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A systematic review of transferable solution options for the environmental impacts of tidal lagoons

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ABSTRACT

Tidal lagoons are presented as an environmentally friendly alternative to tidal barrages. This does not mean that their environmental impacts can be overlooked. A UK government review recommended a pilot scheme lagoon go ahead, with careful environmental monitoring. Despite recent government rejection of a lagoon scheme, it is still more important than ever to consider environmental solution options for any future lagoon developments. There are no operating lagoons in the world and so their environmental impacts are not fully understood. However, there is a vast quantity of literature available from other industries addressing similar impacts in the coastal, ocean and river environments. This systematic review follows the PRISMA and CEE guidance. Using this methodology the available literature covering relevant solution options from other industries that could be applied to future lagoon developments was quantified. This presents an investigation into solution options only, giving a quantitative analysis of what resources are available, how this compares to industry understanding, where the expertise lies globally, what impacts are being addressed and how applicable the solutions are for lagoon application. This paper analyses the extent and relevance of this available research on solutions as a resource for the nascent lagoon industry. Over half of the solutions found in this review require only small shifts in development for them to be realistic solution options for the lagoon industry in the future. This review opens the door on a vast and valuable resource and justifies the need for further investigation into solutions for the lagoon industry.

1. Introduction

Tidal range technology extracts energy from the tides by creating an artificial difference in water levels, or head. Higher water levels are constrained by barrage or lagoon walls and sluice gates; when these are opened, the flow of water drives turbines to generate electricity [1]. The key advantages of tidal range energy include a high level of predictability [2], the ability to phase shift energy to provide a continuous base load supply [3] and the long expected life span [4]. Despite these advantages there are concerns surrounding high capital cost and environmental impacts, and the Severn Barrage in the UK has been repeatedly rejected since 1920s for these reasons [5–7]. Whilst there are barrages in successful operation, such as the La Rance 240 MW barrage in Brittany, France and the Sihwa Barrage in South Korea, there have been numerous environmental issues associated with them, primarily sedimentation and water pollution issues [1]. Tidal lagoons are often presented as environmentally friendly alternatives to barrage developments [6,8,9], but this does not mean their environmental impacts can be overlooked.

A total of 145 countries signed the recent Paris Agreement for action on climate change [10]. As part of this the UK has ambitious carbon reduction targets of 80% reduction on 1990 levels by 2050 [11]. In addition, the UK is legally obliged to provide 20% of its energy needs from renewable sources by 2020 [12]. Drastic action is required to meet this, since under ‘business as usual’ conditions the UK will fail to reach this target in the next two years [13]. The UK has the greatest tidal energy resource in the world [7]. It is expected that a national fleet of lagoons could supply 8% of the UK's electricity [14].

The most recent developments in the lagoon sector have been in the UK, with Tidal Lagoon Power Ltd (TLP) proposing a fleet of lagoons for deployment and the government undertaking an extensive review into their feasibility. The focus of this paper is on the UK, because of these recent developments. Despite this focus, the analysis and key findings of the paper are relevant to any country wishing to develop a lagoon in the future. The government review recommended that a pilot scheme lagoon be deployed with careful environmental monitoring as a precursor for national lagoon development [9]. Whilst other sites and lagoons have been investigated, the most advanced project has been the

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Swansea Bay Tidal Lagoon from TLP [7,15,16]. The lagoon was awarded a Development Consent Order (DCO) in 2015, but was recently rejected by the UK government based on cost concerns [14,17]. Despite this set back, there are numerous lagoon projects in the pipeline in the UK and globally and there is a certain expectation placed on the first mover to set a precedent for an environmentally sustainable lagoon industry.

Progress has been made in identifying the environmental impacts of tidal lagoons such as the hydrodynamics [18–23], morphodynamics [24,25], water quality [26,27], ecological interactions and society [6], environmental knock on implications [1] and industry perspectives on the environmental impacts of lagoons [28]. Less well researched are the potential solution options for the identified and estimated environmental impacts. Whilst a few papers consider the operation of a tidal lagoon and its influence on the hydrodynamic regime [29,30], at the time of writing, no existing papers holistically investigate a variety of solution options to address numerous environmental impacts that are likely to arise from tidal lagoons. This is not surprising given that there are currently no operational, energy generating, man-made tidal lagoons in the world, and therefore no operational data on the environmental impacts of lagoons or lessons to be learnt on potential solution implementation options.

Recent industry engagement with the UK lagoon sector considered what the industry (developers, regulators, policy makers, consultants, conservation bodies, government bodies) believed to be the key impacts of lagoon developments and what the potential solution options could be [28]. The key findings of this research found that, from the industry's perspective, the most significant environmental impacts are: sediment regime changes, hydrodynamic change, impacts on habitats and biodiversity and impacts on marine mammals and fish [28]. The solution options presented by the industry in this research are mainly focused around engineering, site or technology design or compensation and catchment based measures [28]. This previous research will be built upon by considering and comparing the literature research available in comparison to this industry perspective referred to throughout this paper as the ‘industry's perspective’ or ‘industry's understanding’.

Tidal lagoons are a new idea, but the key concepts making up this idea are not new. Other industries have applied similar technology and engineering concepts and as such have had similar environmental impacts. These other applications include use of walls to impound water in the coastal defence, dam, barrage and hydropower industries, and use of turbines to generate energy in river run, pumped storage and tidal stream applications. In addition, environmental impacts such as water and sediment pollution, fish and marine mammal impacts, marine spatial planning conflicts and loss of marine habitats and biodiversity are commonly addressed in maritime and river industries such as the offshore wind industry, shipping, port development, aquaculture, river catchment land management, and offshore oil and gas industries, to name only a few. It is expected that the nascent lagoon industry can draw from the experiences seen in these industries that have already successfully managed similar environmental impacts.

This systematic literature review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidance [31] alongside guidance from Collaboration on Environmental Evidence [32]. This methodology and reporting style is already established and recommended for research that uses systematic reviews to further knowledge in marine policy or ocean management sectors [33–35]. Using this methodology the extent and relevance of the available literature covering solution options from other ocean, coastal and river industries that could be applied to future lagoon developments is quantified.

This paper presents a quantitative investigation into the literature resources surrounding solution options only, it does not look in detail at the environmental impacts of tidal lagoons (only those being addressed by the solutions found) and it does not provide detailed qualitative analysis on the solutions options. The review gives a quantitative picture of what literature resources are currently available to the industry, how this compares to current industry understanding and perspective [28], where the clusters of expertise lie globally, what impacts are being addressed, where the solutions fit on a mitigation hierarchy and how well developed and applicable the solutions are in terms of their potential application to future lagoon development. This information determines whether the current research on solutions to environmental impacts from other industries is substantial and relevant enough to warrant further investigation by the lagoon sector into transferrable environmental policy and management options.

2. Methodology

2.1. Literature search

This review uses the PRISMA statement as a reporting style guide [31] alongside guidance from Collaboration on Environmental Evidence (CEE) [32] on systematic literature review methodology. This method was chosen based on its existing use and recent recommendation in the marine environmental sector [33–35]. Whilst the PRISMA methodology was used and followed in full, Sections 5 and 6 of the CEE were used as secondary supporting guidance to inform key parts of the methodology, such as conducting a literature search and screening documents for eligibility.

The literature search was performed on three databases: Google Scholar (https://scholar.google.co.uk/), SciVerse Scopus (https://www.scopus.com/home.uri) and Science Direct (http://www.sciencedirect.com/). Together, these form a comprehensive database of peer-reviewed research. The collected papers were between 1987 and the cut-off date of 04/04/2017. The following search terms in the title, abstract or keywords allowed the papers to be included in the initial literature search: ‘Marine’ or ‘Ocean’, ‘Environmental impact’ or ‘Environmental risk’ and ‘Solution’ or ‘Mitigation’.

The search terms were entered into the search engines. The initial literature search brought up 1114 papers, 688 papers after duplicates removed, Fig. 1 shows a flow chart of paper selection, which is a standard PRISMA reporting guideline. Grey literature such as websites or documents outside traditional commercial or academic publishing, and non-English publications were excluded from the review at this point if found.

2.2. Selection criteria

The 688 papers from the initial search were screened in terms of their abstract contents. A total of 559 papers were excluded at this stage (Fig. 1) the exclusion criteria, with the number excluded for each reason are shown in Table 1. The remaining 129 paper abstracts included information on solutions which could be applied to the impacts likely to be presented by tidal lagoons in the future. As a general rule, if the abstract was unclear or any uncertainty surrounded its inclusion it was included for the next stage of screening.

The next stage was full text screening of the 129 papers selected from the abstract screening. The exclusion criteria here were the same as the abstract screening stage listed above, with the additional exclusion factor of books and any further grey literature found (Table 1). Books and ‘grey literature’ were excluded as any new, credible and innovative solutions are expected to be represented in the up-to-date, peer reviewed research papers. ‘Grey literature’ was defined in this study as any documents or websites that had not been peer reviewed or were not from a reputable company or organisation, expert judgement was used to exclude sources as ‘Grey Literature’. A total of 52 papers were excluded at the full text screening stage of the review.

Following this final screening stage a total of 77 papers were included in the final data collection and quantitative analysis (Fig. 1). All the papers included had viable solution options presented in their full text that could be applied in the future to address the marine and

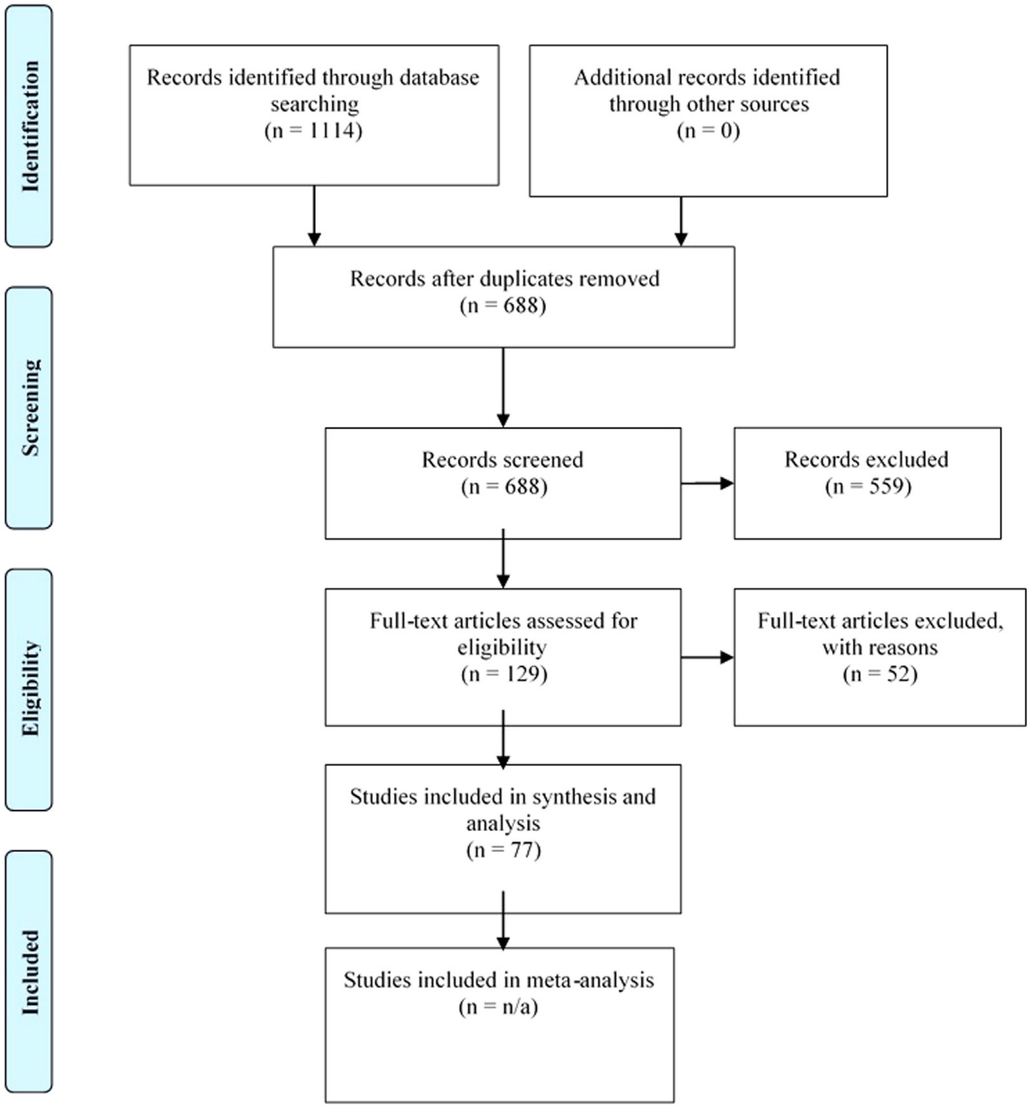

Fig. 1. Flow chart of the review paper selection process and the number of papers excluded at each stage. This follows the PRISMA statement guidelines on reporting review process [30].

coastal environmental impacts that may arise as a result of the implementation of tidal lagoons in the UK.

2.3. Data extraction

From the final 77 papers that remained after the screening process, information for analysis was extracted. The data extracted from the papers centred around two main themes: 1) characteristics of the paper; and 2) solution options presented for environmental impacts. The data extracted from the papers along with information on the purpose for extraction is detailed in Table 2.

The information extracted allowed a quantitative analysis of patterns, identification of knowledge gaps and further interpretation of the potential solution options that could be applied to the environmental impacts likely to arise in the future tidal lagoon industry. Applying expert judgement, the scaled scoring noted in Table 2 was used to determine the development stage and applicability of the solutions to lagoon application. Combining this with the other data extraction, a

Table 1
Paper exclusion criteria at abstract and full text screening stages with number excluded for each reason shown.

Exclusion Criteria	Abstract Screening	Full Text Screening
Impacts presented could not be related to lagoons	146	16
Impacts identified but no solution options given	143	11
Focus of the paper is not on environmental impacts	96	16
Focus of the paper on carbon emissions or climate change	67	1
Impacts are purely terrestrial/not relevant to lagoons	49	1
Paper is for global scale impacts	44	0
Impacts are of the environment on engineering	13	1
Not available/ Not Found	1	1
Books or grey literature publications	0	5

Table 2
Data extracted from the final 77 papers, further details and the reason or purpose for extraction.

Data Extracted	Details	Purpose
Publication year	Year first published	Provides timeframe information
Author location	Based on first author affiliation	Provides geographical location and indication of expertise location
Study location	If applicable (not all focus on a location)	Indication of application location and relevance of studies
Type of paper data	Review, model or analysis of existing data, direct observation, expert opinion	Provides indication of the quality and type of data available is it real world or theoretical
Paper Discipline	Environmental, engineering, social, economic, legal	Indication of from which disciplines solutions are arising
Study area type	Marine, coastal, river, other	Indication of relevance to coastal lagoon applications
Environmental Impact being addressed	e.g. fish and marine mammals, pollution (sediment/water), hydrodynamics, habitats and biodiversity, sediment regime	Indication of which impacts are well researched in terms of solution options
Description of solution option	Qualitative description	Provides understanding of the solution options available
Solution Type	Engineering, site of technology design, operation and maintenance, compensation or catchment based measures.	To determine at what stage solutions are most well researched, to identify any knowledge gaps
Mitigation hierarchy of solutions	Avoid, reduce, compensate/catchment based	To determine at what stage solutions are most well researched, to identify any knowledge gaps
1–5 Scale of solution development application[a]	1 = Theoretical 2 = Simulated or modelled 3 = Tested 4 = Applied at pilot scale 5 = Applied at large scale	Gives indication of how developed the solutions are
1–5 Scale of solution applicability to lagoons[a]	1 = Other Industry 2 = Other industry, easily adapted to lagoons 3 = Marine Industry, not easily adapted 4 = Marine industry, easily adapted 5 = Lagoon or barrage specific	Gives an indication as to how applicable the solutions are to application in the lagoon industry

[a] Scores assigned based on expert judgement

picture was built on the extent and relevance of the literature available and if the solution options presented from other industries could be valuable in the future lagoon industry.

3. Results

3.1. Analysis of included literature

The number of papers on solution options for environmental impacts increased significantly after 2012, with 70% of the included papers from 2012 onwards (Fig. 2). From the first paper in 1987 to 2011 there was an average of only 1 paper published per year. In comparison from 2012 to 2017 the average number of papers per year was 11. This suggests that this research field of beginning to address environmental impacts is relatively new and momentum is building on the subject of solution options.

The majority of papers are review papers (39%), followed by modelling or analysis of existing data (25%) with the remainder being direct observation studies (19%) and expert opinion (17%). The high number of review papers has allowed a greater net to be cast in terms of studies covered in this review (directly or via another review).

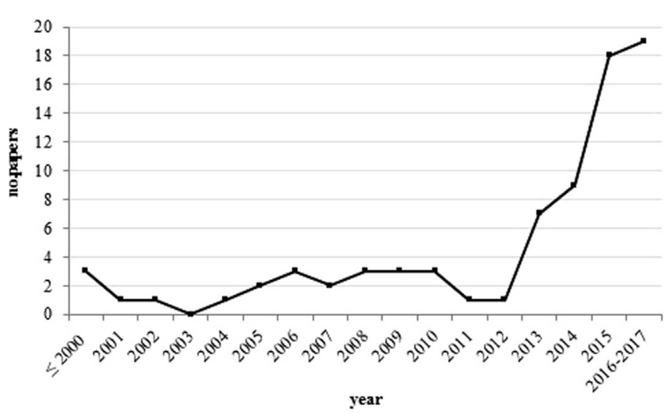

Fig. 2. Number of papers per year.

Although it is a concern that the review papers will only provide theoretical ideas rather than concrete data, this is mitigated by the fact that a fifth of the papers included are direct observation papers, indicating that papers that have implemented and directly observed solution options to environmental impacts are present in the study.

A large majority of papers on solution options (75%) are from an environmental discipline with the remaining quarter from either social (12%), engineering (9%), economic (3%) or legal (1%) disciplines. This is not surprising given the strong grounding in environmental disciplines required when considering solution options to environmental impacts. 87% of the papers included in the research are from either coastal or marine view points, this is not surprising given the aim of the study to find solutions for tidal lagoons using search terms 'ocean' and 'marine'. However the remaining 13% of papers that met the criteria for inclusion were from river or other areas such as inland aquaculture farms or wetlands, showing that a wide variety of industries could contribute transferable solutions to the lagoon industry. This suggests that widening the search to include these parameters in the search terms may be beneficial in future literature reviews (Fig. 3).

Assuming that paper author affiliation and study area represents geographical areas of expertise, the main clusters of expertise on solution options to environmental impacts relevant to tidal lagoons lie within North America (30%), Western Europe (14%) and Southern Europe (14%) (Fig. 4). The author affiliations and number of papers mapped in Fig. 4 show a truly global perspective on the solution options to environmental impacts. A large proportion of the papers (40%, No. 31) had no specific area of study. The study area clusters align partly with the main author affiliation locations, with key clusters in Europe, North America and Australasia. Fig. 4 represents the review papers' global information gathering on solution options to the environmental impacts that tidal lagoons may present in the future. Despite the most progress on lagoon deployment being made in the UK, Fig. 4 suggests that there are lessons to be learnt globally from other industries on potential environmental impact solutions, in particular from the key clusters in North America, Europe and Australasia.

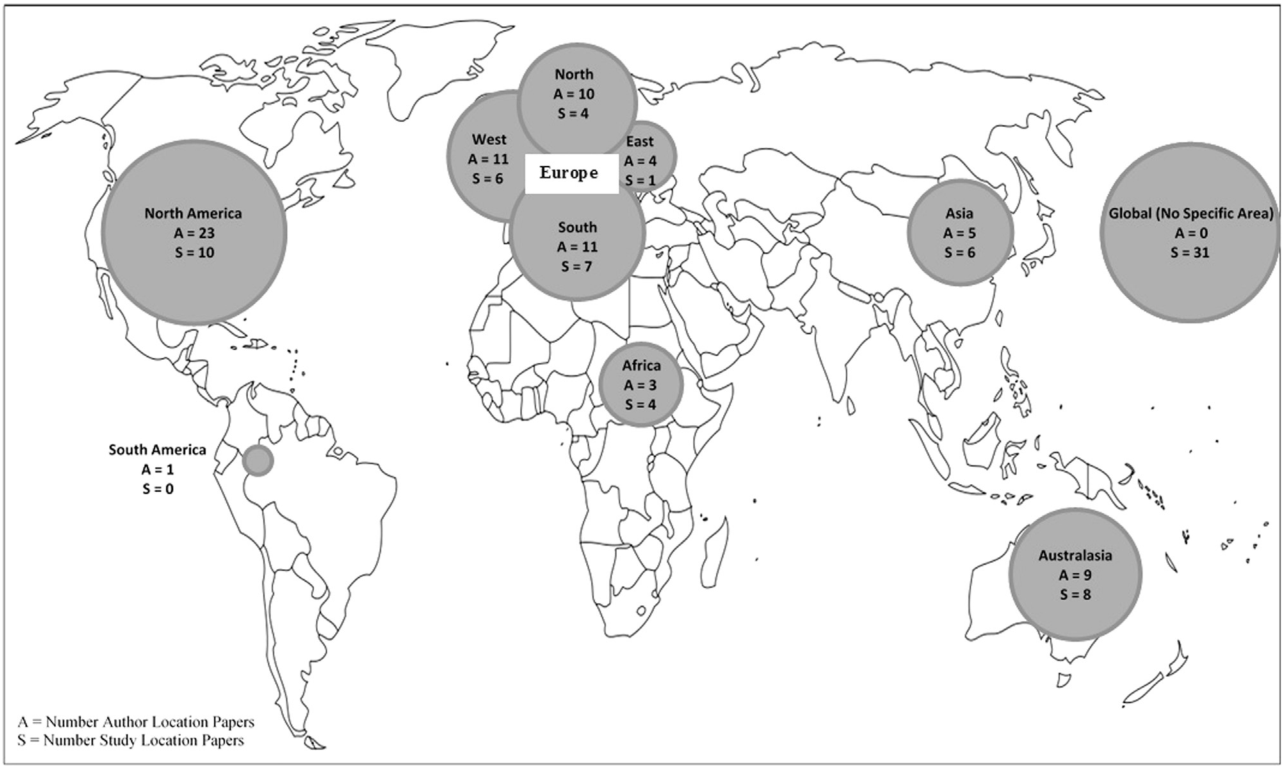

Fig. 3. Number of papers per author affiliation location (A) and study area location (S). 31 papers of 77 (40%) had no specific area of study. (Base Map Source: [91]).

3.2. Environmental impacts being addressed

The environmental impacts addressed in the included papers are varied and numerous. In order to provide an analysis each paper has been broadly categorised into one of the impacted groups as follows: Sediment regime, hydrodynamics, habitats and biodiversity, fish and marine mammals, pollution (water or sediment) and general impacts (more than 5 impacts considered in one paper). Fig. 4 shows the percentage number of papers against the impacted group which the papers addressed. The environmental impact categories were therefore defined based on what environmental impacts have been addressed by the solution options discovered in the literature review papers.

Almost a quarter (22%) of the papers consider solution options for the impact of either water pollution or pollution in the sediment. These impacts included marine water quality pollution from oil spills, increased vessel activity and associated pollution, pollution within entrapped or enclosed water bodies and marine litter due to increased tourism. They also included sedimentation pollution due to increased dredging activities and disturbance of contaminated sediments, entrapment of outflows and the pollution of sediment and benthic communities. The relatively high number of papers on these impacts could suggest that they have been common impacts in other marine, coastal and river industries and therefore may also be an issue for lagoons. All the papers present solution options for these impacts, so on the other hand the high number of papers could suggest that these impacts are well researched and therefore more easily addressed.

18% of the papers considered the impacts on fish and marine mammals, including noise pollution due to the construction of marine infrastructure, increased seismic marine surveys and vessel activity, blade interaction, barriers to migration and disruption to breeding grounds. A further 16% of papers considered changing hydrodynamics as the key environmental impact, 13% covered the impact on habitat or biodiversity loss, with 12% focusing on sediment regime changes including morphodynamics, bathymetry alterations, coastal sedimentation and/or erosion.

All the environmental impacts considered in the included papers are thought to be applicable to tidal lagoons in the future. The solutions presented in the literature to address these impacts could also potentially provide the foundation for solution options for the environmental impacts of tidal lagoons.

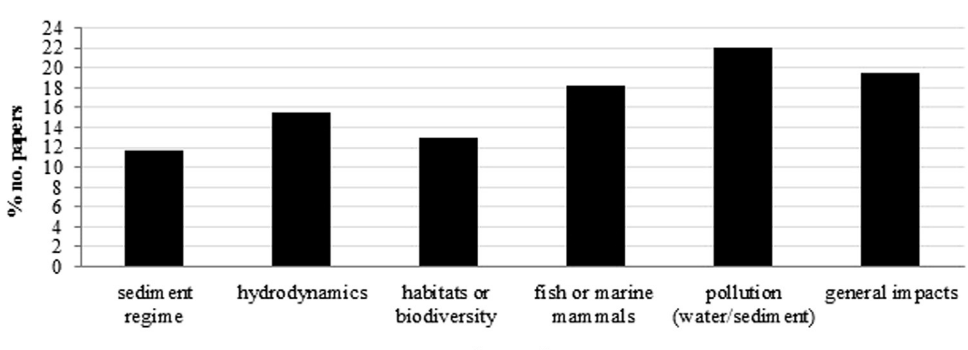

Fig. 4. Percentage number of papers addressing different environmental impacts.

Table 3
Selection of example solutions within each solution category.

Solution Category	Selection of Examples
Engineering, Site, Technology Design	Sensitive site selection, 'safe' exposure levels and distances from protected or otherwise sensitive areas [39]
	Site selection in terms of best potential for habitat creation within the structures themselves, site selection to promote habitat creation on the structure over that lost during installation [40]
	Using artificial reefs or installing marine structures with appropriate materials that will allow for an enhanced reef effect providing habitat [41]
	Building and designing of green infrastructure within the design plans such as providing green (or in lagoon case blue) corridors or hubs or targeting particular keystone or umbrella species in the design of structures [42]
	Use of multi-purpose offshore installations to reduce impacts and increase viability of blue growth projects [43]
	Advancements in turbine design to reduce collision risk, careful selection of turbines to suit not only energy generation but sensitive species in the area [6]
	Incorporation of bubble curtains, flashing lights, passive acoustic monitoring, fish ladders, spill gates, fish lifts, surface collector or guidance nets, hydro sound dampeners in the initial engineering design for the impacts on fish and marine mammals[44–46]
	Use of nearby land sloping characteristics in the initial design of a structure to predict and prevent the amount of run-off related water contamination or in the lagoon case pollution entrapment [47]
	Incorporation of engineering flooding options in the initial engineering plans such as use of beach nourishment or artificial sand dunes to avoid coastal erosion [48].
	Better use of modelling, monitoring, incorporation of historic knowledge and advancements in new techniques, transfer of knowledge between industries, holistic view coupling of models to better understand and select sites, technology and engineering design [49–57].
Operation & Maintenance	Use of coastal geo-indicators and ecological indicators to provide rapid response to operation and maintenance plans [58, 59]
	Integration of ecosystem functioning and ecosystem based management into coastal management practices to reduce environmental impacts, using an ecosystem based approach [60, 61]
	Use of dredge and fill beach nourishment techniques to reduce erosion [62]. Could be dredged material from the lagoon.
	Control of sedimentation through sediment retention before entrance, sediment bypassing, control of hydrodynamic flow to reduce sediment accumulation, flushing or sluicing and managing existing deposits through sensitive dredging. Optimal dredging times and frequency. Potential end use of dredged sediments in civil engineering such as road subgrade layers. [63–66]
	Use of linkage framework to manage cumulative and overlapping ocean activities resulting in cumulative environmental impacts [67]
	Use of flora to filter pollutants or effluents [68]
	Spatial and temporal zonation and exclusion zones of activities to reduce environmental impacts [69–72]
	Energy generation operation to reduce hydrodynamic impacts [28]. Careful operations management of vessel activity, relocation of vessel movement to lower risk areas, careful monitoring of vessel speed limits, optimal vessel use in terms of time at sea and frequency of trips to reduce noise and water pollution and chance of collisions or oil/fuel spill [70,73].
	In situ sediment pollution remediation techniques, including thin capping, solidification, sediment flushing, nanocompite reactive capping and bio reactive capping, Stabilisation of sediments using hydraulic binders [65,74]
	Visitor education on environmentally friendly practices in and around tourist attractions to reduce marine litter and pollution [75,76]
Compensation or Catchment Based Measures	Use of habitat creation through wetlands and vegetated ditches to reduce flooding or storm damage or to mitigate water pollution, improve water quality and compensate for loss elsewhere [77–81]
	Use of satellite remote sensing data to find and repair/compensate damage to ecology or habitat loss, mainly used for oil spills currently but could be applied to habitat loss [82]
	Use of geoengineering such as urea fertilisation to increase fish populations or using natural sediment transport systems to deposit sediment along the coastline to compensate for loss [83]
	Use of natural resources to increase flood defence level, such as mangrove restoration or afforestation [84]
	Use of Payment for Ecosystem Services (PES) schemes to conserve threatened ecosystems or to compensate over and above the value of ecosystem lost [85]
	Soft engineering approaches to provide compensation such as mangrove afforestation, coral reef transplants or introductions, marine reserves, planting of water filtering plants [86]
	Use of bioremediation methods like those seen in water pollution incidents [87]
	Incorporating net gain bargaining in development of marine energy, integrating ecosystem service impacts into decision making [88]
	Targeting certain impacts to improve status of certain species, some impacts more effectively mitigated than others [89]
	Predicting need for biodiversity offsetting for habitat or biodiversity loss using a projects Environmental Impact Assessment [90]

Note: These solutions are just to provide examples within each category. They are not a comprehensive list of solution options

3.3. Solution options and application for lagoons

Every one of the 77 included papers addressed a tidal lagoon-relevant environmental impact with a solution. Some of these solution options were the same, but nevertheless a database of literature on both the environmental impacts of lagoons and their potential solution options has been created through this systematic literature review. For analysis the solution options have been grouped into: 'Engineering, site or technology design', 'Operation and maintenance' and 'Compensation and catchment based measures'. Whilst it is impractical to list all of the solution options Table 3 provides examples of solutions within each of these categories and the accompanying database is published alongside this paper. Fig. 5 shows the spread of papers within these solution option categories.

Within the literature, 44% of the solution options fall under the 'Operation and maintenance' category. This includes, but is not limited to, temporal and spatial zonation of activities, sustainable dredging options and management of dredging material, advances in environmental monitoring, planning vessel activity and safety and operational timing and structure of energy generation. 30% of the solutions were within the 'engineering, site or technology design' category. This category refers to environmental awareness within site location, site design around sensitive locations, novel data or models to aid in site selection, integration of green infrastructure such as coral reefs, careful selection of building materials to promote target habitats, selection of technology to reduce impacts, wall design to reduce impacts and enhance potential environmental benefits. The lowest solution category reported in the literature is that of compensation or catchment based measures (25%). Within those solutions examples include habitat creation or restoration papers, payment for ecosystem services (PES)

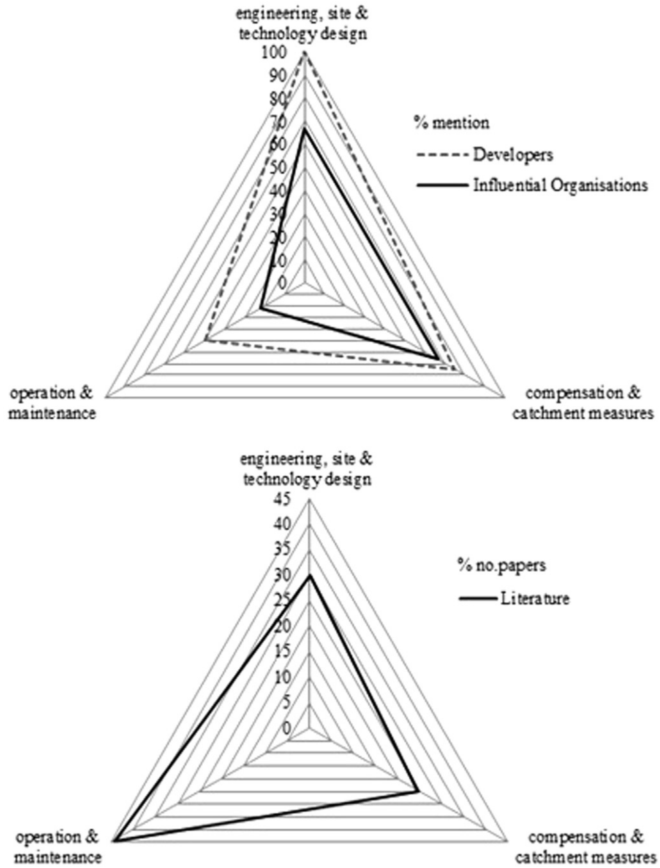

Fig. 5. Spread of solution options mentioned in a recent study on industry engagement for tidal lagoons (top) [27] and within this literature review study (bottom) over three basic categories.

schemes or other catchment based activities. Table 3 provides a more detailed list of solution examples.

A recent paper describing the lagoon industry perspective on solutions to environmental impacts sways more towards either engineering, site or technology design, or compensation and catchment based measures [28] (top triangle, Fig. 5). Neither developers nor influencing organisations mention operation and maintenance strategies most frequently. In comparison the literature found in this review on the potential solution options which could be applied to the impacts of tidal lagoons shows that the majority of papers are on operation and maintenance type solutions. Fig. 6 compares the industry's view on solutions [28] to the solution categories uncovered as part of this literature review. The results suggests that the gap in operation and maintenance understanding found in a recent paper on the industry's view of solutions [28] could be filled with the operation and maintenance solution options found within this literature review.

Traditionally solution options for environmental impacts follow the mitigation hierarchy [36,37]. This includes first avoiding environmental impacts, then reducing and finally compensating where necessary. Although the effectiveness of the mitigation is often questioned [38] it is still an established framework for addressing environmental impacts [39]. The solution options found in the literature review were categorised according to this basic mitigation hierarchy and compared to the text book version (Fig. 6). In reality the number of solution options found within this paper do not follow the theoretical hierarchy in that ‘avoiding’ solutions do not present in the majority of papers, with ‘reducing’ solutions next and ‘compensation’ least. The majority of solutions presented are to reduce environmental impacts, then to avoid and finally to compensate.

The 77 papers included in this review present a wide variety of solutions, some theoretical, others already applied in large-scale industries. Some of the solution application industries are similar to tidal lagoons, for example tidal barrages, others from less similar industries, like the natural hazard management sector. Each solution was ranked based on two scales, the first on level of development (theoretical or applied), and the second on relevance to lagoons (lagoon specific or other industry) (Fig. 7). The purpose of this was to determine how developed and relevant solutions presented in the literature might be to the future lagoon industry and therefore if it is a resource that should be further investigated and utilised in the future. The majority of solutions fall in the middle of being not quite lagoon-specific, but perhaps related to marine renewable energy and not fully applied, for example, applied at pilot scale or in testing. The bold black box in Fig. 7 shows that over half of the solution options presented need only minor shifts in either their development to applied scale or to be adapted to be lagoon-specific before they could potentially be implemented in the lagoon industry.

4. Discussion

The field of solution options for the environmental impacts likely to arise as a result of tidal lagoons is relatively new. The large growth in the number of papers over the last 5 years shows that the environmental industry is gaining momentum. This momentum is supported by the growth of the regulatory and legislative environmental sector and the increasing pressure for corporate environmental awareness and responsibility.

The lagoon industry is nascent, and environmental impacts are one of the key concerns for any future lagoon industry. With no operational man-made energy generating tidal lagoons in the world, there are no operational data on the environmental impacts of lagoons and no solution option guidelines to work by. Whilst tidal lagoons are a new

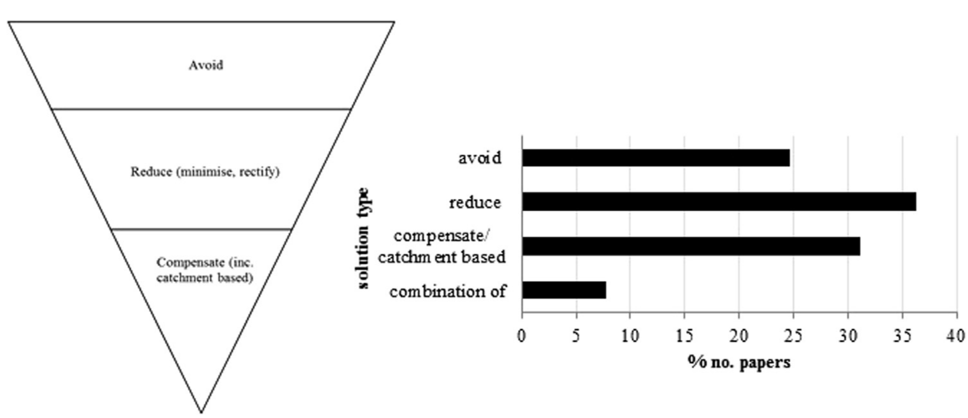

Fig. 6. Traditional mitigation hierarchy (left) compared to the solution options found within this systematic literature review (right).

Solutions Matrix		Theoretical →				Applied
		1	2	3	4	5
Other Industry ↓	1	0	2	0	1	0
	2	1	4	7	6	3
	3	2	2	7	8	5
	4	2	6	5	5	6
Lagoon Specific	5	0	0	2	2	1
					Total	77

Fig. 7. Matrix of solution options in terms of their development to applied scale (1 to 5, 5 = fully applied, 1 = Theoretical) and adaption to be lagoon specific (1 = Other Industry, 5 = Lagoon or Barrage specific). Graded Colour Scale: No. Papers ≤2 Light Greens, 3–5 Medium Green, ≥5, Bright Greens.

concept, the technology and engineering feat they present is not new, and the individual engineering applications have been applied in other industries e.g. tidal barrages, dams, hydroelectric power stations, tidal stream turbines, breakwaters and coastal defence mechanisms. As such, the environmental impacts likely to arise from tidal lagoons are also likely to have already arisen and been addressed in other industries. This systematic review shows that there are wide-ranging solution options documented in the literature which have been either applied or suggested in other industries to address impacts similar to those which are likely to arise in the future lagoon industry. The review quantitatively analyses the literature to show the relevance and development stage of these solutions and if this resource warrants further investigation in the future.

The solution options have been analysed in terms of their potential to fill gaps, specifically the gaps in industry knowledge found in a recent paper [28], the cluster of expertise on solution options globally, the impacts which they seek to address and how well developed and adapted they are to a potential application in the lagoon industry.

4.1. Environmental Impacts

All the papers included in the review consider environmental impacts relevant to tidal lagoons. One of the key impacts addressed in this literature review is that of water or sediment pollution. The high level of research on this impact suggests that it is a common impact in other coastal and marine industries globally and therefore should be further investigated in terms of the lagoon industry. Water or sediment pollution was not within the top three environmental impacts suggested by the lagoon industry in recent industry engagement research [28]. It may not have been flagged by the industry as a key issue because there are a number of well-known solutions to address it.

The lagoon industry has indicated that one of the top three most significant impacts that tidal lagoons could present in the future is the impact on fish and marine mammals through restricted passage and migration [28]. This systematic review provides evidence that there are a relatively high number of papers within the body of knowledge that provide solutions to address this impact, and therefore the lagoon industry should use this knowledge to address the issue.

If it is assumed that the number of papers for an environmental impact relates to the level of research of solution options available for that impact, then the impacts with the lowest number of papers are the impacts with the least research on solution options available. These impacts may present a higher risk for the lagoon industry. The impacts with the lowest number of papers in the review, suggesting the lowest level of research on solution options are sediment regime changes, hydrodynamic change and impacts on habitats and biodiversity. These impacts were also highlighted by industry as being the most significant environmental impacts that lagoons could present in the future [28]. It can be inferred then that these impacts are likely to be key barriers in the development of the lagoon industry unless suitable solution options can be found, adapted and applied at lagoon scale.

Although the number of papers for these key impacts is lower than for other impacts, there are still some solutions presented, and therefore solutions available to address these key impacts. In addition the quantity of papers does not necessarily reflect on the quality or quantity of solution options presented. The solution options found in the literature should be used as a foundation or starting point for a drive and focus towards the development of applied, lagoon-specific solutions for these key environmental impacts.

4.2. Application of solutions

The literature presents a vast global knowledge base, spanning a variety of marine, coastal and river industries that could be drawn upon to address the potential environmental impacts that might arise from tidal lagoons in the future. The tidal lagoon industry has the benefit of hindsight and learning from other industries with similar environmental industries. It could and should utilise this.

The lagoon industry at present is very UK-orientated; the developers, regulators, policy makers, practitioners and consultants involved are largely based in the UK [28], however this review has shown there is relevant expertise from other industries worldwide. One of TLP's main goals is to boost the UK's supply chains, employment and economy [15], and this can still be achieved using a global outlook. This systematic review into solution options shows a global knowledge base of options available to address environmental impacts from other industries. There are clusters of expertise on impact solutions all over the world. The nascent lagoon industry should draw upon this global expertise. Using, adapting and implementing global knowledge within tidal lagoons will help address and progress global goals, such as that of addressing climate change. The recent advancements in the UK tidal lagoon industry therefore has global relevance. This audience also has solution options and knowledge to provide and the lagoon industry should capitalise on this opportunity.

The review shows that the majority of solution options arise from environmental disciplines. This is understandable given that a strong understanding of environmental impacts is essential to provide effective solution options. Environmental impacts are likely to have multidisciplinary implications, such as on the economic, social, engineering and legal sectors. As such, it would be beneficial for the lagoon industry if these sectors were also involved in the designing of solution options for environmental impacts, providing a multidisciplinary approach to a multidisciplinary issue.

It was found that the majority of industry stakeholders focused on solution options related to engineering, site or technology design or compensation and catchment based measures [28]. A gap in the industry solution options was presented in the form of those relating to operation and maintenance strategies [28] (Fig. 6). In contrast, the literature presents the majority of solutions to be in the operation and maintenance category. The knowledge base within the literature could help fill gaps in the industry's understanding of solution options.

Combining both the industry understanding on solution options and the solution options found within the literature it seems that most bases are covered for addressing the environmental impacts of tidal lagoons. It is important for the lagoon industry to not only draw upon expert advice within the industry and from its stakeholders but also to refer and investigate further the available literature from other industries. In this way, the lagoon industry can find solution options from engineering, site and technology design, operation and maintenance and compensation and catchment based measures. This will reduce the number of gaps seen in the solution options available. Whilst most bases are covered in this way, the key question is now: are the solution options available actually developed enough and specific enough for applications in the lagoon industry?

Whilst the majority of papers included in this review are reviews themselves, 19% are direct observation. This suggests that some of the solution options being presented in the literature have also been applied and observed and therefore are not just theoretical ideas. Fig. 7 in the results gives a clearer picture of the number of solution options which are applied as opposed to theoretical and lagoon specific as opposed to from other industries. The majority of solution options presented in the literature are more advanced than purely theoretical but not quite applied yet on a large scale. Similarly the majority of solutions are in the marine or coastal industries but not yet specific for use in the lagoon industry. Over half of the solution options in the literature are on the brink of being realistic options for lagoon scenarios in the future. Work is required to shift them towards being applied at larger scales and adapting them for lagoon specific applications, but they are ready and waiting to be advanced.

The key message is that even though the lagoon industry is nascent and there is uncertainty surrounding its potential environmental impacts, the solution options do not have to be completely new, novel or innovative. The review suggests that with a relatively small amount of development, previously successful solutions applied to similar environmental impacts in related industries can be adapted to successfully address any environmental impacts that may arise in the future lagoon industry. This review shows that there is a valuable global literature resource representing solutions from other industries which should be further investigated for tidal lagoons.

5. Conclusion

There is pressure on the lagoon industry and in particular on Swansea Bay lagoon as a pilot scheme to ensure that any environmental impacts which may arise are addressed successfully. Swansea Bay lagoon needs to set the precedent on addressing its environmental impacts if the future UK and global lagoon industry is to flourish sustainably. With no operational tidal lagoon data available, there is no guidance on solution options for tidal lagoon environmental impacts. This review uses the PRISMA reporting guidelines methodology along with guidance from Collaboration on Environmental Evidence to consider a total of 1114 papers with a final 77 papers presenting solution options to the environmental impacts likely to arise as a result of tidal lagoon development.

The key environmental impacts according to industry engagement [28] are also shown in this review to have a reduced level of research available on solution options. These could present further concern for the industry and should be a focus for further research. Whilst this is a concern, the categories of solution options presented in the literature have also been shown to fill a gap in the current industry understanding.

The global spread of solution options gives the tidal lagoon sector a global audience and arena within which to both import and export knowledge and skills. The literature resource on solution options is vast and should be a valuable resource for the nascent lagoon industry. Other industries have applied similar engineering and technology concepts presenting and addressing the same environmental impacts which are expected of tidal lagoons. The lagoon industry can benefit from their hindsight and should capitalise on the opportunity to learn from their experience.

To conclude, this paper quantitatively analyses environmental management literature to identify the extent and relevance of this available research as a resource for the nascent lagoon industry. It opens the door on a vast and valuable research resource that the industry should be investigating. Over half of the solutions found in this review require only small shifts in their development for them to be realistic solution options for the lagoon industry in the future. This finding highlights and justifies the need for further investigation into transferable environmental management and policy options for application in the lagoon sector.

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