1-1-2023

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Mischa P. Turschwell

Christopher J. Brown

Myriam Lacharité

Jess Melbourne-Thomas

Keith R. Hayes

See next page for additional authors

10.1016/j.envsci.2023.06.008
Turschwell, M. P., Brown, C. J., Lacharité, M., Melbourne-Thomas, J., Hayes, K. R., Bustamante, R. H., & Fulton, E. A. (2023). Co-designing a multi-criteria approach to ranking hazards to and from Australia's emerging offshore blue economy. Environmental Science & Policy, 147, 154-168. https://doi.org/10.1016/j.envsci.2023.06.008

Authors
Mischa P. Turschwell, Christopher J. Brown, Myriam Lacharité, Jess Melbourne-Thomas, Keith R. Hayes, Rodrigo H. Bustamante, Jeffrey M. Dambacher, Karen Evans, Pedro Fidelman, Darla H. MacDonald, Ingrid Van Putten, Graham Wood, Nagi Abdussamie, Mathilda Bates, Damien Blackwell, Steven D'Alessandro, Ian Dutton, Jessica A. Ericson, Christopher L. J. Frid, Carmel McDougall, Mary-Anne Lea, David Rissik, Rowan Trebilco, and Elizabeth A. Fulton

Environmental Science and Policy 147 (2023) 154–168

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

Co-designing a multi-criteria approach to ranking hazards to and from Australia's emerging offshore blue economy

Mischa P. Turschwell [a,*], Christopher J. Brown [a,1], Myriam Lacharité [b,c,1], Jess Melbourne-Thomas [c,d,1], Keith R. Hayes [e,1], Rodrigo H. Bustamante [f], Jeffrey M. Dambacher [e], Karen Evans [c,d], Pedro Fidelman [c,g], Darla Hatton MacDonald [c,h], Ingrid Van Putten [c,d], Graham Wood [c,i], Nagi Abdussamie [j], Mathilda Bates [k], Damien Blackwell [l], Steven D'Alessandro [m], Ian Dutton [c,l], Jessica A. Ericson [n], Christopher LJ Frid [o], Carmel McDougall [a], Mary-Anne Lea [b,c], David Rissik [p], Rowan Trebilco [c,d], Elizabeth A. Fulton [c,d]

[a] *Australian Rivers Institute – Coastal Marine Research Centre, Griffith University Nathan, 4111 Queensland, Australia*
[b] *Institute for Marine and Antarctic Studies, University of Tasmania, Hobart 7053, Australia*
[c] *Centre for Marine Socioecology, University of Tasmania, Hobart, Tasmania 7001, Australia*
[d] *CSIRO Environment, Hobart, Tasmania 7001, Australia*
[e] *CSIRO Data61, Hobart, Tasmania, 7001, Australia*
[f] *CSIRO Environment, St Lucia, Queensland 4072, Australia*
[g] *Centre for Policy Futures, The University of Queensland, St Lucia, Queensland 4072, Australia*
[h] *Tasmanian School of Business & Economics, University of Tasmania, Sandy Bay, Tasmania 7005, Australia*
[i] *School of Humanities, University of Tasmania, Launceston 7250, Australia*
[j] *National Centre for Maritime Engineering and Hydrodynamics, Australian Maritime College, University of Tasmania, Launceston, Tasmania, Australia*
[k] *College of Science and Engineering, James Cook University, Townsville, Australia*
[l] *Department of Natural Resources and Environment, Hobart, Tasmania 7001, Australia*
[m] *School of Business and Law, Edith Cowan University, Western Autralia, 6027, Australia*
[n] *Cawthron Institute, Private Bag 2, Nelson 7042, New Zealand*
[o] *School of Environment & Science, Griffith University, Southport, Queensland 4222, Australia*
[p] *Deloitte, Brisbane, Queensland 4000, Australia*

ARTICLE INFO

Keywords:
Sustainability
Equity
Seafood production
Renewable energy
Ocean multi-use

ABSTRACT

A multi-sectoral assessment of risks can support the management and investment decisions necessary for emerging blue economy industries to succeed. Traditional risk assessment methods will be challenged when applied to the complex socio-ecological systems that characterise offshore environments, and when data available to support management are lacking. Therefore, there is a need for assessments that account for multiple sectors. Here we describe the development of an efficient method for an integrated hazard analysis that is a precursor to full risk assessments. Our approach combines diverse disciplinary expertise, expert elicitation and multi-criteria analysis to rank hazards, so it encompasses all types of hazards including human-caused, natural and technological. We demonstrate our approach for two sectors that are predicted to grow rapidly in Australia: offshore aquaculture and marine renewable energy. Experts ranked *Climate Change* as the hazard with the highest overall concern, but hazards including *Altered Ecosystem Function*, *Biosecurity*, *Cumulative Effects*, *Structural Failure* and *Social Licence* were also highly ranked. We show here how outputs from this approach (multi-criteria scores and ranks) could be used to identify hazards that; i) could be safely retired, ii) should be progressed to more quantitative risk assessments or iii) require ongoing information collection. The approach can encompass all types of hazards, which enables it to holistically consider priorities. The expert-based multi-criteria approach outlined here represents a pragmatic way to solve some of the challenges of applying risk assessments to emerging industries by using a method that can be applied across multiple blue economy sectors.

* Corresponding author.
E-mail address: m.turschwell@griffith.edu.au (M.P. Turschwell).
[1] These authors contributed equally to this manuscript

https://doi.org/10.1016/j.envsci.2023.06.008

Available online 23 June 2023

1. Introduction

The last decade has seen a transition in thinking around the nature of economic activities in the marine environment with the adoption and promotion of the term *'Blue Economy"* (United Nations, 2012). The vision for the blue economy includes an explicitly sustainable and equitable approach to drive development and economic growth in the marine environment (Wenhai et al., 2019). United Nations member states have committed to ocean sustainability (United Nations, 2012), but since then there has been a tension between the original sustainability ethic of the blue economy and blue growth (a more general description of expanding marine industries). Ocean management in the face of both blue economy and blue growth requires integrated approaches that can manage ecosystems and the larger socio-ecological systems they sit within (Winther et al., 2020).

The fast-moving pace of the blue economy means we need hazard screening approaches that are interdisciplinary, cover a diverse range of hazards, and can be rapidly applied (*sensu* Escande et al., 2016). Traditional, discipline-specific, forms of risk assessment are based on a common language and understanding of the system being assessed (Ericson, 2015). We need a new approach for several reasons. First, several diverse disciplines are involved in the research, development, and implementation of emerging multi-sector industries, and each have different vocabularies. Second, approach(es) to risk assessment are often sector specific, making it difficult to apply a one-size-fits-all assessment within and across industries and between sectors, which limits the scope of risk assessment to specific typologies of hazards (Hodgson et al., 2019). Finally, risk assessments are often based on the International Organisation for Standards (ISO) principles and guidelines; however, ISO risk standards and terminology have often been criticized for being too vague to be helpful (Leitch, 2010; Aven, 2011; Björnsdóttir et al., 2021). Integrated risk assessment (an assessment of risk that integrates the viewpoints of many traditionally disparate disciplines) has been proposed as a potential decision support tool for emerging blue economy industries (Hodgson et al., 2019). However, these assessments are resource intensive and logistically challenging in emerging industries where there is little operational experience and hence limited empirical data to draw upon, especially for probabilistic risk assessments which demand quantified outcomes.

The identification of hazards and the causal event-chains that link initiating events (either planned or accidental) to adverse outcomes are fundamental to risk assessments. There are a diversity of approaches to identify and analyse hazards, and a range of typologies for what constitutes a hazard (Leimeister and Kolios, 2018). Hazard identification techniques traditionally rely on information obtained by observing outcomes from industry operations, from mapping of natural hazard data, and by drawing upon expert judgement (Halpern et al., 2008; Teck et al., 2010; Lonsdale et al., 2020). For emerging industries, however, information sources are limited and expert knowledge may only stem from broadly similar activities occurring in different environments and/or the emergent (but again limited) expertise in novel environments. A further challenge for hazard identification is that the context and scale of development is often unknown at the early stages of planning for new industries, as are potential interactions (positive or negative) between these new industries and the broader socio-ecological context. The end goal of a hazard analysis is to identify and prioritise hazards that should be considered and progressed to full risk assessment, and to identify and downgrade those of lower concern (Staid and Guikema, 2015; Copping et al., 2020). The benefits of hazard screening and prioritisation can be realised by a range of stakeholders including potential investors, operators, regulators civil society organisations, or even research institutions. A flexible, generalized, readily re-iterated approach to hazard analysis that can be applied across diverse industries and wider sectors is therefore necessary to help emerging multi-sector blue industries identify and prioritise the range of potential hazards. The process needs to integrate approaches used in multiple disciplines and learn from mistakes made in analogous industries, for example, path dependency (where past decisions influence future decisions), which has hindered progress in commercial fisheries management to meet the triple-bottom-line (Fulton, 2021).

Eliciting information from a diversity of stakeholders can more comprehensively represent interdependencies in complex systems and provide more accurate predictions than those based on homogenous groups or a single person's judgement (Burgman et al., 2011; Mellers et al., 2014; Aminpour et al., 2021). Here, we outline an approach (co-developed with experts from diverse disciplinary backgrounds) to integrated hazard analysis based on expert elicitation and multi-criteria decision analysis that can be undertaken across multiple industries and provides outputs accessible to diverse stakeholders. Thus, we break from the tradition of applying hazard analysis within the context of only a single sector. In this paper we will deal with hazards to the establishment and operations of blue economy activities and those hazards that the activities may create for other parts of marine systems. This two-way consideration of hazards goes beyond what is typical in extant cumulative effects assessment approaches, which predominantly focus on how activities may affect environmental or social system components (often focusing on undesirable change – see the methods reviewed in Stelzenmüller et al., 2018; Evans et al., 2021). The hazards considered within this assessment thus encompass multiple existing hazard typologies and include human-caused (e.g., social, hazardous materials), natural (severe weather, natural disasters) and technological (e.g., structural failure, cybersecurity) hazards (Federal Emergency Management Agency, 2023). A broad view of what defines a hazard was essential to ensure the approach was holistic in capturing all potential issues that industry and government may need to respond to when expanding offshore development. Our application of an integrated hazard analysis via a multi-criteria decision analysis framework allows us to identify future needs and opportunities for hazard analysis of multi-sector operations, including the offshore blue economy in Australia and also other nations where the number of offshore industries is expanding.

2. Methods

2.1. Overview

An eight-step approach was implemented to identify and rank hazards using two expert workshops and multi-criteria decision analysis (Fig. 1). Participants had expertise in aquaculture, environment, and society (each domain of expertise had ~23% of participants), economics (~13%), renewable energy production (~12%) and marine engineering (~6%). For each step, the objective to be achieved, and best estimates of the time required to complete the process are provided. All workshops were conducted in accordance with the human ethics guidelines of Griffith University (GU reference number 2021/071).

2.2. Step 1: literature review of hazards

We compiled a preliminary hazard list by consulting the published and grey literature, targeting elements associated with blue growth: aquaculture and renewable energy production, as well as key supporting sectors including: marine engineering, interactions with the environment, society (including policy considerations) and economics. We recorded a description of how the hazard impacts each domain. Where possible we also noted the domain the hazard originated from, and which domain(s) were most likely to be impacted by the hazard. For example, the hazard '*escaped fish from production pens'* originates from the aquaculture domain, but has impacts on aquaculture and economics (through lost revenue), the environment (through escaped fish interacting with wild populations and local ecosystems), and society (through a potential decrease in the social acceptance of aquaculture activities).

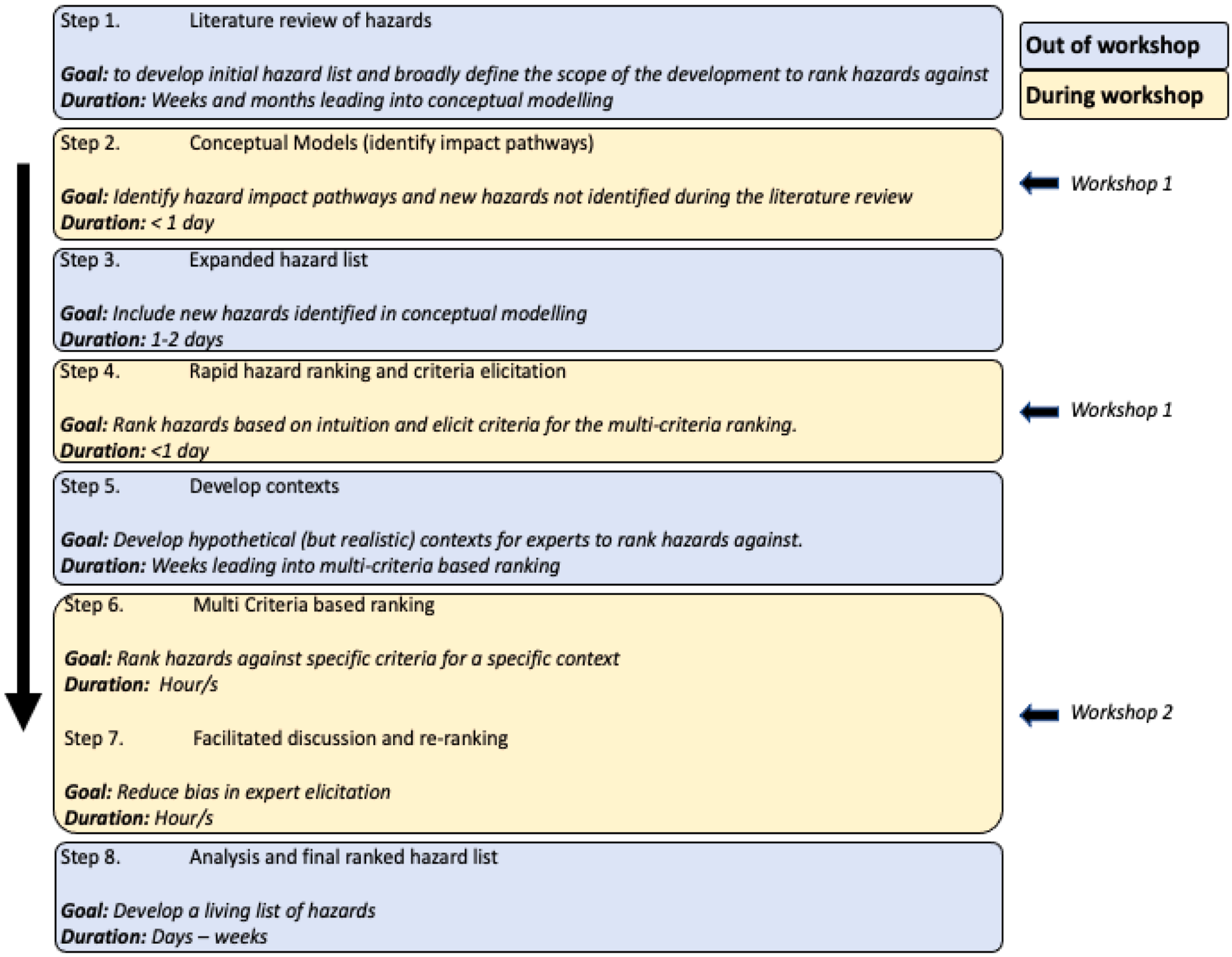

Fig. 1. Workflow of the integrated hazard analysis methodology. Numbers refer to the steps in the method. Out of workshop sessions (blue) were led by a core team while workshops (yellow) included all project participants.

2.3. Step 2: conceptual models

The first workshop (Fig. 1) focused on 1) identifying additional hazards not identified from the literature review, and 2) documenting impact pathways (causal event chains) and connections among hazards. Conceptual modelling was used to draw on the collective expertise of the workshop's participants.

Conceptual modelling exercises, codified using qualitative signed diagraphs (Dambacher et al., 2009), have been previously used to identify hazards (see for example Hayes et al., 2007) and document current understanding by defining two key characteristics of a system:

1. The components (or 'parts') of the system (often drawn as a node)
2. The positive, negative, or unknown relationships between the components (represented by lines and arrows). A positive sign from one node indicates the source node increases the receiver node, with a negative sign indicating the opposite, while a question mark indicates an unknown relationship between nodes. In Fig. 2, for example, 'Biofouling' *increases* 'Disease potential' and *decreases* 'Sensor effectiveness'.

The interactive software Mental Modeller was used to build the conceptual models. Mental modeller is an interactive tool that is accessible to a diverse audience of experts (Aminpour et al., 2021). Participants were split into pre-assigned groups of 4–6 participants with diverse expertise and experience. In a participatory approach, each group was assigned a facilitator to drive the software and ask follow-on questions in the conceptual modelling. Each group was provided with a different list of hazards that was a subset of the full pre-compiled list from Step 1, however, groups were not constrained to this initial list. Each group choose a particular hazard and then mapped impact pathways for that hazard and its connections to other domains, hazards and concepts, until the group was satisfied all the primary connections had been identified (e.g., Fig. 2). The group was then requested to choose another hazard from its list and repeat the process. This exercise was also used to identify opportunities and needs for future research and development. For example, robust materials development was identified as a research need for the *biofouling* hazard (Fig. 2).

2.4. Step 3: expanded hazard list

The facilitators revised the hazard list from step 1 and added new hazards from the conceptual models that were not found in the initial literature review. The same process set out in Step 1 was then applied to each of the new hazards. To prepare for the second workshop, individual lists of domain-relevant hazards were created based on the potential for impact on each domain (noting the same hazard could occur across multiple lists if it impacted more than one domain). Domain specific lists

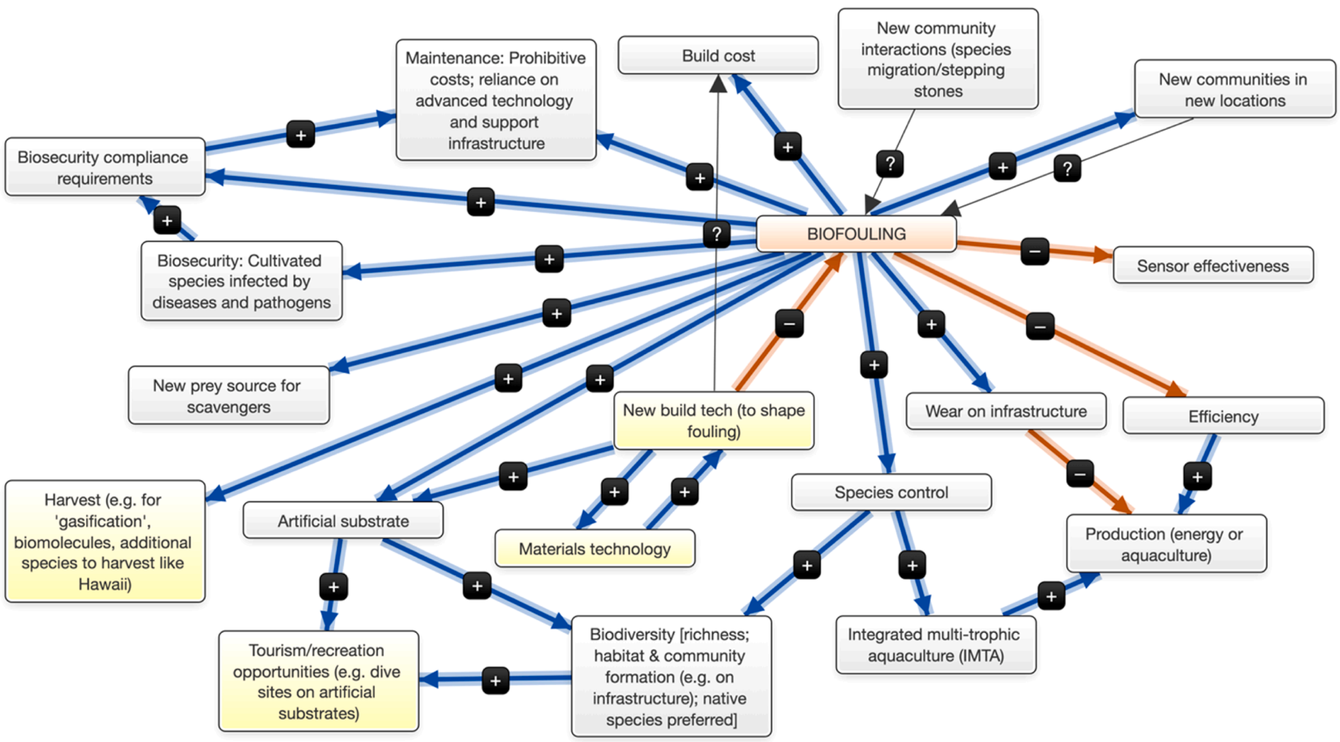

Fig. 2. Example of a conceptual model, developed in the second step of the hazard analysis process showing the positive (blue arrows) and negative (orange arrows) connections associated with the hazard 'biofouling' (orange node). Thinner black arrows indicate an unknown relationship. Opportunities and further research and development needs identified during the modelling exercise are highlighted in yellow.

ensured experts were not asked to rank the entire list of hazards (many of which were outside their expertise), reducing the potential for expert fatigue. Each domain specific hazard list was uploaded to an online survey (using Google forms) that experts could easily navigate during the workshops, streamlining data collection.

2.5. Step 4: rapid hazard ranking and criteria elicitation

The goals of the individual rapid ranking exercise were to (1) capture what experts perceived to be an appropriate preliminary ranking of hazards that need to be considered and managed (or retired), ranging from the most concerning to least concerning hazards, and (2) to understand the criteria that individuals used to undertake this intuitive ranking activity. The most concerning hazards were described as hazards likely to have significant impacts and require active management, while least concerning hazards were described as hazards not likely to have any impacts and therefore not needing active management over the next 10–15 years. A 10–15 year timeframe was chosen because experts felt more confident commenting on this scale rather than longer timescales.

Experts were asked to choose a domain relevant to their expertise, which then determined which hazards they had to rank. Each domain-specific list contained between 30 and 40 hazards. If an expert felt comfortable ranking across multiple domains, (i.e., ranking hazards to aquaculture and society), they could complete multiple lists. From the domain specific hazard list(s) experts were asked to select the top five most concerning hazards, as well as the five least concerning hazards for each list. This was intended to be an intuitive selection based on expert knowledge of the systems. The experts used a bespoke online survey tool, developed with the RShiny software (Chang et al., 2017) to do the rapid ranking. This tool was then used to generate graphical summaries of the rankings that were provided back to the group during the workshop. These summaries included: 1) The most concerning and least concerning hazards overall, 2) The most concerning and least concerning hazards for each domain, 3) Hazards that were shared across domains (highlighting opportunities for joint mitigation).

To provide context to this ranking exercise, we then sought to make explicit the different types of criteria the experts had used implicitly to assign their individual ranks. Experts discussed the criteria in small breakout groups, identifying why some hazards were ranked differently by different people. Discussions were prompted by the breakout group facilitators who provided examples of two common criteria used to rank hazards: consequence and likelihood. From these discussions an initial list of criteria was developed for use in the formal multi-criteria ranking (Step 6). We restricted the number of criteria taken forward into the next stages of the analysis to four to minimise the elicitation load for workshop participants.

Some examples of common criteria identified by experts through discussions following the rapid ranking exercise included the scale, intensity, and spatial footprint of the hazard; temporal intensity of the hazard (i.e. single vs continuous events); the availability of mitigation and management options for the hazard (and their effectiveness); the consequence of the hazard; the likelihood of the hazard occurring; the reversibility of the impacts from the hazard; and the ease of detection of the hazard. From this broader list of criteria, the final four criteria selected for the multi-criteria based ranking exercise were:

1. **Likelihood:** Captures the likelihood (e.g., times per year) the hazard has an impact on the outcome of interest (rather than the likelihood of the hazard itself). For example, consider the frequency of storms that damage infrastructure (rather than just the frequency of storms)
2. **Consequence:** Captures the degree of impact from the hazard – expressed for example in opportunity costs, lost production, loss of physical and mental human wellbeing, loss of community wellbeing, or decline in the integrity of the ecosystems. For example, if considering physical impacts to people, low consequence may be

minor injury causing inconvenience, while high consequence may be multiple fatalities

3. **Difficulty detecting the impacts of the hazard:** Captures how difficult it is to detect the impacts of the hazard. Considers aspects such as the probability of being able to detect the impact, and the time taken to detect the impact. Impacts that are hard to detect tend to be harder to manage or mitigate. Labelling hazards as 'extreme' means their impacts are extremely hard to detect. For example, consider how easy it is to detect the impacts of a pathogen on aquaculture production species.
4. **Difficulty responding to the impacts of the hazard**: Captures how challenging it is to manage, mitigate or reverse a hazard's impact. This could be influenced by how persistent the impact of the hazard is. Similarly, labelling hazards as 'extreme' means it is extremely challenging to manage, mitigate or reverse a hazard's impact. For example, consider how difficult it is to reverse the impacts of biofouling on offshore infrastructure.

2.6. Step 5: develop contexts

An important step in any hazard analysis or risk assessment involves defining the scope and context of the analysis. To avoid differences in subsequent (more formal) hazard ranking (Step 6) that might originate from different interpretations of the background context, we developed a set of narrative-driven hypothetical scenarios that aimed to reflect realistic multi-sector developments that could occur in the Australian marine environment. These scenarios captured different industry combinations, scales of operations, and different climates via visual representations (Fig. 3) with the aim of capturing the power of visual media to overcome cognitive barriers (Blythe et al., 2021). The primary context considered in this assessment was integrated multi-trophic aquaculture (starting with salmonid and bivalves) supported by wind-based renewable energy production occurring on or near the aquaculture site (Fig. 3). Production was hypothesised to occur in an oceanic climate in temperate waters off Tasmania, Australia. Hazards were considered on a 10-year horizon. Other contexts included kelp aquaculture integrated with wind energy in temperate waters; a tropical context.

with remote communities cultivating tropical fish and crustaceans in conjunction with co-located ocean thermal energy conversion; and finally oyster production co-located with wave and floating photovoltaic energy (SI Fig. 3).

2.7. Step 6: multi criteria based ranking

Multi Criteria Decision Analysis (MCDA) describes a variety of methods developed to help decision makers identify optimal or preferred outcomes from among groups of competing possibilities based on the extent to which each possibility meets criteria relevant to the decision (Ananda and Herath, 2009). A simple Multi Criteria Analysis (MCA) using a commonly used weighted summation algorithm (Janssen, 2001; Adem Esmail and Geneletti, 2018) was considered most suitable for our purpose due to the lower elicitation load required compared to approaches such as Multi Attribute Utility Theory and the Analytic Hierarchy Process (see also the discussion in Hayes et al., 2020). Weighted summation involves selecting and weighting criteria, scoring each hazard against each criteria, and multiplying the weights and scores to give an overall rank for each hazard.

The weighted overall score for hazard *i*, u_i, is expressed as:

$$u_i = \sum_{j=1}^{n} v_{i,j} w_j$$

Where $v_{i,j}$ is the score for hazard *i* against criteria *j*, and w_j are the weights for criteria *j*. Weights are non-negative and sum to one. In this instance, equal weighting of criteria is assumed (i.e., each of the four criteria is assigned a weight of 0.25).

To facilitate this process, a custom RShiny application was developed. Experts were asked to classify hazards into four categories – low, moderate, high, or extreme – on a relative scale of 0–1 for each of the criteria. A slider bar allowed the user to alter the range across which scores could be assigned to each of the categories – so they could set what range of scores defined low, medium high and extreme. A user could leave the settings at their defaults (which evenly split the scale across the 4 categories) or they could use the slider to set what range of scores defined each category. For example, they could constrain the extreme values to only a small range of values, adjusting one of more of the other categories to cover a wider span of scores. For subsequent analyses, all hazards within each category were assigned the midpoint between the slider breaks (e.g., if the 'Low' hazard category ranged 0–0.25, hazards categorised as 'Low' were scored 0.125).

Experts were only asked to rank hazards where they had sufficient expertise and therefore in some cases did not rank all hazards in the list. Prior to the elicitation, experts were also provided with a training questionnaire which openly acknowledged and provided examples of common heuristics and biases associated with expert elicitation (*sensu*

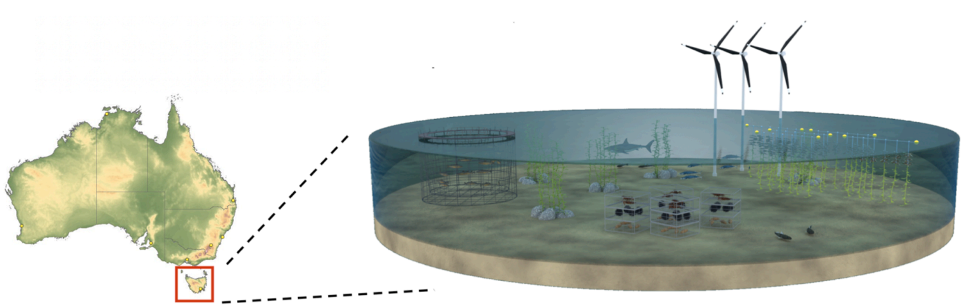

Fig. 3. An example of a hypothetical multi-sector operation developed for experts to rank hazards against. Other scenarios utilised are available in the online supplementary material.

recommendation 1 in Kynn, 2008).

2.8. Step 7: facilitated discussion of results and re-ranking

Following the MCA, experts were presented anonymised data summaries to discuss in facilitated breakout sessions. Ideally, we would have used a Delphi process (Mukherjee et al., 2015), however the COVID-19 pandemic and the difficulty of engaging people online prevented us from doing so.

Facilitated discussions with workshop participants were important for the co-development of the approach, which was adaptively updated based on the needs and inputs from our group of expert participants. Following structured hazard ranking, experts who had an opportunity to discuss rankings were open to updating their ranking based on shared discussions and from hearing about perceptions from other experts (often from other domains of expertise). For many of the hazards, experts often assumed there were planning and/or regulatory frameworks in place (and where they exist, work as intended) that would reduce the likelihood of some hazards (e.g., pollution).

While the majority of the ranking was done by experts who participated in the second workshop, the limited number of representatives available for the workshop from a number of disciplines meant it was necessary to follow up with an expanded list of experts to complete the ranking outside the workshop setting. These external rankings were done in such a way as to try to replicate the workshop experience – including a period of discussion, reflection and the opportunity to revise their ranking.

2.9. Step 8: ranked hazard lists

Hazards were ranked at two levels based on the weighted summation algorithm described in Step 6. First, user scores were pooled across all domains to give an overall hazard score and subsequent rank. Second, hazards were ranked within each domain (e.g., a hazard ranking specific to aquaculture production). The range and variance of the multi-criteria scores for each hazard were also calculated to capture the variability in scoring perceptions across experts and domains. A subset of hazards were selected to visually explore how perceptions varied across different criteria and domains. Hazards with tied scores were assigned the lowest rank.

Equal weighting of experts was assumed due to a lack of evidence to suggest otherwise (Armstrong, 2001). The dataset had many missing values, as individual experts did not rank all hazards against all criteria. To test the robustness of the ranking, given these missing values, rankings were also assessed when missing values were replaced with the mean domain score for that hazard.

2.10. Hazard triage

Using the final ranked hazards lists, a decision tree was developed to facilitate and demonstrate how the multi-criteria scores (or ranks) could be used in a hazard triage process. This decision tree was based on the overall multi-criteria score (or rank), the variability in that score across experts (i.e., consensus in scoring from experts), and then suggested next action. When the multi-criteria score is low and variability in the multi-criteria score is also low, the hazard can safely be retired. When there is high variability in the multi-criteria score (regardless of the score), further information is required before making the decision to either retire the hazard or proceed to a full risk assessment. Finally, when the multi-criteria score is high and variability in the score is low (indicating consensus from experts), the hazard must be carried forward and included in a detailed risk assessment(s) prior to project development. The numerical values/ranks mapped in each step are not prescribed and vary depending on the risk appetite of those conducting the assessment.

3. Results

3.1. Literature review and hazards identified from conceptual models

A total of 74 hazards associated with marine engineering, renewable energy production, aquaculture, interactions with the environment, society (including policy considerations) and economics were identified from the literature review. Through the conceptual modelling exercise, participants identified an additional five hazards not in the original list. The consolidated list of 79 hazards was considered too large for expert elicitation, so the hazard list was revisited, and similar hazards were collapsed into broader groupings. The final list contained 56 unique hazards (SI Table 2).

3.2. Rapid ranking

The top hazard for each domain from the rapid ranking exercise included: Climate change related extreme weather events (environment), adverse weather affecting operations (marine engineering, renewable energy production, aquaculture) the potential for cumulative impacts, concerns around biosecurity (society) and lack of capital investment (economics) (full results in supplemental material). All of these hazards also featured in the multi-criteria ranking.

3.3. Multi-criteria rankings

Based on information associated with 56 hazards across six domains, 52 sets of hazard rankings from 46 experts were compiled (SI Tables 2–3). Six experts with cross-disciplinary expertise submitted ranks across multiple domains. Aquaculture, environment, and society were ranked by the most experts (12 ranks for each), followed by economics (seven ranks), renewable energy production (six ranks) and marine engineering (three ranks).

Of the criteria identified by experts, the multi-criteria score (calculated across all domains) was most strongly correlated with likelihood and consequence (Pearson's $r = 0.67$ and 0.64 respectively – Fig. 4). Pooling data across all domains, hazards classed as of high consequence were generally perceived to also be harder to respond to ($r = 0.51$). 'Hard to detect' hazards had the greatest range in scores across participants from all six domains ($r = 0.44$).

3.4. Top hazards overall

Pooling data across all domains, experts ranked *Climate Change* as the hazard with the highest overall score (Table 1). Hazards pertaining to *Altered Ecosystem Functioning*, *Biosecurity: Source and Vector*, *Cumulative Effects*, *Structural Failure* and *Social Licence* were also highly ranked (Table 1). Hazard ranks were variable for each criterion. For example, *Altered Ecosystem Functioning* was considered the hardest to detect and the likelihood of the hazard occurring was ranked 24th of 56th overall. The replacement of missing values with the mean domain score did not alter the overall rankings (Pearson's Correlation Coefficient = 0.92, SI Fig. 1).

3.5. Domain specific hazards and hazard mismatches

While the highest ranked hazards were not identical across domains (partly due to the domain specific hazard lists), *Climate Change*, *Cumulative Effects*, *Rough Weather*, *Social Licence* and *Structural Failure* were consistently highly ranked amongst the top hazards across domains, highlighting a potential opportunity for the joint mitigation or

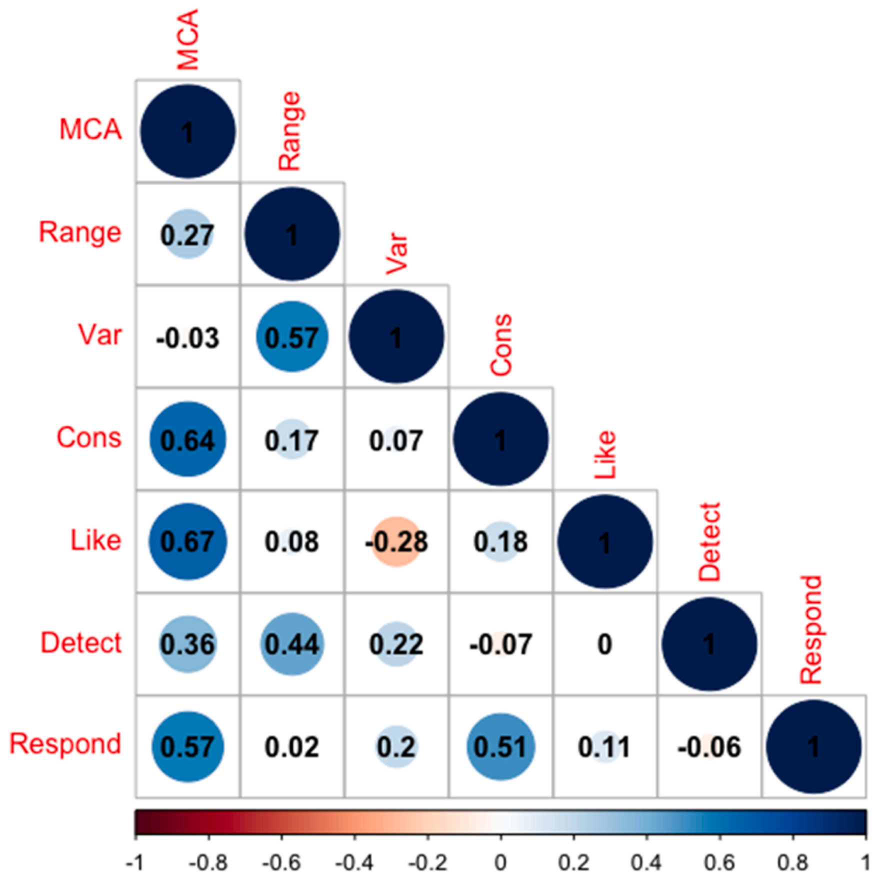

Fig. 4. Correlation matrix between multi-criteria score, the four criteria used in the multi-criteria analysis and two indicators of variability (Range and Variance). The size of the circle show the absolute value of corresponding correlation coefficients. Blue colours indicate positive correlations and red colours indicate negative correlations. MCA = multi-criteria score; Cons = consequence; Like = likelihood; Detect = difficult detecting; Respond = difficulty responding.

management of hazards across domains (Table 2 A). Similarly, *Biosecurity: Infection, Development Costs,* and *Market Access* were also ranked highly across multiple domains (Table 2 A). Nine more hazards were ranked in the top ten of two domains, with a further 15 hazards ranking in the top 10 of a single domain (and for many of these they were equally ranked 7–10th).

A number of hazards were ranked low across the majority of domains, particularly, *Reliance on Technology, Maritime Transport, Light and Chemical Pollution* and *Marine Debris* (this was true even for the environmental domain). Six more hazards within two domains were amongst the lowest ranked and a further eight hazards ranked low within a single domain. These low ranked hazards could be retired for individual sector assessments and both *Reliance on Technology* and *Maritime Transport* could potentially be retired across all domains (Table 2B, Fig. 7).

At least three hazards associated with the society, economics, environment, and marine engineering domains were only ranked high by experts in association with that domain. Indeed, the hazards that were the focus of concern for a single domain often ranked very low in other domains (see Table 3 – hazard mismatches). For example, *Decommissioning Uncertainty* was amongst the lowest ranked hazards within all domains except society, where it was ranked in the top ten. Similarly, *Uncertain Risk Standards* was the third highest ranked hazard within the society domain, but was in the bottom ten for both aquaculture production and economics.

3.6. Hazard perceptions across domains

3.6.1. Climate Change: changes in ocean properties (including marine heatwaves)

All domains that ranked this hazard showed that it was difficult to respond to (indicated by the clustering of points in Fig. 5). However, experts contributing to ranking of hazards within domains varied in their perceived likelihood and consequence of the hazard. Experts associated with the environment and aquaculture perceived the likelihood of the hazard occurring as high (bordering extreme), while experts within the domains of marine engineering and renewable energy production perceived the likelihood of the hazard occurring as the lower end of medium (Fig. 5). A similar pattern was obtained for the criteria of consequence with experts within renewable energy production identifying the consequence at the higher end of medium and those within marine engineering bordering medium and high (Fig. 5).

3.6.2. High-tech industry: reliance on technology rather than manual labour

All domains identified that this hazard had a low likelihood of occurring within the temporal scope of the assessment (10–15 years), and low consequence if it did occur (Fig. 6). Domains identified that this hazard was relatively easy to detect and respond to, meaning that this hazard can likely be retired from both single sector and multi-sectoral assessments.

Table 1
Ten highest ranked hazards based on the ranked multi-criteria score (MCA) grouped across all domains. Note some hazards were equally ranked (indicated by =) so numeric gaps exist where there are ties. Darker colours indicate a higher ranking. Ranks for other criteria are also shown.

Hazard (short)	Hazard (long)	MCA	Variance	Consequence	Likelihood	Difficulty detecting	Difficulty Responding
Climate change	Climate change: changes in ocean properties (including marine heatwaves)	1	19	11	=3	6	2
Altered ecosystem functioning	Altered ecosystem functioning due to offshore activities	2	9	6	24	1	3
Stress on cultivated species	High-energy environment: excessive stress on cultivated species	=3	53	8	2	12	6
Rough weather	Rough weather/ocean conditions	=3	16	5	1	53	5
Cumulative effects	Inadequate assessment of cumulative effects	5	=29	13	9	4	13
Biosecurity: infection	Biosecurity: Cultivated species infected by diseases and pathogens	6	=29	4	=3	37	=7
Conflict over Blue Economy values	Conflict over values guiding the development of the Blue Economy	7	21	17	6	25	10
Biosecurity: vector	Biosecurity: Cultivated species as source or vector of diseases, pathogens, pests	=8	32	11	29	8	=7
Social licence	Social licence: Public opposition to development	=8	27	18	14	32	12
Structural failure	Structural failure due to high-energy ocean conditions	10	40	2	11	47	16

4. Discussion

To achieve the quadruple-bottom-line objectives of social, economic, governance, and environmental outcomes, sectors must work collaboratively to effectively manage and mitigate hazards. The developed approach provides a clear process for evaluating hazards. It solves some of the challenges of applying risk-based approaches by evaluating expert's concerns for the multiple hazards derived from emerging industries.

We identified hazards shared by multiple domains that can provide opportunities for sectors to jointly mitigate or retire hazards, traditional single sector hazard analyses could not have identified these opportunities. Hazards that may be retired include *Reliance on Technology* (rather than a manual labour force), hazards from *Maritime Transport* or hazards associated from some forms of *Pollution* (light and chemical, assuming appropriate and effective regulation is in place). Other studies combining expertise from diverse stakeholders including developers, regulators and environmental researchers, have suggested that environmental hazards including electromagnetic fields and noise pollution can be retired for small numbers of marine renewable energy devices (Copping et al., 2020). While some hazards could be retired, at the other extreme, *Climate Change* (influence on ocean properties), *Rough Weather* (and with that potential structural failure), the current inadequacy of *Cumulative Effects* assessments, aspects of *Biosecurity*, *Market Access,* and *Social Licence* should all be the focus of more detailed risk assessments or mitigation efforts almost irrespective of the domain of interest. This suggests strong synergies are possible from collective action on these topics. For example, both *Biosecurity* and *Cumulative Effects* were considered important to experts from aquaculture and environmental domains, and therefore should be a priority for collaboration between regulatory bodies, industry practitioners and academics to address and aim to mitigate such hazards. This also suggests areas in which regulatory advice and frameworks could be most beneficial, for example, through the development of a comprehensive framework and legislative requirements for assessing cumulative effects (Anthony et al., 2013).

While there were commonalities, there were also systematic differences in hazard rankings across domains. This variation is consistent with earlier studies; for example, expert opinion of the effects of climate change differed between economists and ecologists (Nordhaus, 1994). Systematic variation in risk perceptions across experts from varying

Table 2
Highest (A) and lowest (B) ranked hazards for each of the six domains based on the multi-criteria (MCA) score. The intensity of colour indicates the strength of the ranking (see the key). Grey indicates that the domain did not score for that hazard (due to domain specific hazard lists).

(A)

Hazard	Aquaculture Production	Economics	Environment	Marine Engineering	Renewable Energy Production	Society (Inc. Policy)
In top 10 hazards for three or more domains						
Climate change						
Cumulative effects						
Rough weather						
Social licence						
Structural failure						
Biosecurity: vector						
Market access						
Development costs						
In top 10 hazards for two domains						
Altered ecosystem functioning						
Stress on cultivated species						
Manufacturing defects						
Marine mammals and birds						
Biosecurity: infection						
Maintenance: costs						
Criminal activity (Cybersecurity)						
Conflict with ocean users						
Market demand						
In top 10 hazards for a single domain						
Uncertain risk standards						
Species escape						
Conflict over BE values						
Environmental liability						
Biofouling						
Difficultly in scaling projects						
Nitrogen pollution						
Misinformation						
Decommissioning uncertainty						
Noise pollution						
Power failure						
Planning for single sectors						
Maintenance: cleaning						
Bribery and corruption						

(continued on next page)

Table 2 (*continued*)

(B)

Hazard	Aquaculture Production	Economics	Environment	Marine Engineering	Renewable Energy Production	Society (Inc. Policy)
Lowest ranking hazards for three or more domains						
Reliance on technology						
Maritime transport						
Light pollution						
Chemical pollution						
Marine debris						
Lowest ranking hazards for only two domains						
Supply chain						
Site selection challenges						
Resource characterization						
Seafloor disturbance						
Local social impacts						
Onshore impacts						
Low ranking hazard in one single domain						
Planning for multiple sectors						
Taxes and fees						
Worker health						
Lack of skilled labour						
Maintenance: access						
Geopolitical stability						
Viewshed pollution						
Electromagnetic fields						

Table 3

Hazard mismatches. Those hazards ranked highest for some domains and lowest for others based on the multi-criteria (MCA) score. The intensity of colour indicates the strength of the ranking (see the key in Table 2, darker browns indicate rankings closer to the lowest, darker blues indicate rankings closer to the top). Grey indicates that the domain did not score for that hazard (due to domain specific hazard lists).

Hazard	Aquaculture Production	Economics	Environment	Marine Engineering	Renewable Energy Production	Society (Inc. Policy)
Uncertain risk standards						
Criminal activity (cybersecurity)						
Biofouling						
Misinformation						
Power failure						
Noise pollution						
Decommissioning uncertainty						
Planning for single sectors						
Maintenance: cleaning						

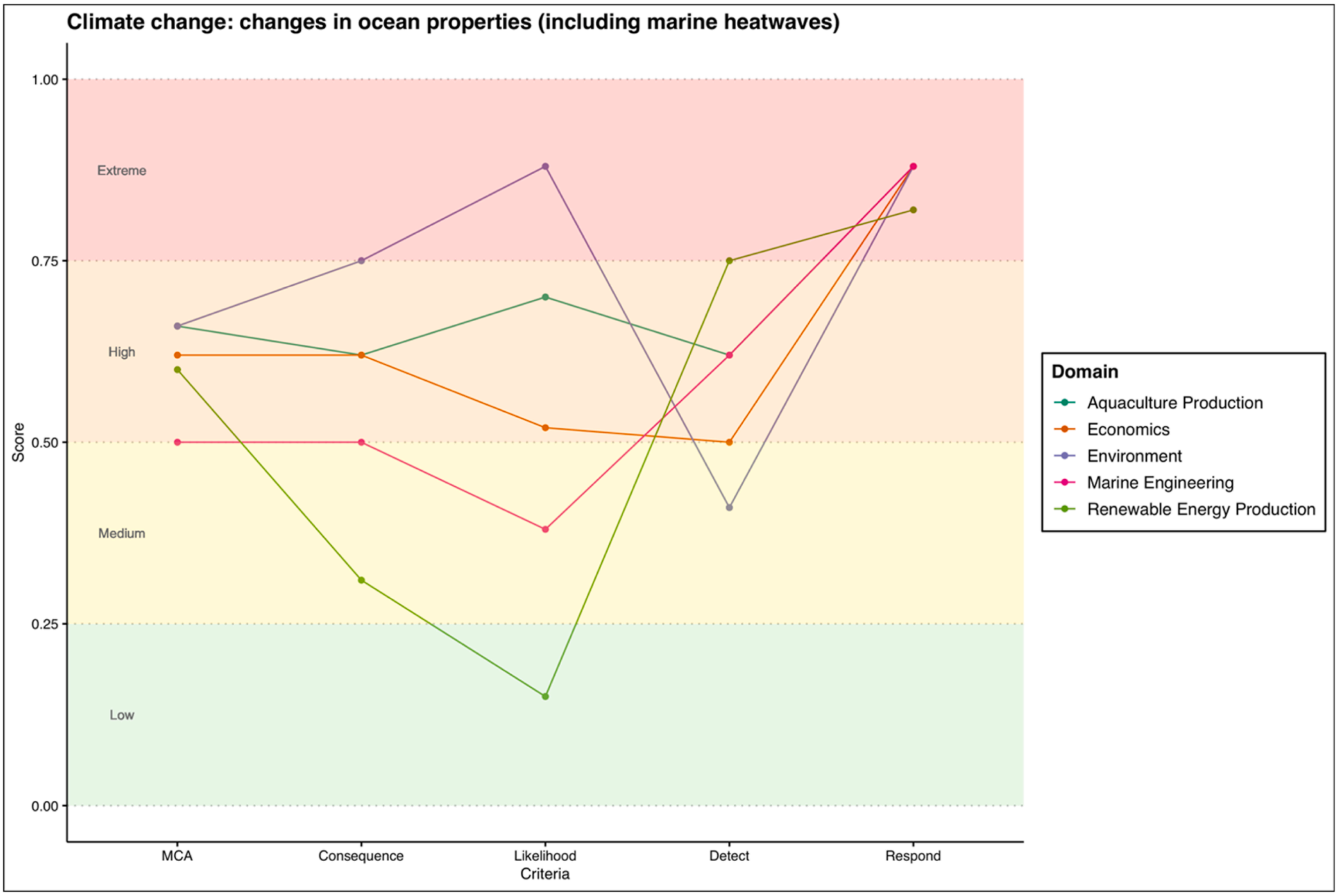

Fig. 5. Median scores across domains for all criteria (including multi-criteria score – MCA) for the hazard *Climate Change: changes in ocean properties (including marine heatwaves)*. The four categories – Low, Moderate, High, or Extreme – are based on equal breaks between 0 and 1 (i.e., Low represents 0–0.25, Medium represent 0.26–0.50 etc.).

domains could be caused by real differences in the outcome variables that domain experts are assessing (e.g., species versus economy), differences in risk perception across domains, characteristics of the hazard itself, or blind spots to certain hazards due to diverse disciplinary backgrounds (Sullivan-Wiley and Short Gianotti, 2017). While our analysis cannot distinguish among these different causes of variation in risk perception, it can shed some light on where further follow-up may be required. For example, social scientists and environmental specialists identified *Biosecurity: vector* as high ranking for consequence, whereas economists and aquaculture production specialists did not rank it on consequence as highly (see SI Table 3). However, *Biosecurity: vector* can have high consequences for economies and aquaculture production as a loss of trust in industry caused by *Biosecurity: vector* outbreaks can lead to a loss of *Social Licence*, having economic implications (Bouwmeester et al., 2021). This suggests that the domain experts in these fields who participated in the exercise might either have a blind spot to the risks posed by this particular hazard as they relate to offshore aquaculture, or they may have additional information regarding methods or new techniques that will neutralise any risk posed by the hazard that experts from other fields are not privy to. In such a scenario, a full Delphi process would provide an opportunity to flag consistent differences and highlight where ongoing consultation might be needed amongst stakeholders to exchange knowledge and reach a consensus point (Mukherjee et al., 2015).

While hazard identification can be an endpoint in its own right, it is most effective when it forms a starting point for a larger risk management process. This process could aim to minimise/remove risks in general (i.e., retire risks across all identified hazards) to facilitate and streamline regulatory process and reduce financial costs to proponents (Copping et al., 2020). More often, hazard identification looks to inform prioritizations of resources for identifying and responding to hazards (see decision tree in Fig. 7). Topics which may prove most contentious are those where there is significant disagreement in the perceived hazard across domains (e.g., *Altered Ecosystem Functioning* – indicated by high variability among participants in their ranks). This disagreement could in part represent real differences in the actuality of the hazard. For example, well known industries like aquaculture will not be as exposed to issues of *Misinformation* regarding new technology as will be the relatively nascent Australian offshore renewable energy sector. Variability in scoring can flag potential sources of disagreement, but also flag where targeted information collection could help resolve the issue. For example, experts on renewable energy production were divided on the hazard posed by issues related to *Planning for Multiple Sectors* and *Environmental Liability*, topics which might be particularly unclear in Australia because legislation is non-existent or in preparation (Techera and Chandler, 2015). For such hazards, further information should be sought before making a decision to either retire the hazard, or proceed to a risk assessment.

We encountered several challenges that provide lessons for improving future multi-disciplinary hazard rankings. For example, bringing multiple disciplines together required a simpler approach compared to the sophisticated methods used for hazard analysis by specific disciplines (Ericson, 2015; Leimeister and Kolios, 2018). Some discipline specific experts chose not to participate because they did not

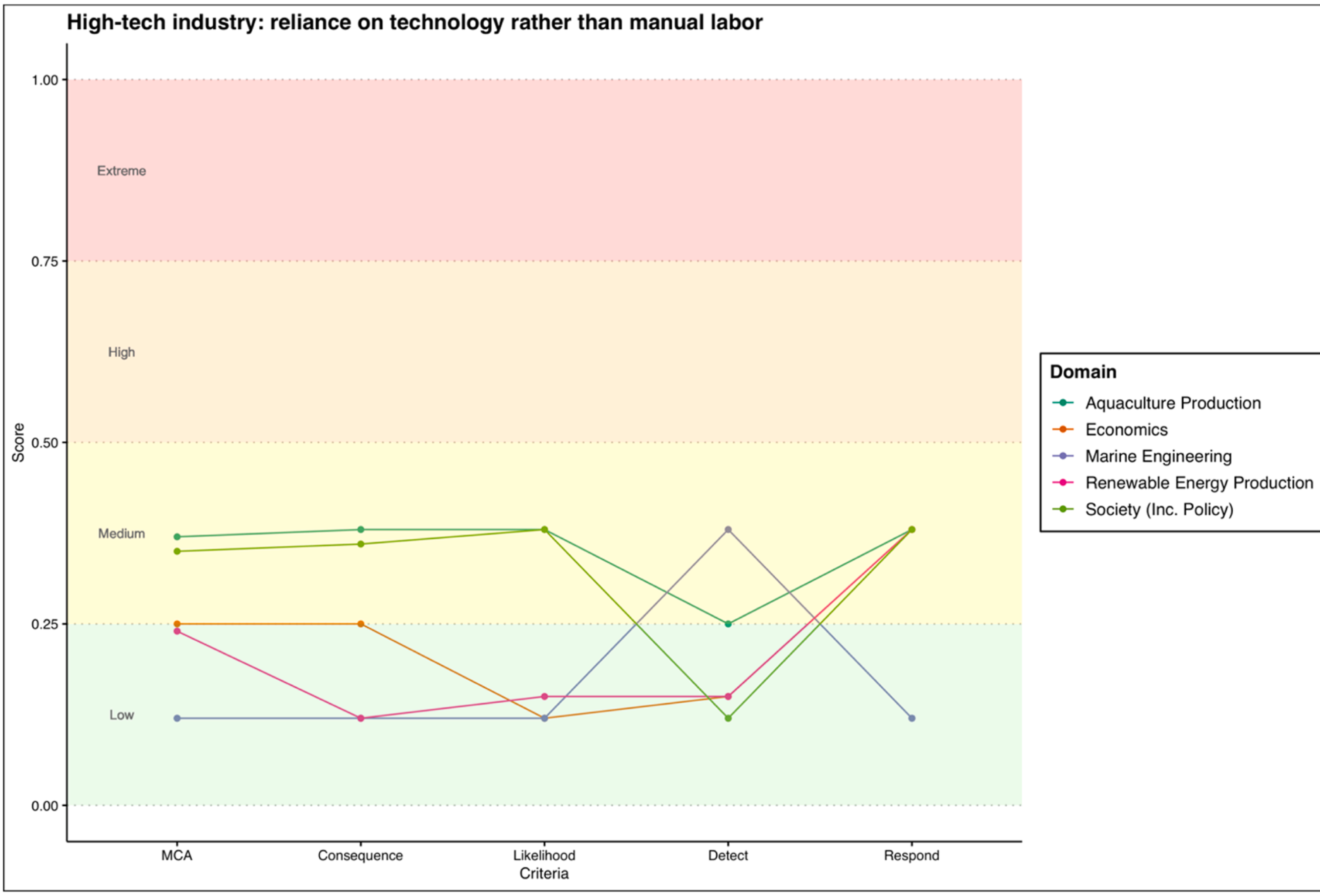

Fig. 6. Median scores across domains for all criteria (including multi criteria score – MCA) for the hazard *High-tech industry: reliance on technology rather than manual labour*. The four categories – Low, Moderate, High, or Extreme – are based on equal breaks between 0 and 1 (i.e., Low represents 0–0.25, Medium represent 0.26–0.50 etc.).

understand the reasoning for our simple approach. For example, some engineers were challenged by being called upon at such an "early phase of the process", stating they would not normally be called upon until a development had already gained sufficient approval, meaning many hazards assessed in the current study would already have been dealt with (e.g., by choosing a site where specific hazards were simply not possible). Different disciplines will have their own more sophisticated methods and expectations about "an acceptable minimum" for what that method should involve. Our choice of approach was guided by our previous experience with other multi-criteria decision making methods, particularly the Analytical Hierarchy Process (Saaty, 1990) and Multi-Attribute Utility Theory (MAUT) (Keeney and Raiffa, 1993), and other methods for identifying and ranking hazards that are typically implemented at the early conceptual or preliminary design stage of a project, such as Failure Modes and Effects Analysis and Hazard and Operability Studies (Ericson, 2005). Key issues that influenced our choices included the time necessary to complete an assessment, the central concepts associated with the method (such as the standard gamble in MAUT), the diversity and background of the participants involved (suggesting a graphical rather than a purely algorithmic approach), and a recognition that moving away from methods that participants were already familiar with can be challenging due to underlying cognitive biases (Fulton, 2021).

Expert-based processes are subject to the biases and knowledge limitations of the experts involved in the process (Hodgson et al., 2019). Biases such as the availability bias (events that come more easily to mind are rated as more probable compared to less memorable events) and representativeness bias (assuming events experienced by an observer are more common than based on actual frequency of occurrence); can influence an individual risk perception, appetite and aversion (Renn, 1998). Drawing attention to these biases – for example through explicit training to acknowledge these biases as per Step 6 in our approach or taking the time to support experts through the process of expanding their vision to have "all in" discussions with people from other backgrounds – can help reduce the influence of biases on the hazard rankings (Pasquini et al., 2019). Similarly, several biases must also be considered in group decision contexts and must be considered in the development of the conceptual models (Pasquini et al., 2019). So long as those implementing the method are aware of potential biases they can be accounted for and minimised.

A further challenge we encountered was getting experts who were comfortable with probabilistic methods to rank hazards in a qualitative manner. Defining common language (i.e., SI Table 1) and expectations early in the stakeholder engagement processes is key to overcoming some of the challenges of linguistic uncertainty (Hayes, 2011) and to help people to see the mutual benefit of engagement even if it takes them out of their comfort zone. Increased information sharing between otherwise siloed domains (e.g., increasing the awareness of engineers to social issues; increased collaboration between natural and social scientists) is critical to achieving integrated assessments for a sustainable blue economy (Hodgson et al., 2019), and can contribute to projects gaining a social licence to operate through behavioural change that improves the management of social issues (Vanclay, 2020).

The drive for a semi-qualitative approach was based on the general

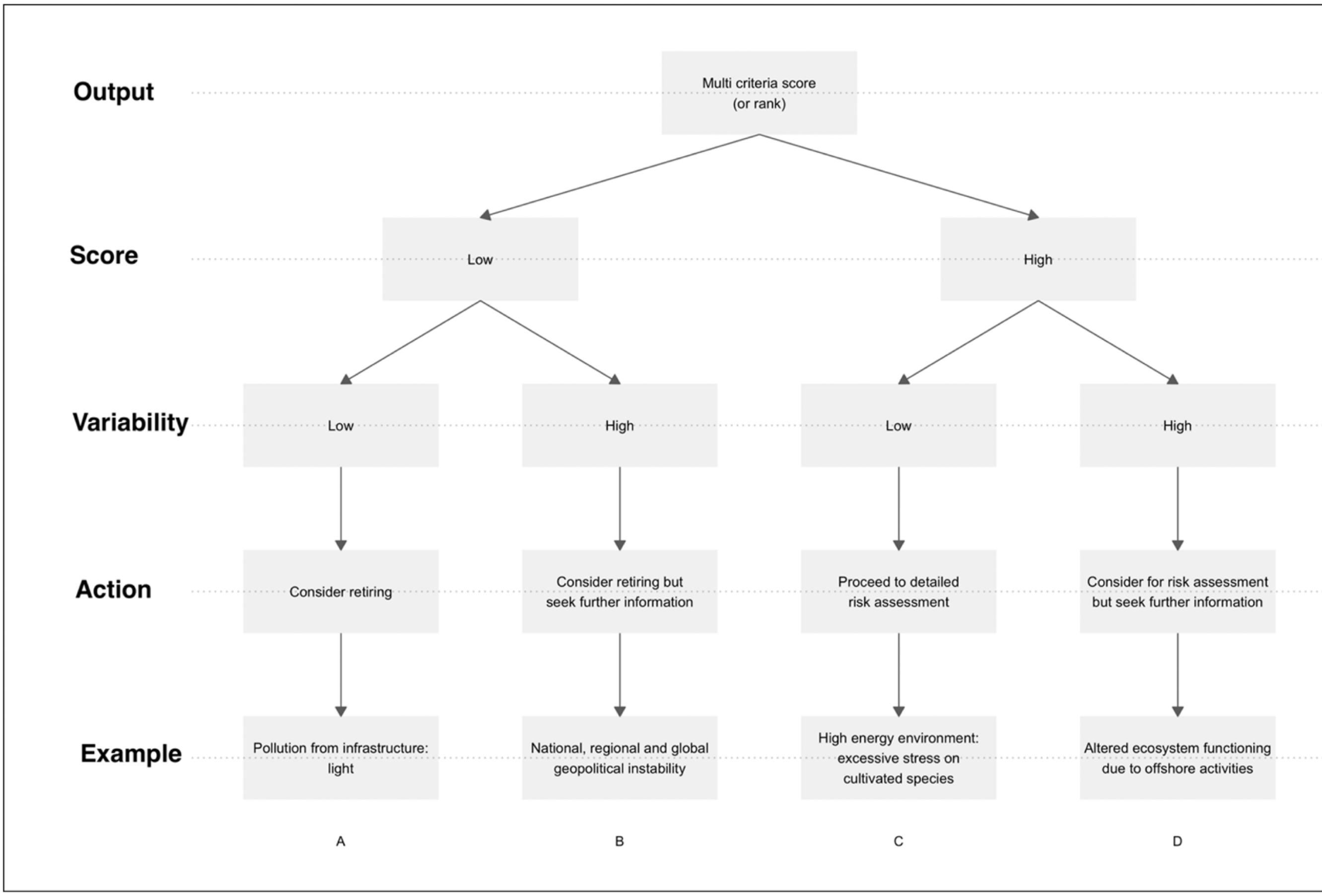

Fig. 7. Decision tree on how to manage ranked hazards. Hazards classified as 'A' can be safely retired. 'B' and 'D' should be considered for risk assessment due to variability in their scores (ranks), while 'C' need to be progressed to full risk assessment. Example hazards from the current hazard analysis are displayed for each decision endpoint.

paucity of data, within Australia and elsewhere, for offshore systems and heterogeneity across domains in the data that does exist. Expert based approaches are a widely accepted approach for dealing with data poor and broad scope questions (Jones et al., 2018; Stelzenmüller et al., 2018), especially when they form the first step of a hierarchical risk assessment approach (e.g. Hobday et al., 2011, Steven et al., 2019). The approach outlined in this paper can be used in that way, as laid out in the decision tree (Fig. 7), helping to reduce a long and comprehensive list of hazards to those that should be the focus of more quantitative risk assessments or ongoing information collection. Our approach is general, so is a starting point only for hazard analysis for particular uses. For instance, investors in blue economy projects will have different requirements of a hazard analysis than government regulators. However, our approach could be a starting point for both groups to identify lists of hazards for assessment that will most impact the values of interest to them.

While innovative approaches (perhaps using concepts from gamification; Robson et al., 2015) may be needed to tackle the issues of fatigue, the method in its current form can be usefully extended. For instance, future iterations could consider the weighting of experts themselves, based (for example) on experience in the field. More could also be done to standardise scoring, accounting for the natural risk attitude held by the individual experts (taking lessons from the work on Multi Attribute Utility Theory), or to draw on the range of scores to start to characterise uncertainty, as done in some expert-based qualitative risk assessments (e.g., Steven et al., 2018). Any further work on uncertainty should prioritise distinguishing between true uncertainty and ignorance. We have attempted to do that here by allowing experts to identify "not applicable" in their responses (which were then filtered out of final analyses or accounted for in other ways). Creating such a distinction will help with appropriate weighting of scores and the prioritisation of hazards for further data collection and refinement. A clear additional consideration to this approach is that consulted experts (preferably 10–20 per domain – Hemming et al., 2018) should ideally stem from a sufficient breadth of disciplines, backgrounds (both cultural and expertise), professional experience, age and gender to ensure their combined views reflect as accurately as possible the complexity of the socio-ecological system they are assessing (Hemming et al., 2018). In situations where that may not be the case, for example because of limited resources and/or expertise, a precautionary approach may be warranted, particularly for hazards with low or inconclusive rankings.

The developed approach is limited in that it does not consider community-based or Indigenous perspectives of risk. Equitable and sustainable blue growth must recognize and protect human rights, including traditional (Indigenous) management and ownership customs. Respectful and meaningful engagement with Traditional Custodians and the wider community would involve a much more involved process than was possible in within the constraints of this study, especially given the COVID-19 pandemic limited participation to an online setting. We therefore recognise this gap and look to fill it in future studies.

Multi-sectoral assessment of risk that integrate knowledge and perspectives from many domains can direct research needs, management directions and investment decisions. Through a structured, multi-criteria based ranking of hazards, the methodological approach developed in the current study can be applied to support strategic decision making and risk mitigation by identifying and prioritising hazards that should be considered and progressed to full risk assessment. Where hazards are deemed significant, a more detailed and rigorous risk analysis can be considered to identify appropriate evaluation, regulatory requirements and mitigation measures reducing the consequence or likelihood of the hazard. The scope of the emerging blue economy makes it a prime candidate for such multi-sectoral considerations, both because of the emergence and potentially rapid and concurrent development of many new sectors, but also because there is interest in creating multiple use zones and platforms to help make these sectors more equitable, economically viable and environmentally sustainable – in line with the core intents of the blue economy concept.

CRediT authorship contribution statement

Mischa P Turschwell: Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Christopher J Brown:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Myriam Lacharité:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Jess Melbourne-Thomas:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Keith R Hayes:** Methodology, Writing – original draft, Writing – review & editing. **Rodrigo H Bustamante:** Methodology, Writing – review & editing. **Jeffrey M Dambacher:** Methodology, Writing – review & editing. **Karen Evans:** Methodology, Writing – review & editing. **Pedro Fidelman:** Methodology, Writing – review & editing. **Darla Hatton MacDonald:** Methodology, Writing – review & editing. **Ingrid Van Putten:** Methodology, Writing – review & editing. **Graham Wood:** Methodology, Writing – review & editing. **Nagi Abdussamie:** Methodology, Writing – review & editing. **Mathilda Bates:** Writing – review & editing. **Damien Blackwell:** Writing – review & editing. **Steven D'Alessandro:** Writing – review & editing. **Ian Dutton:** Writing – review & editing. **Jessica A Ericson:** Writing – review & editing. **Christopher LJ Frid:** Writing – review & editing. **Carmel McDougall:** Writing – review & editing. **Mary-Anne Lea:** Writing – review & editing. **David Rissik:** Writing – review & editing. **Rowan Trebilco:** Writing – review & editing. **Elizabeth A Fulton:** Funding acquisition, Conceptualization, Methodology, Formal analysis Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The authors do not have permission to share data.

Acknowledgements

The authors acknowledge the financial support of the Blue Economy Cooperative Research Centre (CRC), established and supported under the Australian Government's CRC Program, grant number CRC-20180101. The CRC Program supports industry-led collaborations between industry, researchers and the community. CJB, and MPT - Discovery Project (DP180103124) from the Australian Research Council. CJB – Future Fellowship (FT210100792) from the Australian Research Council. Thank you to Derek Fulton for developing Figure 3 and the scenario figures in the supplementary information. Thank you to members of Seascape models lab for testing the online ranking web application. J.A. Ericson's participation was supported by the Cawthron Shellfish Aquaculture Platform (MBIE contract CAWX1801).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2023.06.008.

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