent.
Proposals must take steps to increase the extent of priority habitats.

Justification for bioremediation

- Bioremediation proposals have the potential to contribute to the net loss of natural coastal habitats.
- However there is also evidence that specific bioremediation options, when used as mitigation measures, are capable of providing high value habitat, e.g. seagrass and *Modiolus modiolus* biogenic reef, provide additional man-made habitats which provide bioremediation functions and wider ecosystem services and additional biodiversity benefits.

Suitable bioremediation options

- All bioremediation options considered in this report have the potential to provide new and/or modify existing habitat. Four options (*O.edulis* bottom culture, *M. modiolus* bottom culture, *Z. marina* restoration and native saltmarsh managed re-alignment) will provide mitigation for the loss of priority habitats.

Additional system benefits

- These will be dependent on the option selected and its location

Potential monitoring approaches

- Habitat mapping; standard metrics of habitat extent against baseline values
- Measures of success
- No net loss of existing coastal habitat
- An increase in the extent of priority coastal habitats

Conclusion

- There is the potential for the net loss of natural coastal habitat within the footprint of bioremediation proposals.
- Options for water quality improvements through bioremediation that also mitigate against habitat loss, and which specifically mitigate against the loss of priority habitats, should be supported.

Limitations

- Bioremediation options may lead to the loss of habitat
- Conflicts between bioremediation options and existing/proposed activities
- Scaling-up to effective operational levels
- Access to the appropriate sites

S-BIO-7c
Proposals that maintain or enhance habitats and species assemblages providing water filtration ecosystem services will be supported. Proposals that may have adverse impacts upon these habitats and species assemblages, must demonstrate (in order or preference):

(a) that there are no adverse impacts on these ecosystem services;

(b) how if there are adverse impacts they will be minimised; or
(c) how if the adverse impacts cannot be minimised how they will be mitigated to ensure continuation of the ecosystem service(s)

Justification for bioremediation

- There is evidence to show that all bioremediation options considered in this report (as a proposed activity or as a mitigation measure) provide filtration mechanisms which improve water quality, although efficacy varies between options

Suitable bioremediation options

- All 13 bioremediation options considered in this report, and especially those based on filter feeding bivalves (*M. edulis* rope culture, *M. edulis* bottom culture, *O. edulis* bottom culture, *C. gigas* bottom, *M. modiolus* bottom culture, *O. edulis* trestle culture, and *C. gigas* trestle culture).

Additional system benefits

- These will be dependent on the option selected and its location

Potential monitoring approaches

- Habitat mapping: testing standard metrics of habitat extent against baseline values
- Standard water quality sampling against baseline values

Measure of success

- Maintenance or enhancement of habitats and species assemblages providing water filtration ecosystem functions

Conclusion

- Proposals for bioremediation activity would be consistent with this policy.
- Bioremediation options could also be used as mitigation measures for other proposals that fail to satisfy the policy objective.

Gaps in knowledge

- Conflicts between bioremediation options and existing/proposed activities
- Scaling-up to effective operational levels
- Access to the appropriate sites
- Adverse consequences of bioremediation waste products

5.1.3 Draft south marine plans policies: co-existence

S-Co-1c
Proposals will consider opportunities for other activities to use the same footprint as their proposal and minimise their use of space. This can be achieved through co-existence of activities.

Justification for bioremediation

- Whilst there is limited evidence from the literature showing co-existence potential, there is a considered view that there is likely to be opportunity for bioremediation options considered within this report to co-exist with other existing and proposed activities

Suitable bioremediation options

- All options provide potential for co-existence.

Additional system benefits

- These will be dependent on the option selected and its location

Potential monitoring approaches

- Spatial analysis of overlap between (potentially) compatible activities; productivity or success of other activities

Measure of success

- Increase incidence of co-existence of bioremediation proposals within the footprint of existing activities

Conclusion

- Consideration should be given to the co-existence of bioremediation proposals with existing or proposed activities

Limitations

- Conflicts between bioremediation options and existing/proposed activities
- Scaling-up to effective operational levels
- Access to the appropriate sites

5.1.4 Draft south marine plans policies: aquaculture

S-AQ-1b

Proposals within areas of existing or potential aquaculture production must demonstrate consideration of and compatibility with aquaculture. Particular consideration must be paid to impacts on water quality and the wider environment that is required for the culture species to grow. Where compatibility is not possible, proposals will demonstrate in order of preference:

a) That they will avoid adverse impacts on the areas identified for aquaculture.
b) How, if there are adverse impacts that cannot be avoided, they will minimise these impacts on aquaculture industry growth.
c) How, if adverse impacts cannot be minimised, they will be mitigated.
d) If mitigation is not possible they should state the case for proceeding.

Justification for bioremediation

- Given that many of the bioremediation options are based upon aquaculture practices, it seems appropriate that proposals for these activities can be sited within areas of aquaculture.
- Based on the ability of particular bioremediation options to address water quality issues pertinent to aquaculture, there is scope for their use as mitigation measures to satisfy the requirements of this policy

Suitable bioremediation options

- All bioremediation options considered in this report address the main water quality issues (via nitrogen removal, microbial reduction, contaminant reduction, turbidity reduction) that may impact on aquaculture activities.

Additional system benefits

- These will be dependent on the option selected and its location

Potential monitoring approaches

- Standard water quality sampling against baseline values
- Aquaculture health and productivity

Measure of success

- Bioremediation proposals will be compatible with aquaculture activities
- Bioremediation as a mitigation measure can facilitate the co-existence of aquaculture and other activities

Conclusion

- Bioremediation is compatible with aquaculture activities
- Within areas of aquaculture production, options for water quality improvements through bioremediation are likely to decrease the impact of other activities on aquaculture and so should be supported

Limitations

- Bioremediation options may compete for natural resources with existing/planned aquaculture activities
- Conflicts between bioremediation options and existing/proposed activities
- Scaling-up to effective operational levels
- Access to the appropriate sites

S-AQ-2a

Proposals that enable the co-utilisation, or diversification of infrastructure for and related industries will be encouraged

Justification for bioremediation

- Given that many of the bioremediation options are based upon aquaculture practices (such as aquaculture apparatus and boating infrastructure, the gathering of biological resources) it seems appropriate that, when proposed as a bioremediation measure, such options will allow for the co-utilisation, or diversification of infrastructure for fisheries and aquaculture and related industries

Suitable bioremediation options

- All options based on aquaculture techniques (*M. edulis* rope culture, *M/ edulis* bottom culture, *O. edulis* bottom culture, *C. gigas* bottom, *M. modiolus* bottom culture, *O. edulis* trestle culture, *C. gigas* trestle culture, and macroalgae rope culture)

Additional system benefits

- Increased demand for aquaculture expertise and input leading to local employment opportunities
- Contribution of bioremediation standing stock to local (bivalve) recruitment

Potential monitoring approaches

- Use and diversification of fisheries and aquaculture infrastructure and/or related activities through co-utilisation of infrastructure with bioremediation options

Measure of success

- The successful co-utilisation, or diversification, of infrastructure for fisheries and aquaculture with bioremediation activity

Conclusion

- There is a significant ability of bioremediation options to co-utilise and diversify existing aquaculture and fisheries infrastructure, and therefore bioremediation options should be supported where possible

Gaps in knowledge

- Ability of existing fisheries and aquaculture infrastructure to contribute to non-aquaculture-based bioremediation options
- Conflicts between bioremediation options and existing/proposed fisheries and aquaculture activities (e.g. potential adverse consequences of bioremediation waste products)

5.1.5 Summary

The degree of support offered by bioremediation varies between the different policies. Bioremediation would strongly support policy S-WQ-3b (activities that can deliver an improvement to estuarine water quality), and also the mitigation element of policy S-WQ-2b (proposals that have an adverse impact upon estuarine water quality). Policy S-BIO-7c (water filtration ecosystem service supported) is clearly relevant for all of the bioremediation services listed in this report, but particularly so for those utilising filter-feeding bivalves. However, not of all the 13 bioremediation options described will apply for those policies that are supported by bioremediation. For example, policy S-BIO-1c (proposals with adverse effects on natural flood defence or carbon sequestration) would be relevant for bioremediation options using seagrass restoration, managed re-alignment of native saltmarsh or modified management of *Spartina anglica* management.

The evidence presented in this report and summarised in sections 5.1.1 to 5.1.4 can be used to further refine the draft marine plan policies. It is also important to question whether bioremediation is of sufficiently high importance to warrant a policy in its own right. Although marine bioremediation and ecosystem restoration has not yet been used significantly in the UK (other than for managed re-alignment), evidence presented in this report suggests that its use should be encouraged. Indeed, there could be considerable financial benefits in using natural ecosystem components rather than conventional land-based treatment facilities to maintain water quality as human populations and economic activity increase. The policy S-BIO-7c, which currently states that “proposals that maintain or enhance habitats and species assemblages providing water filtration ecosystem services will be supported", would benefit from being re-worded based upon the findings of this report to include nitrogen and chemical reduction as follows:

- Proposals that maintain or enhance habitats and species assemblages providing water filtration, nutrient assimilation or hazardous chemical sequestration ecosystem services will be supported.

Further modification of draft marine policies could include a recommendation that artificial substrata used in coastal engineering be modified in such a way that biological colonisation by filter-feeders and macroalgae is encouraged. On the basis of the combination of a high score for wider ecosystem services and benefits and a low cost of implementation, it would be possible to suggest the removal of unwanted opportunistic algal blooms as a stand-alone policy which could be encouraged for eutrophication problem areas. At the same time, environment managers would be encouraged to take an holistic view using the natural remediation capacity. In particular, such a revision of the draft policies emphasises that ‘double-wins’ can be achieved using eco-engineering, e.g. both water quality remediation and habitat enhancement.

5.2 Existing water quality monitoring in the south marine plans

The south marine plan areas have water quality problems arising from a range of human pressures. The minimisation of these problems is a goal of water management measures such as the WFD. However, before commencing any management action, it is necessary to investigate the power of the monitoring / surveillance system to establish cause-effect relationships and to detect any improvements if management action is taken. The implementation of a robust and accurate water quality monitoring system for the south marine plan areas could be recommended as a policy in its own right. In particular, it is needed to test the efficacy, cost-effectiveness and cost-benefit outcome of management measures.

Of the four types of problem identified here, the highest quality evidence of water quality issues is for microbial contamination of bathing waters and designated shellfish beds of the South coast. The sampling programme for each type of water is relatively high frequency, with weekly sampling for bathing beaches during the bathing season. For shellfish hygiene, sampling of new areas is at least ten times per three months, which is reduced to monthly sampling once a location has an established biological profile. The spatial scale of microbiological sampling is also high for waters of this area, with >100 bathing beaches and many active shellfish sites in the sampling programmes. Hence, the nature of the microbial contamination problem is precisely constrained in space and time which aids in identifying bioremediation techniques, i.e. the density of sampling allows the contamination issue to the narrowed down by location and time periods thus allowing a targeted management response. Sampling for eutrophication (ecological quality) and chemical quality is less frequent than weekly and the number of stations is also less. Whilst nutrient inputs to estuaries and harbours are relatively well-characterised, and can be apportioned to different types of pressure (agriculture, industrial, urban) the occurrence of ‘undesirable disturbance’ is more difficult to detect. Phytoplankton bloom events are particularly difficult to sample due to their intermittent nature, but the presence of opportunistic green algal mats is a persistent signal which is easy to observe and can trigger management action.

Turbidity and changing levels of (re-)suspended sediment are not detected with accuracy with the present south marine plan areas monitoring systems and were not investigated in detail in this report. Within estuaries, turbidity levels are related to erosion-deposition cycles which operate on diurnal, weekly, spring-neap, equinoctial and seasonal (high-low river flow conditions) cycles (Wolanski and Elliott, in press). Turbidity changes on these short time scales together with the influence of meteorological forcing over which may be superimposed peaks caused by dredging, dredged material disposal and vessel movements. Hence, a high frequency observing programme would be needed to track long-term changes and to determine if any anthropogenic pressure is responsible for changes.

6. Summary

The UK government has a vision for the future of our seas, and a set of high level objectives that define the framework for marine management (HM Government, 2009): achieving a sustainable marine economy, ensuring a strong, healthy and just society; living within environmental limits; promoting good governance, and using sound science responsibly. These high level objectives are based on the five principles of sustainable development and give the direction to marine planners. Of relevance to this report are the visions within these objectives that our seas will be cleaner and healthier than they are now, that they will be ecologically diverse and dynamic, and that pollutants, contaminants and toxins will be at levels that do not significantly affect human or ecosystem health. These align with legislation under the WFD and MSFD for environmental protection and the Maritime Spatial Planning Directive for encouraging sustainable economic development.

The vision that ecosystems will be resilient to environmental change to enable delivery of the goods and services we need for present and future generations is important in the context of restoration and bioremediation, so that future generations can obtain at least the same and preferably more benefits from the marine environment. The high-level objectives and aims for sustainable development are articulated further in the Marine Policy Statement (HM Government 2011). This describes how marine plans will be used to achieve sustainable use of the seas, enabling a move to a low-carbon economy, promote a healthy functioning marine ecosystem, and contribute to societal benefits of the marine area. Marine plans will be built on a strong evidence base, as far as possible and will use the precautionary principle where necessary.

One of the overarching marine planning goals is that of having coasts, seas, oceans and their resources that are safe to use. This is important in the context of this report for the south marine plan areas as there is a clear risk that water quality in the south marine plan areas may decline in the future because of increasing activities and anthropogenic pressures. At present, the south marine plan areas have a range of marine habitats providing a water-cleansing function, but as a whole, their ecological condition is not good. In areas such as the Solent, there is strong evidence that vegetated intertidal habitats such as saltmarsh are in decline and across both sides of the English Channel there is evidence that populations of the large brown seaweeds are in decline. Stock sizes of native oysters are now very small hence the filtration capacity of these populations has most likely decreased. Climate change poses a further threat to the stability and function of the existing ecosystem services of the region and any assessment of the impact of local pressures, and indeed the effect of measures to address those pressures, has to be interpreted against that global climate change (Elliott *et al.*, 2015).

Efforts are being made to counteract declining biodiversity by implementing ecosystem conservation and restoration projects. The EU Biodiversity Strategy gives the target that by 2020, ecosystems and their services are maintained and enhanced by establishing green infrastructure and restoring at least 15% of degraded ecosystems[32]. The European Environment Agency 'State and Outlook 2015' report[33] shows that during only 23% of species and 16% of habitats were considered to be in favourable conservation status. Furthermore, for both species and habitats, the overall percentage in favourable condition was higher in terrestrial ecosystems than in freshwater and marine ecosystems.

A number of knowledge gaps have been identified through this report. Further evidence filling these gaps would increase the confidence in the use of bioremediation to improve water quality in the south marine plan areas. Specific details are discussed in sections 3.3.1 to 3.3.4 and 5.1.1 to 5.1.4 and it is recommended that these are addressed through further research. At a high level these gaps include:

- Improvements to quantitative information on bioremediation potential of all options for all four water quality issues including estimated costs and area required.

- Estimation of the contribution of biodeposit burial and denitrification loss for bivalve species to overall bioremediation potential.

- Improvements are needed to inform evaluation of existing sites of natural environmental remediation and sites potentially suitable for environmental remediation in the south marine plan areas including addressing issues such as:
    - inaccurate and inadequately resolved habitat maps.
    - varying spatial quality and confidence in habitat and species maps.
    - incomplete spatial coverage for protected habitats and species.
    - habitats and species maps represent a snapshot in time and do not reflect the temporal variability demonstrated in the marine environment
    - lack of information on habitat and species condition.
    - absence of current and future baseline layers for ecosystem services provision.

- The suitability of different bioremediation options relative to the exposure of sites (e.g. whether an area is closed, semi-enclosed or open).

- Whilst the potential for bioremediation to reduce dissolved nutrient concentrations and turbidity is well-supported by the literature, knowledge gaps exist regarding the sequestration of hazardous chemicals such as tributyltin and mercury, or for microbial-contaminated shellfish biomass. Further work would be beneficial to investigate possibilities for disposal or use of cultivated material, and any additional costs involved.

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[32] EC (2011). Our life insurance, our natural capital: an EU biodiversity strategy to 2020. Brussels, 3.5.2011, COM(2011) 244 final

[33] EEA, 2015, The European environment — state and outlook 2015: synthesis report, European Environment Agency, Copenhagen.

- Development of effective culture and management schemes to enable optimum bioremediation for non-established aquaculture practices.

- Conflicts/synergies between bioremediation options and other marine uses including clarification of the implications of land disturbance close to shore through managed re-alignment for the wider estuary/coastal area.

- The issues of scaling up environmental remediation options to operational scales including access to the sites and adverse consequences of bioremediation waste products.

With an expanding population and economic growth foreseen for the next 20 years, pressure on existing water treatment facilities will increase in order to maintain or improve water quality. Greener alternatives exist, and the evidence base in this report shows that an active restoration of ecosystem services is likely to bring about water quality improvements. It is therefore recommended that marine plans for the region refer to the appropriate bioremediation or restoration facilities, in order to encourage proposals to be submitted which will improve water quality problem areas in a cost-effective manner.

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Annex 1: Definitions of coastal and marine intermediate services, final services and goods/benefits

All definitions are taken from Turner *et al.* (2015)

Intermediate Services	Definition	Example
Primary production	The synthesis of organic matter by coastal and marine biota from atmospheric or aqueous carbon dioxide	Quantity and / or quality of primary production from a given area of saltmarsh or volume of seawater
Larval and gamete supply	The production and supply of larvae and gametes from coastal and marine biota	Quantity and / or quality of larvae or gametes supplied to a given coastal or marine location
Nutrient cycling	The influence of coastal and marine biota on the movement or exchange of organic and inorganic matter	Change in the concentration of nitrates / phosphates in coastal or marine waters / sediments
Water cycling	The influence of coastal and marine biota on the movement or exchange of water between the coastal and marine environment and adjacent environments (including the atmosphere)	Change in the amount of water retained within a coastal saltmarsh or reedbed
Formation of species-habitat	The contribution of coastal and marine biota to habitat formed by one species but providing suitable niches for other species	Change in the formation of mussel beds, kelp forests, cold-water coral reefs
Formation of physical barriers	The contribution of coastal and marine biota to the formation of physical barriers	Changes in reef extent by reef-forming organisms (e.g. *Sabellaria* spp.), impacting on the local hydrographic regime
Formation of seascape	The contribution of coastal and marine biota to supporting the formation of different coastal and marine views ('seascapes')	Changes in area per type of seascape e.g. algae-covered rocky shore, kelp forest
Biological control	The contribution of coastal and marine biota to the maintenance of population dynamics,	Oystercatchers controlling intertidal cockle population numbers; cleaner fish (e.g. ballan wrasse)

Intermediate Services	Definition	Example
	resilience through food web dynamics, disease and pest control	removing sea lice from salmon
Natural hazard regulation	The area of suitable coastal and marine habitat which is available to absorb energy	Width or area of saltmarsh / mudflat / reedbed / sea grass
Waste breakdown and detoxification	The presence of coastal and marine biota which have the potential to remove anthropogenic contaminants and organic inputs	The presence of reedbeds, mussels beds, etc.
Carbon sequestration	The net capture of carbon dioxide by coastal and marine biota	Change in the net amount of carbon stored within an area of coastal saltmarsh within a certain period
Final Services	**Definition**	**Final Services**
Coastal and marine biota	The flow of coastal and marine biota	Change in the quantity / quality of North Sea cod population, seaweed stock, genetic material, ornamental materials, etc. over time
Climate regulation	The contribution of coastal and marine biota to the maintenance of a favourable climate through the regulation of greenhouse gases	Healthy climate
Natural hazard protection	The contribution of coastal and marine biota to the dampening of the intensity of environmental disturbances such as storms, flooding and erosion	The reduction in the intensity of environmental disturbances resulting directly from coastal and marine ecosystem structures such as saltmarsh and sea grass beds
Clean water and sediments	The contribution of coastal and marine biota to the provision of clean water and sediments	Quantity of waste (tonnes) that is recycled or immobilised by coastal and marine biota over a period of time
Places and seascapes	The contribution of coastal and marine biota to places and seascapes	Number of coastal sites designated for internationally important seabird colonies
Goods/Benefits	**Definition**	**Example**
Food (wild, farmed)	Extraction of coastal and marine biota for human consumption	Tonnes of cod landed for human consumption

Intermediate Services	Definition	Example
Fish feed (wild, farmed, bait)	Extraction of coastal and marine biota for non-human consumption	Tonnes of sandeel harvested to be processed into fishmeal; volume of mackerel caught for use as bait in crab/lobster pots
Fertiliser and biofuels	Fertiliser (biocides) or energy sourced from coastal and marine biota	Biomass of algae harvested to be processed into fertiliser
Ornaments and aquaria	Extraction of coastal and marine biota for decoration, fashion, handicraft, souvenirs etc. or for display in aquaria	Number of European lobster extracted for display in aquarium exhibits; amount of skins, shells, corals, plants, extracted from the coastal and marine environment for decoration, fashion etc.
Medicines and blue biotechnology	Extraction of coastal and marine biota in order to produce medicines, pharmaceuticals, animal and plant breeding and biotechnology	Marine-derived pharmaceuticals such as the use of sea lettuce (*Ulva lactuca*) in cosmetic and personal care items including make-up remover, shampoo and shaving lotion
Healthy climate	Improvements to human well-being as a result of a healthy climate	Bodily harm avoided as a result of natural carbon sequestration by coastal and marine biota
Prevention of coastal erosion	Reduction in hazards resulting from the natural prevention of coastal erosion by coastal and marine biota	Prevention of gradual damage to property and land by dunes
Sea defence	Reduction in flooding related hazards as a result of the natural protection provided by coastal and marine biota	Saltmarsh providing a natural form of sea defence in the coastal region
Waste burial / removal / neutralisation	Contribution of coastal and marine biota to achieving pre-defined policy standard related to waste levels in water by natural waste burial, removal and neutralisation	Natural waste breakdown by coastal and marine biota such as reedbeds – in contexts in which pre-defined regulations / standards apply
Tourism and nature watching	Benefits from recreation, leisure driven by coastal seascapes and their associated coastal and marine biota	Human welfare benefits associated with watching seabirds, marine mammals
Spiritual and cultural	Ability to enjoy preferred lifestyle, culture,	The importance of coastal and marine environments

Intermediate Services	Definition	Example
wellbeing[34]	heritage, folklore, religion, creative inspiration, and spirituality; sense of place (use-driven) based on ecosystem aspects	in cultural traditions (e.g. traditional cobble fisheries on east coast) or folklore (e.g. sea shanties)
Aesthetic benefits[35]	Enjoyment of the beauty of coastal and marine seascapes	Higher house prices in coastal locations
Education, research[36]	Enjoyment of formal and informal education, research and science, knowledge systems, etc. in which coastal and marine biota play a role and are a source of information	Amount of funding secured for research on coastal and marine biota; number of scientific research papers published which focus on coastal and marine biota
Health benefits[37]	Relate to human physical and psychological health benefits associated with the direct and indirect use of the coastal and marine environment	Psychological health benefits includes the increased psychological well-being from direct or indirect experience of the coastal and marine environment, while physical generally relates to the coastal and marine environment providing opportunities for exercise and increase physical well-being

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[34] Overlap with recreation and human health related goods and benefits categories should be checked and where possible avoided in the in the valuation assessment. Similarly, there is some ambiguity in the distinction between art and design and aesthetic benefits.

[35] Aesthetic benefits may also be reflected in tourism and nature watching and ornamental values.

[36] Overlap with the category Medicines and blue biotechnology should be avoided in the valuation assessment.

[37] Overlap with tourism and nature watching, spiritual and cultural wellbeing, medicines and food.

Annex 2: Assessment of potential ecosystem service provision as a result of different bioremediation scenarios.

All potential effects are assessed against a baseline of the present day ecosystem service provision.

Ecosystem Services and Goods/Benefits	***Mytilus edulis* long-line**	***Mytilus edulis* bottom culture**	***Ostrea edulis* bottom culture**	***Crassostrea gigas* bottom culture**	***Modiolus modiolus* bottom culture**	***Ostrea edulis* trestle culture**	***Crassostrea gigas* trestle culture**	**Macroalgae rope culture**	**Harvesting opportunistic macroalgae**	**Artificial habitat for macroalgae**	**Seagrass bed restoration**	**Managed realignment (saltmarsh)**	***Spartina anglica* modified management**
Intermediate Services													
Primary production(1)	o	o	o	o	o	o	o	++	--	++	++	++	+
Larval and gamete supply(2)	+	+	+	-	+	+	-	+	-	+	+	+	-
Nutrient cycling(3)	++	+	+	+	+	+	+	++	-	++	++	++	+
Formation of species habitat(4)	+	++	+	o	++	+	+	+	o	++	++	++	+
Formation of physical barriers(5)	o	+	+	+	+	o	o	o	o	+	o	+	+
Formation of seascape(6)	-	++	+	-	+	-	-	-	+	++	++	++	+
Biological control(7)	++	++	++	-	++	o	o	+	++	++	++	++	+
Natural hazard	o	++	++	++	++	o	o	o	o	+	+	++	+

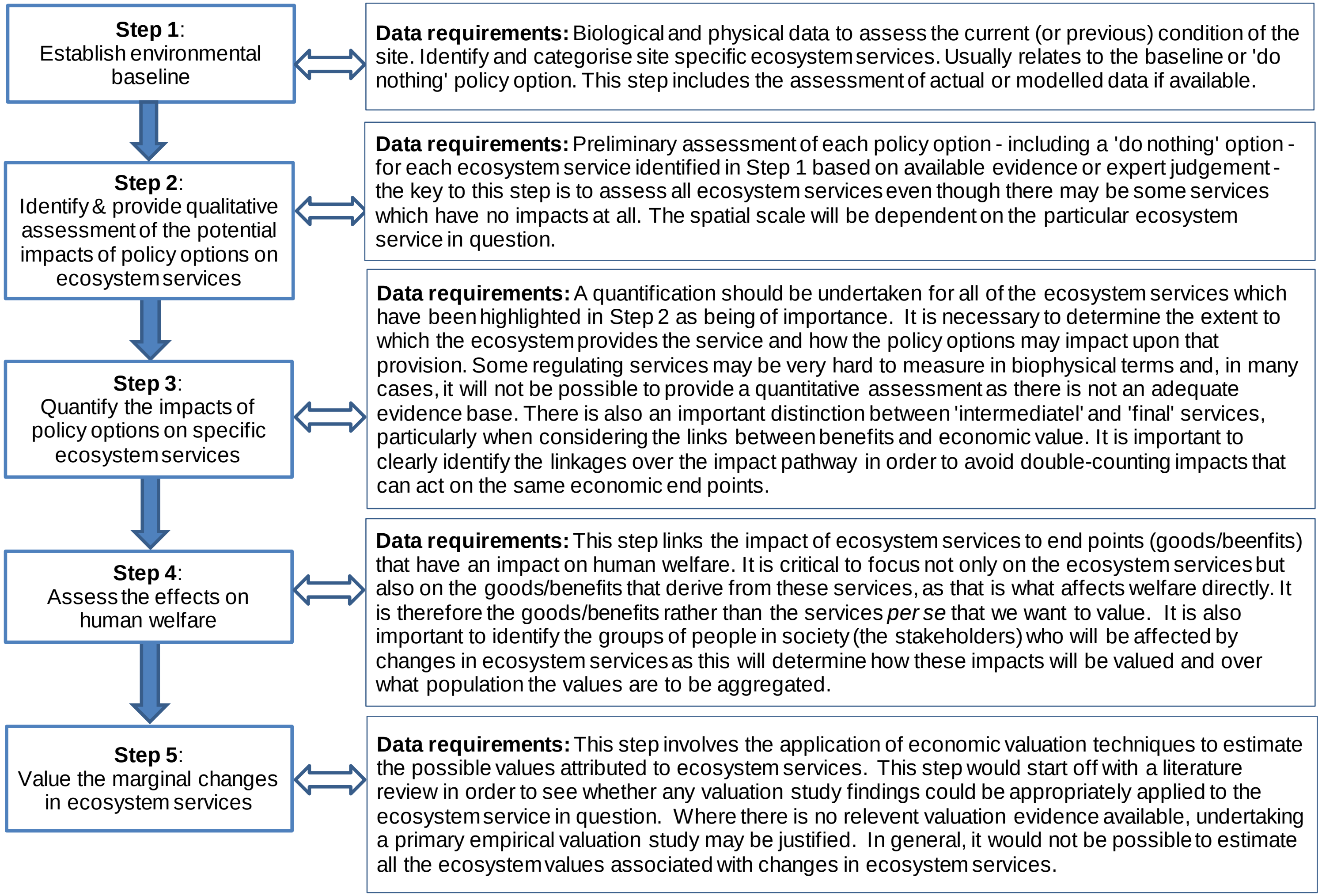
regulation(8)													
Waste breakdown and detoxification(9)	++	++	++	++	++	++	++	+	+	+	+	++	+
Carbon sequestration(10)	+	+	+	+	+	+	+	+	+	+	++	++	+
Final Ecosystem Services													
Fish and shellfish(11)	++	++	++	++	++	++	++	+	o	++	+	++	+
Algae and seaweed(12)	+	+	+	+	+	+	+	++	++	++	+	+	+
Ornamental materials(13)	+	+	+	+	+	+	+	o	o	o	o	o	o
Genetic resources(14)	+?	+?	+?	+?	+?	+?	+?	+?	-?	+?	+?	+?	+?
Water supply(15)	o	o	o	o	o	o	o	o	o	o	o	o	o
Climate regulation(16)	+	+	+	+	+	+	+	+	+	+	+	++	+
Natural hazard protection(17)	o	+	+	+	+	o	o	o	o	+	o	++	+
Clean water(18)	++	+	+	+	+	+	+	++	+	+	+	++	+
Clean sediments(18)	o	-	-	-	-	-	-	o	+	o	o	o	o
Places and seascapes(19)	+	++	+	+	++	o	o	+	+	++	++	++	+
Goods/Benefits													
Food (wild, farmed)(20)	++	+	+	+	o	++	++	+	o	+	o	+	+
Fish feed (wild, farmed, bait)(21)	o	o	o	o	o	o	o	o	o	o	o	o	o
Fertiliser and	o	o	o	o	o	o	o	+	++	+	o	+	+

biofuels(22)													
Ornaments and aquaria(23)	+	+	+	+	+	+	+	o	o	o	o	o	o
Medicines and blue biotechnology(24)	?	?	?	?	?	?	?	+	+	+	?	?	?
Healthy climate(25)	?	?	?	?	?	?	?	+	+	+	+	++	+
Prevention of coastal erosion(26)	o	+	+	+	+	o	o	o	o	+	+	++	+
Sea defence(27)	o	+	+	+	+	o	o	o	o	+	o	++	+
Waste burial / removal / neutralisation(28)	+	++	++	++	++	++	++	+	++	+	+	++	++
Tourism and nature watching(29)	+/-	+	+	--	++	+/-	+/-	+/-	++	+	++	++	+
Spiritual and cultural well-being(30)	-	+	+	-	+	-	-	-	+	+	+	+	-
Aesthetic benefits(31)	-	+	+	+	+	-	-	-	++	+	++	++	-
Education, research(32)	+	+	+	+	+	+	+	+	+	+	+	+	+
Health benefits(33)	o	+	+	o	+	o	o	o	++	+	+	++	+
Goods/benefits score (/28)	**3**	**11**	**11**	**5**	**11**	**4**	**4**	**4**	**14**	**12**	**10**	**18**	**8**
% Goods/benefits score	**11**	**39**	**39**	**18**	**39**	**14**	**14**	**14**	**50**	**43**	**36**	**64**	**29**
Relative goods/benefits score**	**L**	**M**	**M**	**L**	**M**	**L**	**L**	**L**	**H**	**H**	**M**	**H**	**M**

Key: ++ Potential significant positive effect (+2); + Potential positive effect (+1); o Negligible effect (0); − Potential negative effect (-1); −− Potential significant negative effect (-2); ? Gaps in evidence; **Relative goods/benefits score: Low (L) = <20%, Moderate (M) = 20-40%, High (H) = >40%.

(1) Service provided by macrophytes and angiosperms only. Harvesting opportunistic algae removes primary production from the system.
(2) Most scenarios introduce additional biological material. Harvesting opportunistic algae removes it from the system. Non-native species are seen as the provision of a potentially negative impact.
(3) Potential related to density – ropes may offer greater potential.
(4) Bed habitats provide a greater potential for forming species habitats. *Crassostrea* beds do not provide this service.
(5) Related to habitat structures on the seabed only.
(6) Beds have greatest potential - ropes and trestles are man-made so have a negative potential.
(7) Bed structures reflect greater potential given their complexity.
(8) Reflects protection provided by bed stabilising and/or reef forming habitats.
(9) Saltmarsh and bivalves are thought to offer greatest potential.
(10) All positive but saltmarsh offers the greatest potential to sequester carbon.
(11) Reflects the addition of shellfish species and fish nursery habitats.
(12) Reflects addition of macrophytes and potential for their colonisation on hard substrate.
(13) Potential only relates to bivalve species for shells.
(14) Addition of biological organisms leads to a potentially larger gene pool.
(15) Not relevant in relation to bioremediation scenarios.
(16) Reflects the potential for carbon sequestration.
(17) Bed structures have the potential to attenuate more wave energy.
(18) Ropes provide greater potential to improve water quality. Bottom culture improves water quality but reduces sediment quality.
(19) Bed habitats provide more complex natural seascapes. Trestles are man-made.
(20) Greatest potential for harvesting bivalves as a food source depending on scenario.
(21) Negligible potential to harvest for animal feed, fishing bait.
(22) Potential for harvesting macrophytes and saltmarsh plants for fertilisers and biofuels.
(23) Potential to harvest bivalve shells for ornaments.
(24) Potential from macrophytes well established, unknown for other bioremediation scenarios.
(25) Potential in relation to carbon sequestration. Unknown for bivalve species.
(26) Reflected by binding properties of seabed habitat structures and attenuation of wave energy.
(27) Saltmarsh offers greatest potential for natural sea defence although bivalve habitats on the seabed will also attenuate wave energy.
(28) Greatest potential from bivalves and saltmarsh. *Spartina anglica* management scenario would also remove additional waste.
(29) Positive in relation to biodiversity e.g. diving/wildlife watching – negative in relation to conflicts with other sea users e.g. ropes and boating, trestles and beach users.
(30) Positive potential from natural habitats – negative in relation to man-made structures and non-native species.
(31) Positive potential from natural habitats – negative in relation to man-made structures and non-native species.
(32) Positive potential from all scenarios in relation to monitoring bioremediation scenarios.
(33) Saltmarsh offers the greatest potential in relation to physical and psychological health benefits.

Annex 3: Evaluation of policy options using an ecosystem services approach (Atkins et al., 2011b, adapted from Defra, 2007).



Step 1:
Establish environmental baseline

Data requirements: Biological and physical data to assess the current (or previous) condition of the site. Identify and categorise site specific ecosystem services. Usually relates to the baseline or 'do nothing' policy option. This step includes the assessment of actual or modelled data if available.

Step 2:
Identify & provide qualitative assessment of the potential impacts of policy options on ecosystem services

Data requirements: Preliminary assessment of each policy option - including a 'do nothing' option - for each ecosystem service identified in Step 1 based on available evidence or expert judgement - the key to this step is to assess all ecosystem services even though there may be some services which have no impacts at all. The spatial scale will be dependent on the particular ecosystem service in question.

Step 3:
Quantify the impacts of policy options on specific ecosystem services

Data requirements: A quantification should be undertaken for all of the ecosystem services which have been highlighted in Step 2 as being of importance. It is necessary to determine the extent to which the ecosystem provides the service and how the policy options may impact upon that provision. Some regulating services may be very hard to measure in biophysical terms and, in many cases, it will not be possible to provide a quantitative assessment as there is not an adequate evidence base. There is also an important distinction between 'intermediatel' and 'final' services, particularly when considering the links between benefits and economic value. It is important to clearly identify the linkages over the impact pathway in order to avoid double-counting impacts that can act on the same economic end points.

Step 4:
Assess the effects on human welfare

Data requirements: This step links the impact of ecosystem services to end points (goods/beenfits) that have an impact on human welfare. It is critical to focus not only on the ecosystem services but also on the goods/benefits that derive from these services, as that is what affects welfare directly. It is therefore the goods/benefits rather than the services *per se* that we want to value. It is also important to identify the groups of people in society (the stakeholders) who will be affected by changes in ecosystem services as this will determine how these impacts will be valued and over what population the values are to be aggregated.

Step 5:
Value the marginal changes in ecosystem services

Data requirements: This step involves the application of economic valuation techniques to estimate the possible values attributed to ecosystem services. This step would start off with a literature review in order to see whether any valuation study findings could be appropriately applied to the ecosystem service in question. Where there is no relevent valuation evidence available, undertaking a primary empirical valuation study may be justified. In general, it would not be possible to estimate all the ecosystem values associated with changes in ecosystem services.

Annex 4: Consistency of bioremediation with south marine plan policy objectives

High level objective	Policy code	Is bioremediation as a proposal consistent with the policy objective?	Can bioremediation support the policy objective as a mitigation measure?
8	S-TR-2c	No - potential to impact	n/a
8	S-TR-2d	No - potential to impact	Yes
9	S-TR-3c	No - potential to impact	No
14	S-TR-4b	Yes / No (context dependent)	Yes
12	S-DEF-1b	n/a	n/a
9	S-CHA-1b	Yes / No (context dependent)	Yes / No (context dependent)
10	S-HER-1c	n/a	No
7	S-WQ-1c	Yes	Yes
13	S-CAB-1b	No	No
13	S-CAB-2b	n/a	n/a
12	S-CO-1c	Yes	Yes
14	S-REN-1c	Yes	n/a
12	S-TIDE-1b	No	n/a
15	S-EMP-1c	Yes	Yes
5	S-DD-1c	Yes (context dependent)	n/a
12	S-DD-2b	No	n/a
8	S-GOV-1b	No	n/a
12	S-AGG-1b	n/a	n/a
12	S-AGG-2c	n/a	n/a
12	S-AGG-3c	No	n/a
8	S-AGG-4c	Yes	n/a
12	S-OG-1a	n/a	n/a
13	S-INF-1c	Yes	Yes
13	S-INF-2c	Yes	Yes
5	S-FISH-5	n/a	n/a
4	S-BIO-2c	Yes / No	No
4	S-BIO-3c	Yes (if correctly managed)	n/a
5	S-BIO-6c	Yes	Yes

High level objective	Policy code	Is bioremediation as a proposal consistent with the policy objective?	Can bioremediation support the policy objective as a mitigation measure?
3	S-MPA-1c	Yes / No	Yes / No
3	S-MPA-2c	n/a	n/a
3	S-MPA-3c	Yes / No	Yes / No
3	S-MPA-4b	Yes / No	Yes / No
3	S-MPA-5c	n/a	n/a
12	S-AQ-1b	Yes / No	Yes
13	S-AQ-2a	Yes	Yes
13	S-PS-1b	No	n/a
13	S-PS-2b	No	n/a
12	S-PS-3b	No	n/a
12	S-PS-4b	No	n/a
2	S-BIO-1C	Yes / No	Yes
4	S-BIO-4c	n/a	n/a
5	S-BIO-5c	Yes	Yes
7	S-BIO-7c	Yes (context dependent)	Yes
4	S-GES-1c	Yes / No	Yes
4	S-ECO-1d	Yes / No (context dependent)	Yes
5	S-FISH-1c	Yes	Yes
8	S-FISH-2c	Yes	Yes
8	S-FISH-3c	Yes	Yes
6	S-DIST-1c	Yes	Yes
6	S-DIST-2c	n/a	n/a
6	S-DIST-3c	n/a	n/a
7	S-WQ-2b	Yes	Yes
7	S-WQ-3b	Yes	Yes
1	S-CC-1c	Yes	Yes
2	S-CC-2c	n/a	n/a
2	S-CC-3c	Yes	Yes
2	S-CC-4c	n/a	Yes
2	S-CC-5c	Yes (context dependent)	Yes (context dependent)
2	S-CC-6c	n/a	n/a