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A synthesis of approaches to support integrated assessments of hazards for the emerging Blue Economy

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ABSTRACT

Growth in offshore blue economies is predicted to accelerate as emerging food and energy production industries look to expand into these environments. Operating in novel environments for these industries inherently fosters uncertainty in outcomes generated by a complex suite of hazards, some of which are unknown prior to deployment. Faced with such uncertainty, a precautionary, flexible, and cross-disciplinary (integrated) approach is recommended to optimize the potential for hazards to be identified in a timely, comprehensive, and robust manner, and mitigated. However, relevant disciplines – such as aquaculture production, marine engineering, and marine renewable energy design, and associated interactions with society and the environment – often evolve with their siloed techniques and lexicons. Here we first provide an overview of selected discipline-specific approaches to hazard analysis as a first step in a pathway that can generate a holistic synthesis of hazards to and from multiple emerging sectors in novel environments. Despite challenges of applying these individual methods to cross-disciplinary projects for emerging industries, we then identify where disciplines share methodological approaches and where opportunities exist to develop integrated methods. With a growing focus on sustainable economic growth and optimizing the use of ocean space through multi-use, our review highlighted that the emerging offshore Blue Economy could benefit from the development of a flexible, integrated approach to identify and assess hazards in a comprehensive, robust and useful manner for successful planning, development, and operations.

1. Introduction

A transition from traditional to emerging blue industries has begun in earnest as more industries look to expand in offshore environments [1,2]. Historically dominated by oil and gas exploitation, commercial fishing, shipping and telecommunications, offshore environments are now increasingly considered for other industries, such as marine renewable energy and aquaculture [3–5]. Global and regional estimates of available aquaculture and energy resources demonstrate their potential, with large-scale projects underway in Europe and Australia, among others [6–9]. Several jurisdictions now seek to better understand the potential and costs associated with these emerging industries, while mitigating negative interactions with the environment and other ocean users, supporting positive interactions as opportunities, and addressing

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challenges associated with governance and socio-cultural impacts e.g. [3,6,10–13].

Expansion in novel environments creates new hazards when limited operational experience exists (e.g., marine renewable energy), or when existing practices may need to be adapted to novel conditions (e.g., aquaculture). New cross-sector and cumulative interactions may also arise with potential to negatively impact ecosystems, especially as some traditional sectors continue to expand in parallel with emerging industries [14]. These hazards could both originate from and impact industry operations over their life cycle from planning to their eventual decommissioning [15]. This includes for example lack of a clear regulatory framework leading to wasted resources during planning or (cumulative) impacts to local ecosystems undetected due to inadequate monitoring programs [15,16]. Understanding and mitigating hazards is necessary to secure investment, ensure cost effectiveness, reduce inter-sectoral conflict and foster socio-economic benefits to local regional communities through food and energy security, while minimizing negative impacts to marine ecosystems.

A risk-based management system that seeks to meet quadruple-bottom-line objectives (environment, economic, social and governance) is needed for emerging offshore industries. A critical first step in such a system is to identify hazards and separate those that must be assessed and perhaps managed, from those that can be safely ignored [17–20]. Comprehensive assessments of potential hazards from diverse expertise across disciplines and sectors could reduce uncertainty due to a lack of operational experiences and maximize the likelihood of prioritizing hazards for mitigation efforts [21]. Such comprehensive assessments are necessary for emerging industries that seek to be sustainable, just, and inclusive – thus creating a positive image with wider society – which will assist in delivering on their objectives and simultaneously maintaining a social license to operate [22,23]. Predicting and managing hazards across multiple sectors and perspectives in an emerging blue economy is critical as it recognizes the interconnected approach to sustainable development through its social, environmental, and economic pillars [24].

Approaches to analyse hazards and assess risks have been developed and applied across a wide variety of disciplines including engineering, medicine, ecology, and economics [21], but these approaches vary widely in their scope and complexity. Concepts of hazard and risk have been studied for decades [25], and 'hazard analysis' is typically a broadly scoped 'screening' step to identify and prioritize possible hazards, and was originally developed for industrial systems safety, aiming to identify hazards, their effects, and their causal factors [26]. In this context, hazard analysis has parallels with more formal risk identification which is part of a larger risk assessment framework including risk analysis and evaluation [27]. 'Hazard analysis' and 'risk identification' are sometimes used synonymously, the latter being defined as the process of finding, recognizing, and describing risks, and involves the identification of risk sources and events, their causes, and their potential consequences [27]. It is however difficult to apply a one-size-fits-all assessment approach to hazard analysis across multiple industry sectors, even when they are operating in the same environment,since disciplines each have different lexicons and their own, often siloed, approach(es) [21]. Furthermore, the individual risk assessments typically come with a specific viewpoint – risks to a development, or risk originating from operational activities, typically only considering direct effects from that development's operations or the combined effect across activities within a single industry [28]; the integration and consideration of broader risks "to" and "by" activities is much rarer. Regional scale strategic assessments can take this broader view [29], but they still tend to come from a specific lens – environmental or economic – and still struggle to bring together comprehensive assessments from multiple disciplinary lenses. To ensure that diverse perspectives are incorporated into any future integrated approach to hazard analysis, it is important in a first instance to identify where disciplines, perspectives or sectors share methodological approaches.

Here, we review hazard analysis approaches (Table 1), evaluation processes and tools – touching on commonly used risk analysis and assessment techniques where relevant – used in several domains involved in establishing an offshore blue economy for food and energy production. Across all frameworks for integrated ocean management, very few integrate across goals for economic, social, environmental and cultural outcomes with different empirical perspectives on data and knowledge [30]. We aim to fill that gap for the blue economy agenda by describing approaches applied to the technical (engineering), environmental, social and economic components associated with food (aquaculture) and renewable energy production (Fig. 1A), particularly when implemented for offshore developments. However, because few examples currently exist, we extend our literature search more broadly. The classification of domains used here is derived from [21] but differs in that we include marine engineering and renewable energy production as a single domain due to potential for co-location of multiple industries in future developments (i.e., aquaculture production co-located with renewable energy production –[31]). Similarly, we group aquaculture production and interactions with the environment due to the similarities in approaches. We synthesise the common themes across domains and provide recommendations to guide the development of an integrated approach to hazard analysis that transcends diverse domains of expertise.

2. A review of approaches to hazard analysis

Taking a comprehensive disciplinary perspective means drawing together views from different backgrounds. Sharing knowledge of the approaches across disciplines allows people from each domain to understand expectations from the other disciplines, find common method overlap and adopt new approaches from outside their field. Nevertheless, a full 'comprehensive' literature review is infeasible given the sheer size of the body of work pertaining to hazard analyses and risk assessment in each domain. However, as much of that reflects repeat implementations of just a few methods, this high-level review is representative of the major methods used in the different domains and allows for the overview and the desired connection of methods.

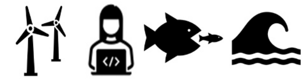
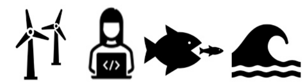
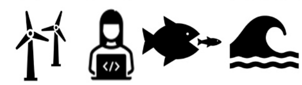
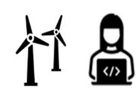
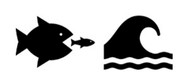
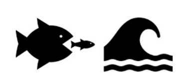
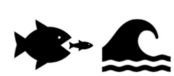
A key challenge for hazard analysis and risk assessments – and likely to be accentuated in integrated, multi-sectoral assessments – is linguistic uncertainty [32]. Here we define the following terms:

- **Hazard** – A situation that in particular circumstances could lead to harm (The Royal Society, 1983).
- **Risk –** Is commonly defined as the product of the likelihood or probability of an event occurring, and the consequences of the event if it were to occur [33], which can be derived from the answer to three questions: (i) What can go wrong? (ii) How likely is it that that will happen? and, (ii) if it does happen what are the consequences? [34]
- **Hazard analysis –** Aims to identify hazards (both real and potential) their effects and the factors that cause them, and was originally developed for systems safety and engineering [26]. The term risk identification is often used synonymously with hazard identification. For consistency, we use the term hazard identification.
- **Risk analysis and risk assessment –** These two terms are sometimes used interchangeably. Here we define risk analysis as the risk calculation step of a risk assessment, that comprises risk identification, risk analysis and risk management e.g. [35].

2.1. *Renewable energy production & marine engineering*

A plethora of approaches to hazard analysis have been developed and applied in industrial systems and are discussed in detail in Ericson [26], with several approaches applied to offshore wind energy with informative and useful outcomes [36]. With respect to renewable energy

Table 1
Summary descriptions of approaches used to assess hazards and risks for the emerging offshore Blue Economy (Refer to Fig. 1 for icon descriptions).

Method	Description	Approach	Primary domains of application
Hazard Identification (HAZID)	High-level, structured approach used to identify a wide range of possible hazards early in the project	Qualitative	
Hazard and Operability Analysis (HAZOP)	Takes a comprehensive view of a system and systematically examines every component to establish how deviations from intended design may occur	Qualitative	
Preliminary Hazard Analysis (PHA)	Can be as simple as conducting a hazard brainstorming session on a system, or a more structured process that helps ensure all hazards are identified	Qualitative	
Failure Modes and Effects Analysis (FMEA)	Bottom-up approach whereby failures are prioritized according to how serious their consequences are, how frequently they occur, and how easily they can be detected.	Qualitative Quantitative	
Holographic Hierarchical Modelling (HHM)	Examines complex systems from different perspectives in order to identify sub-systems, and then examines how the components of these sub-systems interact to identify hazards	Qualitative Quantitative	
Bow-Tie, Fault Tree Analysis (FTA), Event Tree Analysis (ETA)	Identifies the causes and consequences of hazards by combining Fault Tree Analysis and Event Tree Analysis (see below). Graphical models are used to identify the combinations of contributing (base) events that cause a top event. The probability of the top event can be calculated when data (empirical observation or expert elicitation) on the frequency of the base events is available. Graphical models used to identify consequences associated with the top event. Probabilities can be assigned to each consequence when data (empirical observations or expert elicitation) are available	Qualitative Quantitative	
Bayesian Networks (BN)	Probabilistic graphical models (formally Directed Acyclic Graphs) that link nodes (discrete random variables) with edges (links between nodes) based on the presumed causal relationships between the nodes. The network is completed by a joint probability distribution over the nodes, commonly represented in conditional probability tables that can be populated from data or expert opinion.	Qualitative Quantitative	
Multi Criteria Decision Analysis (MCDA)	Broad approach that encompasses several methods that explicitly address multiple criteria to aid decision making. The criteria scores are commonly elicited from experts and combined using appropriate algorithms such as the weighted sum of scores.	Qualitative Quantitative	
Digital Twin (DT)	Digital representations (processs-based simulation models) of physical objects or systems that facilitate scenario-based analyses to identify component failures, improving design and overall safety in offshore systems.	Quantitative	
Socioecological system models (SEMod)	Span environmental drivers, simplified food web representations, the different major industries operating in an area, human demographic and use models and simple representations of the regional economy. These large models are conceptually aligned with the digital twin approach, but with many more degrees of uncertainty and extensive data demands.	Quantitative	
Ecological Risk Assessment (ERA)	Assessments often consider specific ecosystem-based criteria such as the sensitivity, vulnerability and adaptive capacity of systems (instead of criteria such as likelihood and consequence) to rank hazards and assess risk. Can itself be hierarchical, beginning with scoping (effectively hazard analyses) followed by qualitative and then increasingly quantitative assessments. Filtering at each stage means only risks identified as being unacceptably high are advanced to the quantitative assessment stages. This helps triage risks when available resources for an assessment are limited	Qualitative Quantitative	
Qualitative Network Modelling (QNM)	Models consisting of nodes that represent components of interest and signed direct arrows that denote the direction (and sometimes strength) of relationships between nodes. These models can be mathematically analysed and used to explore a range of alternative scenarios (and system stability).	Qualitative Quantitative	
Geographic Information Systems (GIS)	Platforms that allow for the spatial layering of existing data to assess cumulative effects of multiple hazards (pressures) to the environment.	Quantitative	
Connectivity models (Conn)	Models including hydrodynamic and dispersal models used for assessing risk of disease infection in aquaculture production systems and estimating potential water quality impacts from waste released by an industry respectively.	Quantitative	
Social Impact Assessment (SIA)	Has parallels with many risk assessment frameworks in that it provides a methodology for engaging stakeholders who are directly affected by development in the assessment process, understanding the social processes (and feedbacks) that cause change, predicting change in social outcomes, and identifying indicators to measure change.	Qualitative	
Monte Carlo simulations (MC)	Commonly used to analyse the effects of uncertainty during quantitative risk assessments. In this context historically used to assess the financial risk to investors and lenders. Have been used to assess factors including weather, political change and financial markets that could impact project cash flow and analyse how adverse events could impact project earnings and subsequent viability as part of cost-benefit analysis of a project incorporating simulations of risk.	Quantitative	

A)

Renewable energy production	Includes the construction, deployment, and operations of technology to capture renewable energy in offshore locations (primarily wind and wave), as well as operational logistics of accessing sites.
Marine engineering	The manufacture and production of structures to be used offshore for renewable energy production, and aquaculture production.
Society (including policy considerations)	Social considerations of new development including obtaining a social licence to operate and impacts on local communities from emerging industries.
Economics and finance	The psychology of decision making and the financial viability of operations for offshore renewable and aquaculture production.
Aquaculture production +	The rearing of species (e.g., fish) in offshore high-energy environments, including operational logistics of accessing sites.
Interactions with the environment	Interactions with the local environment from renewable energy production, aquaculture production and marine engineering.

B)

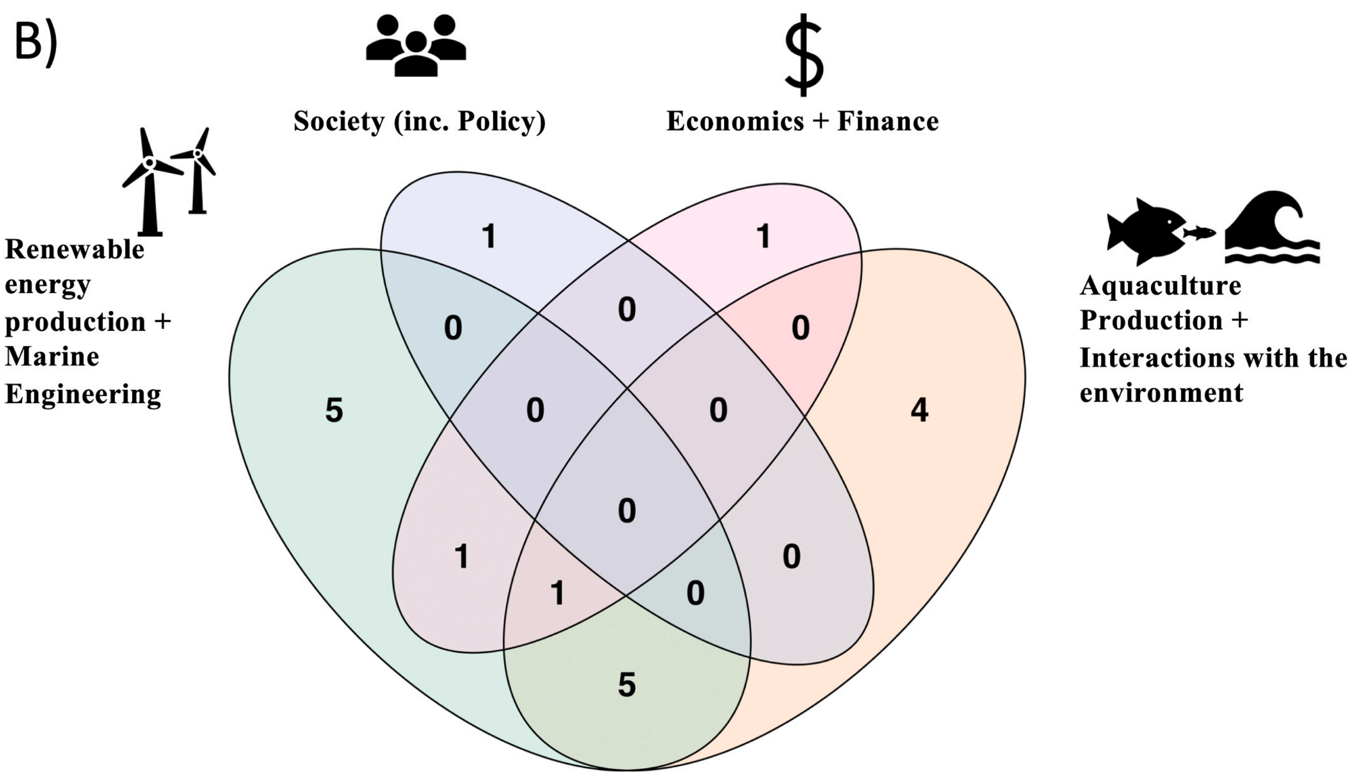


Fig. 1. A) Descriptions of the research domains involved in establishing a food and energy generating offshore blue economy, B) Venn Diagram showing overlap of number of approaches (and abbreviated names) for each domain identified from the review.

production and marine engineering more generally, approaches including Hazard Identification (HAZID), often performed as part of a Preliminary Hazard Analysis (PHA), and Hazard and Operability Analysis (HAZOP), are common, and have been used to identify and assess a variety of hazards for offshore wind energy, and offshore seaports and associated barge transportation systems [36–39]. Preliminary Hazard Analysis can be as simple as conducting a hazard brainstorming session on a system, or can be a more structured process that aims to ensure all hazards are identified [26]. Hazard Identification is one of the high-level, more structured approaches used to identify a wide range of possible hazards early in a project's life-cycle [38], and differs from HAZOP, which requires a comprehensive description of the project (and may therefore occur later in the life-cycle) and systematically examines every component of the project system to establish how deviations from intended design may occur [40]. Failure Mode and Effects Analysis (FMEA) is a bottom-up approach and has been used to determine critical components of offshore wind farms [41]. Through the application of FMEA, failures are prioritized according to how serious their consequences are, how frequently they occur, and how easily they can be detected. Alternatively, Holographic Hierarchical Modelling (HHM) is a technique particularly suited to complex systems. This form of modelling decomposes complex systems into groups of sub-systems by examining the overall system from different “perspectives” (such as economic, environmental, social) and studies the interactions between the components of these different sub-systems to identify hazards [42, 43]. While these methods could be comprehensive in principle they tend to focus tightly on specific developments or sectors and so are not examples of the comprehensive multi-lens approach required for a true multi-disciplinary approach required for emerging offshore developments.

Bow tie risk assessment frameworks are also commonly used to identify hazards and assess risk in offshore systems. The bow-tie approach has also been used across disciplines for coastal fisheries risk assessment [44]. Bow-tie risk assessments identify the causes and consequences of hazards [37,45,46]. Fault tree analysis (FTA) uses graphical methods to identify the combinations of contributing events that cause a top event (i.e., the hazard for the system being considered) to occur. This top event may, for example, be the failure to contain a hazardous substance. If the subsequent consequences associated with the top event are identified then this approach can be extended into an Event Tree Analysis (ETA) [26,37]. If probabilities can be assigned to the base events in the fault tree, and the consequence in the event tree, then FTA and ETA can be used to compute risk [26]. While common in engineering fields, these approaches are more difficult to apply to ecological systems because it is difficult to estimate the probability of the base events in the fault tree and end consequences identified in the event tree, especially for emerging industries where there is little empirical data on the risk of hazards [47] or the hazards are only theorised.

Other approaches including Bayesian Networks (BNs) are also used to assess risk in offshore engineering. This approach uses probabilistic graphical models (formally Directed Acyclic Graphs) that link nodes (discrete random variables) with edges (links between nodes) based on the presumed causal relationships between the nodes (formally the edges encode conditional dependencies between the nodes). The BN is completed by a joint probability distribution over the nodes, commonly represented in conditional probability tables that can be populated from data or expert opinion. Bayesian Network predictions can be updated by conditioning on observations and as when new information becomes available [45,48,49]. One of the drawbacks of this approach is that it does not allow for recognition of feedbacks between different parts of the system, something which is important for a systemic perspective – especially in terms of the consequences of domain interactions.

Multi Criteria Decision Analysis (MCDA) is a broad approach that encompasses several methods that explicitly address multiple criteria to aid decision making [50]. This approach has been commonly applied in engineering associated with renewable energy to rank hazards against a series of criteria, including the consequence associated with the hazard, and the frequency of the hazard occurring [51,52]. The criteria scores are commonly elicited from experts and combined using appropriate algorithms such as the weighted sum of scores. Weighted sum of scores has been used to rank and compare offshore multi-use platform designs while incorporating hazards [31]. The additive algorithm Technique for Ordered Preferences using Similarity to the Ideal Solution (TOPSIS) has been used to rank risk for components in an offshore wave energy converter [53]. More computationally intensive methods such as digital twin simulations, which are digital representations (typically processs-based models) of physical objects or systems, can be used to assess risk of structural failure of components. Digital twin simulations run scenario-based analyses to identify potential component failures, improving design and overall safety in offshore systems [54,55].

2.2. Aquaculture + Interactions with the biophysical environment

Several hazard analysis methods (and their adaptations) including HAZOP, FTA, ETA, FMEA, and HHM have been applied in ecological contexts [26,56–60] and thus have the potential for application to both aquaculture and interactions with the biophysical environment. In assessing hazards from aquaculture, and interactions with the biophysical environment, most published studies generally incorporate the hazard analysis into the risk identification step of a comprehensive ecological risk assessment (ERA). These assessments often consider specific ecosystem-based criteria such as the sensitivity, vulnerability and adaptive capacity of systems instead of, or in addition to criteria that are commonly used within engineering domains to rank hazards and assess risk, such as likelihood and consequence [61–67].

Risk assessment approaches utilised to consider aquaculture production or effects on the biophysical environment range from qualitative to fully quantitative. The exact method employed varies depending on the scope of, and resources available to, the assessment, because it can be challenging to quantify the probability of events and their consequences in biological systems [68]. Tiered risk assessment frameworks are one way to approach this challenge [62]. Tiered frameworks are hierarchically structured, becoming increasingly complex and data intensive at higher levels. Beginning with simple qualitative approaches to calculate risk, focal subjects of the assessment (such as species populations’ exposure to aquaculture or marine energy sites) that cannot be confidently assigned a low-risk status are progressed into more quantitative tiers for more thorough assessments. This is a cost-effective approach as situations or activities assessed as low-risk are not required to go through additional more costly steps. This is somewhat like the engineering concept of ‘retiring’ a risk that is found to be inconsequential [18]. A three-tiered risk assessment was recently performed to evaluate disease, organic pollution and whole-of-system risks encountered during the production cycles of salmon farming leases in southern Chile [69]. This approach used qualitative models (a method discussed in the next paragraph) for the first tier, statistical methods for a second tier focusing on operational issues, and socioecological system models (that span environmental drivers, simplified food web representations, the different major industries operating in an area, human demographic and use models and simple representations of the regional economy) at the third tier. This tier considered system-scale development scenarios and the potential interactions that might arise across the system. These large process-based models are aligned with the engineering digital twins, but in socio-economic and environmental systems these models have many more parameters, higher degrees of uncertainty and more extensive data demands in order to initialise and accurately parameterise.

Other common approaches to identify and analyse hazards to the environment include graphical qualitative network models (formally signed directed graphs or signed digraphs). These models consist of nodes which represent components of interest and signed direct arrows that denote the direction (and sometimes strength) of relationships between nodes. Qualitative network models can be mathematically analysed and used to explore a range of alternative scenarios (and system stability). They have been used in a very broad range of contexts, such as to assess risk to ecological components from cumulative effects on the Great Barrier Reef [70], within a larger toolkit of approaches to predict the ecosystem effects of genetic control options for invasive species [71], to consider monitoring of the effects of fishing [72], aquaculture production [73], harbour monitoring and management [74] and the implications of the development of offshore wind [75], to name but a few. In contrast to Bayesian Networks, qualitative network models can resolve the influence of feedbacks across the modelled system. A drawback to these qualitative models, however, is that quantification of effects is not possible. If quantitative estimates are required, then process-based models (as used in tiered assessments, [69]), Bayesian Networks or statistical models more generally must be employed. Similar to engineering-based disciplines, Bayesian Networks have been used to examine interactions of production activities with the biophysical environment, and can also be used to validate qualitative network model structures when constructed with observational data [71,76,77].

Spatial approaches to assess risk and hazards to the environment primarily use Geographic Information Systems (GIS), and involve the layering of spatial data on pressures and threats. These spatial layering approaches are commonly used to assess cumulative effects of multiple hazards (pressures) to the environment [78], and are often foundational for broader governance tools such as marine spatial planning, which in its own right is a tool to manage and mitigate hazards to the environment [79]. Finally, connectivity models (e.g., hydrodynamic models that capture diffusion and advection dynamics to represent dispersal) have considerable application for aquaculture and interactions with the environment. For example, connectivity models have been used to assess risk of disease infection in aquaculture production systems [80], and to estimate potential water quality impacts from waste released by an industry.

2.3. Society (including policy considerations)

Within the social sciences, Social Impact Assessment (SIA) is a conceptual framework for predicting social responses to industry development, policy, or conservation [81,82]. This framework has some analogues to risk assessment. It is similar to risk assessment in that it is initially based on developing an understanding of the social context of the development or project. It then considers the direct and indirect social impacts arising – such as impacts on community values, cultural values and quality of life – and plans appropriate mitigation strategies for potential negative impacts (while also identifying opportunities). Finally, SIA engages with communities to design ongoing monitoring of the impacts and options for adaptive management. In this way, SIA facilitates social license to operate, because it aims to assist in delivering better outcomes for all project stakeholders [83].

Social Impact Assessments are similar to many risk assessment frameworks [84,85], in that they provide a methodology for engaging stakeholders who are directly affected by development in the assessment process, understanding the social processes (and feedbacks) that cause change, predicting change in social outcomes, and identifying indicators to measure change [81]. The breadth of hazards identified in a SIA depends on the context and interactions between the project and the economic, political, sociocultural and security context in which it is constructed and operated [81,86]. Methods for conducting SIAs include qualitative interviews, focus groups, and participatory workshops where participants work through scenario analyses [82]. The framework can also be adapted to use a risk matrix approach. In general, this approach invites stakeholders to participate in workshops where different scenarios are explored, and consequence and likelihood are assigned on rating scales (e.g., [1–10]).

2.4. Economics and finance

Within behavioural/experimental economics and finance literature, techniques for eliciting perceptions and attitudes to risk have been developed, with a particular focus on the psychology of decision making and risk preferences as opposed to different ways to conduct hazard analysis [87]. As with the aquaculture and interactions with the biophysical environment domain, most economic studies focus on risk analysis, rather than hazard analysis. Economic risk assessments are generally quantitative, and data driven [88]. For example, Monte Carlo simulation approaches are commonly used in economic risk assessments for aquaculture production and renewable energy structures. Monte Carlo approaches assess how uncertainty in weather, environmental stressors, political change and financial markets could impact project cash flow [89–92]. Model results are then used to inform financial risk for investors and lenders. Derivatives of MCDA approaches (including analytic hierarchy process – see [93]) have also been used for economic risk analysis to combine numerous factors and assess investment risk for land-based renewable energy projects [16]. In this approach, the analyst is simulating a series of efficient solutions which maximise social well-being or minimise cost. The analyst then presents the set of options for the decision-maker to choose amongst.

With reference to financial risks in aquaculture, the primary methods to assess risk fall under probabilistic (e.g., probability trees, Bayesian Networks, Monte Carlo simulation) and non-probabilistic estimation methods (e.g., scenario-based analysis, sensitivity analysis, and break-even analysis). These methods are discussed in more detail in [94], who also highlight the benefit of using both qualitative and quantitative approaches to assess financial hazard and risks. For example, solely relying on quantitative historical data without reference to qualitative current market information could lead to under or over representation of financial risk.

3. Discussion

The approaches used for hazard analysis generally come down to the domain(s) involved in the assessment, the user, and the complexity of the system being assessed (Table 1). The decision to use qualitative or quantitative methods is largely due to the resources and data available in any given situation, noting that data in the form of empirical observations (rather than expert elicitation) are often a limiting factor for many emerging industries (e.g., suitable biodiversity data for assessments or untested operating conditions – [95]). The primary approaches to hazard analysis and risk assessment across the domains that are central to the development of food and renewable energy centered offshore blue economies are:

- Renewable energy production and marine engineering both use hazard analysis and risk analysis approaches and prefer probabilistic methods.
- Aquaculture production and interactions with the environment primarily use ecological risk assessment approaches, which can range from qualitative to fully quantitative, but methods from renewable energy and marine engineering have also been successfully applied to these domains.
- As a domain, society uses social impact assessment, which has many parallels with risk assessment, but differs in that social impact assessments place greater emphasis on minimising risks to communities and increasing the likelihood of maintaining social license to operate.
- Economic approaches place a large focus on the psychology of decision making and different ways to elicit risk. Formal risk analyses can be qualitative or quantitative.

Risk assessments applied within a single sector may touch on aspects drawing on multiple domains – for example an assessment of aquaculture may consider structural failure (engineering), interactions with the environment (ecological risk analysis), economic risks (financial viability, access to markets) and social risks (lack of social license) – however this falls short of the systemic consideration required for a truly multi-sector, multi-perspective, comprehensive analysis. While such a focused view may be sufficient for individual developments (as required under national legislation in various countries), the focussed approach has been criticised for falling short of what is needed for strategic regional planning [28,96,97]. Few tools are available for considering hazards simultaneously across domains. While there have been a number of academic e.g. [78,96] or planning processes e.g. [98–100] that aim to address the issue of cumulative effects, they predominantly do so through a single lens, often an environmental effects lens [101]. More generally, most of the quantitative frameworks for integrated ocean practice focus on a single normative goal, like the environment or economy, rather than considering multiple laws and policies, sectors, and goals and objectives [30,102]. In the context of individual development proposals social, economic and environmental impact assessments may be required, but the multi-domain consideration is much rarer in the full planning processes. It is true that some approaches have been successfully applied across multiple sectors (Fig. 1). Nonetheless, it is also apparent that methods from one domain are challenging to apply to cross-disciplinary projects due to differences in terminology, and epistemology [32]. Navigating the challenges of multiple sector integration and obtaining a comprehensive, systemic view of the hazards can be worthwhile, as integrating expertise from diverse backgrounds will highlight opportunities and potentially perverse incentives that would be missed from a narrower perspective [103,104].

While benefits can be derived from taking a broader view or looking for methodological inspiration from other domains, there are multiple pitfalls if hazard and risk analysis tools developed in one discipline were to be applied to a different discipline. At the simplest level, without the appreciation of nuance derived from deep disciplinary background the method may be misapplied or be prone to naïve mistakes. Working in true collaboration across disciplines forestalls such a hurdle, however other cross-disciplinary consequences can be harder to deal with. For example, the application of risk assessments based on likelihood and consequence to social issues may shut down the conversation to broader perspectives on impacts and social change processes, which social impact assessments are designed to address [81]. Further, classic risk analysis does not represent feedbacks between development and society, the understanding of which is a crucial part of social impact assessment [105]. Broader views also engender understanding more complexity, involve more uncertainty and typically require more resources. The later in particular is challenging for proponents and is why linking project (proponent level) and regional (government or research driven) approaches may be a pragmatic way of obtaining a more integrated view while still keeping resourcing to more practical levels.

Many of the risk assessment approaches we reviewed are part of legal mandates for impact assessment of development proposals. However, legal mandates for impact assessment can be fragmented across different aspects of the blue economy [102]. The patchwork of existing governance structures may constrain application of new ideas for integrated assessments and pose challenges for them to meet their legal requirements [106]. Specifically, formal governance structures are often complex and fragmented, where multiple entities manage marine resources on a sectoral basis. The lack of coordinated governance approaches and policies and legislation that are fit for the purpose of the blue economy, especially for the development of co-located offshore activities, represent major obstacles to the operationalisation of integrated hazard and risk analyses. The methods we highlighted will often comply with or exceed standards in many countries, so what is needed next is to develop integrative ocean management frameworks that will provide the governance 'quilt' of ocean management [102]. These mixed assessments could be conducted as part of the early stage of planning and will meet the different assessment needs of different parts of government.

4. Conclusions

There are clear benefits in attaining a more holistic understanding of how particular domains are affected by or generate the same hazards, and how industries can thus jointly manage and mitigate such hazards [21]. Identification of joint mitigation options could be a first step towards overcoming the challenges associated with differences in approaches across disciplines. Nevertheless, more can be achieved by going further to develop empirical tools that consider objectives of multiple sectors [30].

The overlap in approaches across the different sectors suggests a way forward for developing a multiple sector approach to risk assessment. Notably, all sectors had methods that included developing network or graphical models to qualitatively understand systems of interconnected components and how they manifest to influence risk. All sectors have also used expert elicitation to quantify a range of risk criteria, such as consequence and likelihood. Therefore, we suggest the most straightforward approach for a multi-sector hazard analysis should integrate systems thinking with graphical models and expert elicitation of risk criteria. In a multi-sector context the risk criteria may need to be broadened beyond the traditional focus on consequence and likelihood to consider criteria that are relevant to diverse stakeholders. One example would be the likelihood of not detecting a hazard, which will be relevant to social license. Additionally, the approach should include stakeholder consultation to identify criteria that are important across different sectors, while seeking to balance the required elicitation load for experts.

A risk assessment that is integrated across domains could be improved by borrowing ideas from social sciences. We found that the social domain had the least overlap in methods with the other domains. A unique aspect of social impact assessment was the requirement for ongoing engagement with community stakeholders. Communities that are expected to be impacted by development are engaged throughout the process, including following the development. The aim being a two-way exchange of knowledge, that involves improving the impact assessment with community knowledge, as well as improving community understanding of the development. Such an approach has advantages over the quantitative and technical assessment methods of other domains in that it helps build social license for the development. Thus, we recommend integrated assessments borrow this idea and incorporate engagement with impacted communities into the risk assessment process.

Developing an integrated, yet flexible, and readily generalisable approach may help set the scene for future successful offshore blue economy planning, development, and operations. We recommend a multidisciplinary, participatory approach to co-develop and test integrated approaches with mixed groups of domain experts in order to meet this need within the constraints of typically available data and resources.

CRediT authorship contribution statement

M.**P. Turschwell:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Visualization, Writing – original draft, Writing – review & editing. **E.A. Fulton:** Conceptualization, Funding acquisition, Investigation, Writing – original draft, Writing – review & editing. **J. Melbourne-Thomas:** Conceptualization, Funding acquisition, Investigation, Writing – original draft, Writing – review & editing. **M. Lacharité:** Conceptualization, Funding acquisition, Investigation, Writing – original draft, Writing – review & editing. **K.R. Hayes:** Conceptualization, Funding acquisition, Investigation, Writing – original draft, Writing – review & editing. **G. Wood:** Conceptualization, Writing – review & editing. **K. Evans:** Conceptualization, Writing – review & editing. **D. Hatton MacDonald:** Conceptualization, Writing – review & editing. **J. Dambacher:** Conceptualization, Writing – review & editing. **R.H. Bustamante:** Conceptualization, Writing – review & editing. **R. Abbassi:** Conceptualization, Writing – review & editing. **P. Fidelman:** Conceptualization, Writing – review & editing. **C.J. Brown:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Visualization, Writing – original draft, Writing – review & editing.

Data availability

No data was used for the research described in the article.

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There are no new data associated with this article.

References

[1] C. Novaglio, N. Bax, F. Boschetti, G.R. Emad, S. Frusher, L. Fullbrook, M. Hemer, S. Jennings, I. Van Putten, L.M. Robinson, Deep aspirations: towards a sustainable offshore Blue Economy, Rev. Fish. Biol. Fish. (2021) 1–22.
[2] T. Stojanovic, C. Farmer, The development of world oceans & coasts and concepts of sustainability, Mar. Policy 42 (2013) 157–165.
[3] S.E. Lester, J.M. Stevens, R.R. Gentry, C.V. Kappel, T.W. Bell, C.J. Costello, S. D. Gaines, D.A. Kiefer, C.C. Maue, J.E. Rensel, R.D. Simons, L. Washburn, C. White, Marine spatial planning makes room for offshore aquaculture in crowded coastal waters, Nat. Commun. 9 (2018) 945, https://doi.org/10.1038/s41467-018-03249-1.
[4] M. Melikoglu, Current status and future of ocean energy sources: A global review, Ocean Eng. 148 (2018) 563–573.
[5] M.J. Spalding, The new blue economy: the future of sustainability, J. Ocean Coast. Econ. 2 (2016) 8.
[6] R.R. Gentry, S.E. Lester, C.V. Kappel, C. White, T.W. Bell, J. Stevens, S.D. Gaines, Offshore aquaculture: spatial planning principles for sustainable development, Ecol. Evol. 7 (2017) 733–743.
[7] M.A. Hemer, R. Manasseh, K.L. McInnes, I. Penesis, T. Pitman, Perspectives on a way forward for ocean renewable energy in Australia, Renew. Energy 127 (2018) 733–745.
[8] E.P. Soares-Ramos, L. Oliveira-Assis, R. Sarrias-Mena, L.M. Fernández-Ramírez, Current status and future trends of offshore wind power in Europe, Energy 202 (2020), 117787.
[9] C.V.C. Weiss, B. Ondiviela, X. Guinda, F. Jesus, J. González, R. Guanche, J. A. Juanes, Co-location opportunities for renewable energies and aquaculture facilities in the Canary Archipelago, Ocean Coast. Manag. 166 (2018) 62–71, https://doi.org/10.1016/j.ocecoaman.2018.05.006.
[10] P.Q. García, J.G. Sanabria, J.A.C. Ruiz, Marine renewable energy and maritime spatial planning in Spain: Main challenges and recommendations, Mar. Policy 127 (2021), 104444.
[11] M.L. Martínez, G. Vázquez, O. Pérez-Maqueo, R. Silva, P. Moreno-Casasola, G. Mendoza-González, J. López-Portillo, I. MacGregor-Fors, G. Heckel, J. Hernández-Santana, A systemic view of potential environmental impacts of ocean energy production, Renew. Sustain. Energy Rev. 149 (2021), 111332.
[12] S.W.K. Burg, J. Aguilar-Manjarrez, J. Jenness, M. Torrie, Assessment of the geographical potential for co-use of marine space, based on operational boundaries for Blue Growth sectors, Mar. Policy 100 (2019) 43–57, https://doi.org/10.1016/j.marpol.2018.10.050.
[13] K.L. Yates, D.S. Schoeman, C.J. Klein, Ocean zoning for conservation, fisheries and marine renewable energy: assessing trade-offs and co-location opportunities, J. Environ. Manag. 152 (2015) 201–209.
[14] B. Crona, E. Wassénius, K. Lillepold, R. Watson, E. Selig, C. Hicks, H. Österblom, C. Folke, J.-B. Jouffray, R. Blasiak, Sharing the seas: a review and analysis of ocean sector interactions, Environ. Res. Lett. 16 (2021).
[15] H. Williams, I. Masters, D. Pletsas, C.F. Grunewald, R. Callaway, M. Blanch, G. Dalton, A risk assessment methodology for combining marine renewables with other blue economy activities via multi-use of spaces and platforms, Proc. EWTEC Cork, Irel. (2017).
[16] Y. Wu, J. Wang, S. Ji, Z. Song, Renewable energy investment risk assessment for nations along China's Belt & Road Initiative: An ANP-cloud model method, Energy 190 (2020), 116381, https://doi.org/10.1016/j.energy.2019.116381.
[17] A. Staid, S.D. Guikema, Risk analysis for U.S. Offshore wind farms: the need for an integrated approach, Risk Anal. 35 (2015) 587–593, https://doi.org/10.1111/risa.12324.
[18] A.E. Copping, M.C. Freeman, A.M. Gorton, L.G. Hemery, Risk retirement—decreasing uncertainty and informing consenting processes for marine renewable energy development, J. Mar. Sci. Eng. 8 (2020) 172.
[19] J.-B. Jouffray, R. Blasiak, A.V. Norström, H. Österblom, M. Nyström, The Blue Acceleration: The Trajectory of Human Expansion into the Ocean, One Earth 2 (2020) 43–54, https://doi.org/10.1016/j.oneear.2019.12.016.
[20] X. Yang, I.B. Utne, I.M. Holmen, Methodology for hazard identification in aquaculture operations (MHIAO), Saf. Sci. 121 (2020) 430–450.
[21] E.E. Hodgson, T.E. Essington, J.F. Samhouri, E.H. Allison, N.J. Bennett, A. Bostrom, A.C. Cullen, S. Kasperski, P.S. Levin, M.R. Poe, Integrated Risk Assessment for the Blue Economy, Front. Mar. Sci. 6 (2019), https://doi.org/10.3389/fmars.2019.00609.
[22] M. Voyer, J. Leeuwen, Social License to Operate and the Blue Economy, Repor t to the World Ocean Council, Australian National Centre for Ocean Resources an d Security, Wollongong, Australia, 2018.
[23] N.J. Bennett, J. Blythe, C.S. White, C. Campero, Blue growth and blue justice: Ten risks and solutions for the ocean economy, Mar. Policy 125 (2021), 104387.
[24] A.M. Cisneros-Montemayor, M. Moreno-Báez, G. Reygondeau, W.W.L. Cheung, K. M. Crosman, P.C. González-Espinosa, V.W.Y. Lam, M.A. Oyinlola, G.G. Singh, W. Swartz, C. Zheng, Y. Ota, Enabling conditions for an equitable and sustainable blue economy, Nature 591 (2021) 396–401, https://doi.org/10.1038/s41586-021-03327-3.
[25] T. Aven, Risk assessment and risk management: Review of recent advances on their foundation, Eur. J. Oper. Res. 253 (2016) 1–13, https://doi.org/10.1016/j.ejor.2015.12.023.
[26] C.A. Ericson, Hazard Analysis Techniques for System Safety, John Wiley & Sons,, 2015.
[27] ISO Guide, Risk management—Vocabulary, 2009.
[28] B. Durning, M. Broderick, Mini review of current practice in the assessment of cumulative environmental effects of UK Offshore Renewable Energy Developments when carried out to aid decision making in a regulatory context, 2015.
[29] D. Casimiro, A. Quintela, J. Matias, L. Sousa, A. Simão, Lopes Alves A. and Lopes Alves, Cumulative Impacts and Strategic Environmental Assessment: Literature review. In support of Deliverable 3.2 of the SIMAtlantic project (EASME/EMFF/2018/1.2.1.5/SI2.806423). 26 pp., 2021.
[30] M. Voyer, C. Moyle, C. Kuster, A. Lewis, K.K. Lal, G. Quirk, Achieving comprehensive integrated ocean management requires normative, applied, and empirical integration, One Earth 4 (2021) 1016–1025.
[31] B. Zanuttigh, E. Angelelli, A. Kortenhaus, K. Koca, Y. Krontira, P. Koundouri, A methodology for multi-criteria design of multi-use offshore platforms for marine renewable energy harvesting, Renew. Energy 85 (2016) 1271–1289, https://doi.org/10.1016/j.renene.2015.07.080.
[32] K. Hayes, Uncertain. Uncertain. Anal. Methods (2011), https://doi.org/10.4225/08/585189e5f2360.
[33] M.T. Gibbs, H.I. Browman, Risk assessment and risk management: a primer for marine scientists, ICES J. Mar. Sci. 72 (2015) 992–996.
[34] S. Kaplan, B.J. Garrick, On the quantitative definition of risk, Risk Anal. 1 (1981) 11–27.
[35] W. (Rick), J. Fletcher, Review and refinement of an existing qualitative risk assessment method for application within an ecosystem-based management framework, ICES J. Mar. Sci. 72 (2015) 1043–1056.
[36] M. Leimeister, A. Kolios, A review of reliability-based methods for risk analysis and their application in the offshore wind industry, Renew. Sustain. Energy Rev. 91 (2018) 1065–1076.
[37] K. Mokhtari, J. Ren, C. Roberts, J. Wang, Application of a generic bow-tie based risk analysis framework on risk management of sea ports and offshore terminals, J. Hazard. Mater. 192 (2011) 465–475.
[38] N. Abdussamie, A. Zaghwan, M. Daboos, I. Elferjani, A. Mehanna, W. Su, Operational risk assessment of offshore transport barges, Ocean Eng. 156 (2018) 333–346.
[39] N. Abdussamie, M. Daboos, I. Elferjani, C. Shuhong, A. Alaktiwi, Risk assessment of LNG and FLNG vessels during manoeuvring in open sea, J. Ocean Eng. Sci. 3 (2018) 56–66.
[40] U. Okoro, A. Kolios, E. Pérez-López, L. Cui, Q. Sheng+5, Wave Energy Converter System Safety Analysis, in: 2015.
[41] K. Sivalingam, M. Sepulveda, M. Spring, P. Davies, A Review and Methodology Development for Remaining Useful Life Prediction of Offshore Fixed and Floating Wind turbine Power Converter with Digital Twin Technology Perspective, 2018 2nd Int. Conf. Green. Energy Appl. (ICGEA) (2018) 197–204, https://doi.org/10.1109/ICGEA.2018.8356292.
[42] Y.Y. Haimes, Hierarchical holographic modeling, IEEE Trans. Syst., Man, Cybern. 11 (1981) 606–617.
[43] J.H. Lambert, Y.Y. Haimes, D. Li, R.M. Schooff, V. Tulsiani, Identification, ranking, and management of risks in a major system acquisition, Reliab. Eng. Syst. Saf. 72 (2001) 315–325, https://doi.org/10.1016/S0951-8320(01)00009-6.
[44] R. Cormier, V. Stelzenmüller, I.F. Creed, J. Igras, H. Rambo, U. Callies, L. B. Johnson, The science-policy interface of risk-based freshwater and marine management systems: from concepts to practical tools, J. Environ. Manag. 226 (2018) 340–346.
[45] N. Khakzad, F. Khan, P. Amyotte, Quantitative risk analysis of offshore drilling operations: A Bayesian approach, Saf. Sci. 57 (2013) 108–117.
[46] M. Abimbola, F. Khan, N. Khakzad, Dynamic safety risk analysis of offshore drilling, J. Loss Prev. Process Ind. 30 (2014) 74–85.
[47] K.R. Hayes, Identifying hazards in complex ecological systems. Part 1: fault-tree analysis for biological invasions, Biol. Invasions 4 (2002) 235–249.
[48] L. Dai, S. Ehlers, M. Rausand, I.B. Utne, Risk of collision between service vessels and offshore wind turbines, Reliab. Eng. Syst. Saf. 109 (2013) 18–31.
[49] S. Zhao, C.G. Soares, H. Zhu, A Bayesian network modelling and risk analysis on LNG carrier anchoring system, 2015 Int. Conf. Transp. Inf. Saf. (ICTIS) (2015) 432–436, https://doi.org/10.1109/ICTIS.2015.7232059.
[50] J. Ananda, G. Herath, A critical review of multi-criteria decision making methods with special reference to forest management and planning, Ecol. Econ. 68 (2009) 2535–2548.
[51] M.M. Abaei, E. Arzaghi, R. Abbassi, V. Garaniya, I. Penesis, Developing a novel risk-based methodology for multi-criteria decision making in marine renewable energy applications, Renew. Energy 102 (2017) 341–348, https://doi.org/10.1016/j.renene.2016.10.054.
[52] R.A. Estévez, V. Espinoza, R.D. Ponce Oliva, F. Vásquez-Lavín, S. Gelcich, Multi-criteria decision analysis for renewable energies: research trends, gaps and the challenge of improving participation, Sustainability 13 (2021) 3515.
[53] U. Okoro, A. Kolios, L. Cui, Multi-criteria risk assessment approach for components risk ranking–The case study of an offshore Wave Energy Converter, Int. J. Mar. Energy 17 (2017) 21–39.
[54] P. Murray, Z. Wattis, B. Bain, M. Golowczynski, A. Sadd, Towards a Digital Twin Supporting Risk Based Decision Making for Offshore Installations, in: Towards a Digital Twin Supporting Risk Based Decision Making for Offshore Installations, OnePetro, 2019, https://doi.org/10.2118/195717-MS.

[55] A. Jaribion, S.H. Khajavi, M. Öhman, A. Knapen, J. Holmström, A Digital Twin for Safety and Risk Management: A Prototype for a Hydrogen High-Pressure Vessel, in: S. Hofmann, O. Müller, M. Rossi (Eds.), Designing for Digital Transformation. Co-Creating Services with Citizens and Industry, Springer International Publishing, Cham, 2020, pp. 369–375.
[56] S. Watts, Britons pioneer assessments of gene hazards, N. Sci. 122 (1989) 32.
[57] K.R. Hayes, Identifying hazards in complex ecological systems. Part 2: infection modes and effects analysis for biological invasions, Biol. Invasions 4 (2002) 251–261.
[58] K.R. Hayes, P.C. Gregg, V. Gupta, R. Jessop, W. Lonsdale, B. Sindel, J. Stanley, C. K. Williams, Identifying hazards in complex ecological systems. Part 3: Hierarchical Holographic Model for herbicide tolerant oilseed rape, Environ. Biosaf. Res. 3 (2004) 109–128.
[59] J. Ford, K. Hayes, B. Henderson, S. Lewis, P. Baker, R. Schmidt, Systematic analysis of water-related hazards associated with coal resource development. Submethodology M11 from the Bioregional Assessment Technical Programme. Department of the Environment and Energy, Bureau of Meteorology, 2016.
[60] K.R. Hayes, G.R. Hosack, G.V. Dana, S.D. Foster, J.H. Ford, R. Thresher, A. Ickowicz, D. Peel, M. Tizard, P. De Barro, Identifying and detecting potentially adverse ecological outcomes associated with the release of gene-drive modified organisms, J. Responsible Innov. 5 (2018) S139–S158.
[61] A. Chin, P.M. Kyne, T.I. Walker, R.B. McAuley, An integrated risk assessment for climate change: analysing the vulnerability of sharks and rays on Australia's Great Barrier Reef, Glob. Change Biol. 16 (2010) 1936–1953, https://doi.org/10.1111/j.1365-2486.2009.02128.x.
[62] A.J. Hobday, A.D.M. Smith, I.C. Stobutzki, C. Bulman, R. Daley, J.M. Dambacher, R.A. Deng, J. Dowdney, M. Fuller, D. Furlani, Ecological risk assessment for the effects of fishing, Fish. Res. 108 (2011) 372–384.
[63] A. Williams, J. Dowdney, A. Smith, A. Hobday, M. Fuller, Evaluating impacts of fishing on benthic habitats: a risk assessment framework applied to Australian fisheries, Fish. Res. 112 (2011) 154–167.
[64] Z.A. Doubleday, S.M. Clarke, X. Li, G.T. Pecl, T.M. Ward, S. Battaglene, S. Frusher, P.J. Gibbs, A.J. Hobday, N. Hutchinson, S.M. Jennings, R. Stoklosa, Assessing the risk of climate change to aquaculture: a case study from south-east Australia, Aquac. Environ. Interact. 3 (2013) 163–175, https://doi.org/10.3354/aei00058.
[65] A. Knights, G. Piet, R. Jongbloed, J. Tamis, L. White, E. Akoglu, L. Boicenco, T. Churilova, O. Kryvenko, V. Fleming, J.-M. Lepannen, B. Galil, F. Goodsir, M. Goren, P. Margonski, S. Moncheva, T. Oguz, N. Papadopoulou, O. Setälä, L. Robinson, An exposure-effect approach for evaluating ecosystem-wide risks from human activities, Ices J. Mar. Sci. 72 (2015) 1105–1115, https://doi.org/10.1093/icesjms/fsu245.
[66] J.T. Mathis, S.R. Cooley, N. Lucey, S. Colt, J. Ekstrom, T. Hurst, C. Hauri, W. Evans, J.N. Cross, R.A. Feely, Ocean acidification risk assessment for Alaska's fishery sector, Prog. Oceanogr. 136 (2015) 71–91, https://doi.org/10.1016/j.pocean.2014.07.001.
[67] J.F. Samhouri, E. Ramanujam, J.J. Bizzarro, H. Carter, K. Sayce, S. Shen, An ecosystem-based risk assessment for California fisheries co-developed by scientists, managers, and stakeholders, Biol. Conserv. 231 (2019) 103–121.
[68] G.L. Taranger, Ø. Karlsen, R.J. Bannister, K.A. Glover, V. Husa, E. Karlsbakk, B. O. Kvamme, K.K. Boxaspen, P.A. Bjørn, B. Finstad, Risk assessment of the environmental impact of Norwegian Atlantic salmon farming, ICES J. Mar. Sci. 72 (2015) 997–1021.
[69] A.D. Steven, S. Aryal, P. Bernal, F. Bravo, R.H. Bustamante, S. Condie, J. M. Dambacher, S. Dowideit, E.A. Fulton, R. Gorton, SIMA Austral: An operational information system for managing the Chilean aquaculture industry with international application, J. Oper. Oceanogr. 12 (2019) S29–S46.
[70] K.R. Anthony, J.M. Dambacher, T. Walshe, R. Beeden, A framework for understanding cumulative impacts, supporting environmental decisions and informing resilience based management of the Great Barrier Reef World Heritage Area: Final Report to the Great Barrier Reef Marine Park Authority and Department of the Environment, 2013.
[71] K.R. Hayes, B. Leung, R. Thresher, J.M. Dambacher, G.R. Hosack, Meeting the challenge of quantitative risk assessment for genetic control techniques: a framework and some methods applied to the common Carp (Cyprinus carpio) in Australia, Biol. Invasions 16 (2014) 1273–1288.
[72] J.M. Dambacher, D.J. Gaughan, M. Rochet, P.A. Rossignol, V.M. Trenkel, Qualitative modelling and indicators of exploited ecosystems, Fish Fish 10 (2009) 305–322.
[73] J.C. Reum, P.S. McDonald, B.E. Ferriss, D.M. Farrell, C.J. Harvey, P.S. Levin, Qualitative network models in support of ecosystem approaches to bivalve aquaculture, ICES J. Mar. Sci. 72 (2015) 2278–2288.
[74] J. Dambacher, K. Hodge, R. Babcock, E. Fulton, S. Apte, É. Plagányi, M.S.J. Warne, N. Marshall, Models and indicators of key ecological assets in Gladstone Harbour, A Report Prepared for the Gladstone Healthy Harbour Partnership. Hobart, Tasmania, 2013.
[75] A. Raoux, J.M. Dambacher, J.-P. Pezy, C. Mazé, J.-C. Dauvin, N. Niquil, Assessing cumulative socio-ecological impacts of offshore wind farm development in the Bay of Seine (English Channel), Mar. Policy 89 (2018) 11–20.
[76] C.A. Pollino, O. Woodberry, A. Nicholson, K. Korb, B.T. Hart, Parameterisation and evaluation of a Bayesian network for use in an ecological risk assessment, Environ. Model. Softw. 22 (2007) 1140–1152.
[77] G.R. Hosack, K.R. Hayes, J.M. Dambacher, Assessing model structure uncertainty through an analysis of system feedback and Bayesian networks, Ecol. Appl. 18 (2008) 1070–1082, https://doi.org/10.1890/07-0482.1.
[78] B.S. Halpern, S. Walbridge, K.A. Selkoe, C.V. Kappel, F. Micheli, C. D'agrosa, J. F. Bruno, K.S. Casey, C. Ebert, H.E. Fox, A global map of human impact on marine ecosystems, Science 319 (2008) 948–952.
[79] V. Stelzenmüller, M. Coll, A.D. Mazaris, S. Giakoumi, S. Katsanevakis, M. E. Portman, R. Degen, P. Mackelworth, A. Gimpel, P.G. Albano, V. Almpanidou, J. Claudet, F. Essl, T. Evagelopoulos, J.J. Heymans, T. Genov, S. Kark, F. Micheli, M.G. Pennino, G. Rilov, B. Rumes, J. Steenbeek, H. Ojaveer, A risk-based approach to cumulative effect assessments for marine management, Sci. Total Environ. 612 (2018) 1132–1140, https://doi.org/10.1016/j.scitotenv.2017.08.289.
[80] F. Bravo, J. Sidhu, P. Bernal, R. Bustamante, S. Condie, B. Gorton, M. Herzfeld, D. Jimenez, F. Mardones, F. Rizwi, Hydrodynamic connectivity, water temperature, and salinity are major drivers of piscirickettsiosis prevalence and transmission among salmonid farms in Chile, Aquac. Environ. Interact. 12 (2020) 263–279.
[81] F. Vanclay, Conceptualising social impacts, Environ. Impact Assess. Rev. 22 (2002) 183–211.
[82] M. Kaplan-Hallam, N.J. Bennett, Adaptive social impact management for conservation and environmental management, Conserv. Biol. 32 (2018) 304–314.
[83] F. Vanclay, Principles to gain a social licence to operate for green initiatives and biodiversity projects, Curr. Opin. Environ. Sustain. 29 (2017) 48–56, https://doi.org/10.1016/j.cosust.2017.11.003.
[84] National Research Council, Understanding Risk: Informing Decisions in a Democratic Society, National Academies Press,, 1996. ⟨https://www.nap.edu/catalog/5138/understanding-risk-informing-decisions-in-a-democratic-society⟩.
[85] National Research Council, Science and Decisions: Advancing Risk Assessment, National Academies Press,, 2009. ⟨https://www.nap.edu/catalog/12209/science-and-decisions-advancing-risk-assessment⟩.
[86] P.B. Bueno, Social risks in aquaculture, Understanding and Applying Risk Analysis in Aquaculture, 2008: 209.
[87] C.A. Holt, S.K. Laury, Assessment and Estimation of Risk Preferences. Handbook of the Economics of Risk and Uncertainty, Elsevier,, 2014, pp. 135–201. ⟨https://linkinghub.elsevier.com/retrieve/pii/B9780444536853000040⟩. accessed December 7, 2020.
[88] C.B. Erb, C.R. Harvey, T.E. Viskanta, Political risk, economic risk, and financial risk, Null 52 (1996) 29–46, https://doi.org/10.2469/faj.v52.n6.2038.
[89] N. Wang, Y.-C. Chang, A.A. El-Sheikh, Monte Carlo simulation approach to life cycle cost management, Struct. Infrastruct. Eng. 8 (2012) 739–746, https://doi.org/10.1080/15732479.2010.481304.
[90] U. Arnold, Ö. Yildiz, Economic risk analysis of decentralized renewable energy infrastructures – A Monte Carlo Simulation approach, Renew. Energy 77 (2015) 227–239, https://doi.org/10.1016/j.renene.2014.11.059.
[91] E.J. da, S. Pereira, J.T. Pinho, M.A.B. Galhardo, W.N. Macêdo, Methodology of risk analysis by Monte Carlo Method applied to power generation with renewable energy, Renew. Energy 69 (2014) 347–355, https://doi.org/10.1016/j.renene.2014.03.054.
[92] J. Moor, A. Ropicki, T. Garlock, Clam aquaculture profitability under changing environmental risks, Aquac. Econ. Manag. 26 (2022) 283–300, https://doi.org/10.1080/13657305.2022.2058113.
[93] T.L. Saaty, What is the analytic hierarchy process?, in: Mathematical Models for Decision Support Springer, 1988, pp. 109–121.
[94] L.E. Kam, P. Leung, Financial risk analysis in aquaculture, Understanding and Applying Risk Analysis in, Aquaculture (2008) 153.
[95] C. Martin, M. Tolley, E. Farmer, C. Mcowen, J. Geffert, J. Scharlemann, H. Thomas, J. Bochove, D. Stanwell-Smith, J. Hutton, A global map to aid the identification and screening of critical habitat for marine industries, Mar. Policy 53 (2015) 45–53.
[96] V. Stelzenmüller, M. Coll, R. Cormier, A.D. Mazaris, M. Pascual, C. Loiseau, J. Claudet, S. Katsanevakis, E. Gissi, A. Evagelopoulos, B. Rumes, S. Degraer, H. Ojaveer, T. Moller, J. Giménez, C. Piroddi, V. Markantonatou, C. Dimitriadis, Operationalizing risk-based cumulative effect assessments in the marine environment, Sci. Total Environ. 724 (2020), 138118, https://doi.org/10.1016/j.scitotenv.2020.138118.
[97] E.L. Hague, C.E. Sparling, C. Morris, D. Vaughan, R. Walker, R.M. Culloch, A. R. Lyndon, T.F. Fernandes, L.H. McWhinnie, Same space, different standards: a review of cumulative effects assessment practice for marine mammals, Front. Mar. Sci. (2022).
[98] S. Korpinen, J.H. Andersen, A global review of cumulative pressure and impact assessments in marine environments, Front. Mar. Sci. 3 (2016) 153.
[99] W. Baxter, W.A. Ross, H. Spaling, Improving the practice of cumulative effects assessment in Canada, Impact Assess. Proj. Apprais. 19 (2001) 253–262.
[100] E.L. Hague, C.E. Sparling, C. Morris, D. Vaughan, R. Walker, R.M. Culloch, A. R. Lyndon, T.F. Fernandes, L.H. McWhinnie, Same space, different standards: a review of cumulative effects assessment practice for marine mammals, Front. Mar. Sci. (2022).
[101] K. Holsman, J. Samhouri, G. Cook, E. Hazen, E. Olsen, M. Dillard, S. Kasperski, S. Gaichas, C.R. Kelble, M. Fogarty, An ecosystem-based approach to marine risk assessment, Ecosystem Health and Sustainability 3 (2017), e01256.
[102] R.L. Stephenson, A.J. Hobday, C. Cvitanovic, K.A. Alexander, G.A. Begg, R. H. Bustamante, P.K. Dunstan, S. Frusher, M. Fudge, E.A. Fulton, M. Haward, C. Macleod, J. McDonald, K.L. Nash, E. Ogier, G. Pecl, É.E. Plagányi, I. van Putten, T. Smith, T.M. Ward, A practical framework for implementing and evaluating integrated management of marine activities, Ocean Coast. Manag. 177 (2019) 127–138, https://doi.org/10.1016/j.ocecoaman.2019.04.008.

[103] M.A. Burgman, M. McBride, R. Ashton, A. Speirs-Bridge, L. Flander, B. Wintle, F. Fidler, L. Rumpff, C. Twardy, Expert Status and Performance, PLOS ONE 6 (2011), e22998, https://doi.org/10.1371/journal.pone.0022998.

[104] P. Aminpour, S.A. Gray, A. Singer, S.B. Scyphers, A.J. Jetter, R. Jordan, R. Murphy, J.H. Grabowski, The diversity bonus in pooling local knowledge about complex problems, Proc. Natl. Acad. Sci. 118 (2021).

[105] A.M. Esteves, D. Franks, F. Vanclay, Social impact assessment: the state of the art, Null 30 (2012) 34–42, https://doi.org/10.1080/14615517.2012.660356.

[106] K.-H. Lee, J. Noh, J.S. Khim, The Blue Economy and the United Nations' sustainable development goals: Challenges and opportunities, Environ. Int. 137 (2020), 105528, https://doi.org/10.1016/j.envint.2020.105528.