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Published in:

ICES Journal of Marine Science

DOI:

[10.1093/icesjms/fsx216](https://doi.org/10.1093/icesjms/fsx216)

Publication date:

2018

Link:

[Link to publication in PEARL](#)

Citation for published version (APA):

Addison, P. F. E., Collins, D. J., Trebilco, R., Howe, S., Bax, N., Hedge, P., Jones, G., Miloslavich, P., Roelfsema, C., Sams, M., Stuart-Smith, R. D., Scanes, P., von, B. P., & McQuatters-Gollop, A. (2018). A new wave of marine evidence-based management: emerging challenges and solutions to transform monitoring, evaluating, and reporting. *ICES Journal of Marine Science*, 75(3), 941-952. <https://doi.org/10.1093/icesjms/fsx216>

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Keywords: adaptive management, biodiversity, fisheries, environmental impact assessment, environment, socio-economic, monitoring, modelling, collaboration.

Abstract:

Sustainable management and conservation of the world's oceans requires effective monitoring, evaluation and reporting. Despite the growing political and social imperative for these activities, there are some persistent and emerging challenges that marine practitioners face in undertaking these activities. In 2015, a diverse group of marine practitioners came together to discuss the emerging challenges associated with marine monitoring, evaluation and reporting, and potential solutions to address these challenges. Three emerging challenges were identified: (1) the need to incorporate environmental, social and economic dimensions in evaluation and reporting; (2) the implications of big data, creating challenges in data management and interpretation; and, (3) dealing with uncertainty throughout monitoring, evaluation and reporting activities. We point to key solutions to address these challenges across monitoring, evaluation and reporting activities: 1) integrating models into marine management systems to help understand, interpret, and manage the environmental and socio-economic dimensions of uncertain and complex marine systems; 2) utilising big data sources and new technologies to collect, process, store, and analyse data; and 3) applying approaches to evaluate, account for, and report on the multiple sources and types of uncertainty. These solutions point towards a potential for a new wave of evidence-based marine management, through more innovative monitoring, rigorous evaluation and transparent reporting. Effective collaboration and institutional support across the science–management–policy interface will be crucial to deal with emerging challenges, and implement the tools and approaches embedded within these solutions.

1 **1 Introduction**

2 In order to more sustainably manage and conserve biodiversity and marine resources in the world's
3 oceans, there has been a push from marine practitioners to implement evidence-based management,
4 where scientific evidence from monitoring and research is used to inform more robust and
5 transparent management decisions. Monitoring, evaluation and reporting (hereafter collectively
6 referred to as MER) are critical stages of evidence-based management, which focus on assessing
7 environmental state and pressures, evaluating management effectiveness, publicly reporting findings,
8 demonstrating public accountability, and delivering the evidence-base to inform adaptive
9 management (Pomeroy et al., 2005; Ferraro and Pattanayak, 2006; Levin et al., 2009; Jones, 2015).
10 The decision-making processes that MER activities are commonly packaged within include:
11 ecosystem-based fisheries management (Long et al., 2015), state-dependent conservation
12 management (Nichols and Williams, 2006), and adaptive management of natural resources (Holling,
13 1978).

14 Marine environmental monitoring has a relatively long history in the environment sector, with some
15 monitoring programs now running for almost 90 years (e.g., the Continuous Plankton Recorder
16 surveys; McQuatters-Gollop et al., 2015). Whilst some of these early monitoring programs
17 commenced as surveillance exercises to discover and explore the marine environment, more recently
18 there has been a push to ensure the monitoring programs are fit-for-purpose to inform management
19 needs (i.e., through evaluation and reporting activities to address evidence-based management;
20 Pomeroy et al., 2005; Ferraro and Pattanayak, 2006; Nichols and Williams, 2006). The imperative
21 for MER and evidence-based management is now reflected in international conventions (e.g.,
22 Convention for Biological Diversity (CBD, 2011) and the Convention for the Protection of the
23 Marine Environment of the North-East Atlantic (OSPAR, 1992)); which, has flowed through to
24 national and regional policy drivers for marine MER (e.g., the European Marine Strategy Framework
25 Directive (European Commission, 2008) and the United States Federal Water Pollution Control Act
26 (USC, 2002)). MER activities will be increasingly required as countries report their progress against
27 the United Nations Sustainable Development Goals, and will be critical in the future management of
28 biodiversity beyond national jurisdiction currently being negotiated at the UN (Druel and Gjerde,
29 2014).

30 Marine MER activities can be integrated within a single program, but in many cases these activities
31 are undertaken completely separately (e.g., undertaken and funded by different organisations). For
32 example, many monitoring programs in the Great Barrier Reef are undertaken by scientists from
33 research institutions for a variety of reasons (e.g., scientific research through to citizen science
34 engagement), and results from these programs are drawn upon by responsible marine decision-
35 makers in evaluation and reporting programs like the Great Barrier Reef Outlook assessment
36 (GBRMPA, 2014). The spatial extent of MER activities ranges from local through to global, and
37 their temporal extent can be short-term through to on-going; these activities vary in extent depending
38 on whether they are designed to address discrete management issues or support on-going
39 management of the marine environment.

40 There are now many notable examples of marine MER activities around the world, that are compiled
41 in outputs such as the recent global assessment of ocean health (OHI, 2017), the State of Europe's

42 Seas (EEA, 2017), and the Great Barrier Reef Outlook assessment (GBRMPA, 2014). In parallel,
43 there has been increasing focus and co-ordination at both national and international levels to develop
44 standardised methods for monitoring ecosystem variables, in order to quantify ecosystem status and
45 trends to inform evaluation and reporting and ultimately feed into evidence-based management.
46 Notable examples include the Reef Life Survey (Stuart-Smith et al., 2017), Integrated Marine
47 Observing System (IMOS, 2016), the Integrated Framework for Sustained Ocean Observing
48 (IFSOO, 2012), Essential Ocean Variables (Lindstrom et al., 2012) and ecosystem Essential Ocean
49 Variables (Constable et al., 2016), and Essential Biodiversity Variables (Pereira et al., 2013).

50 Drawing on elements of the notable examples outlined above and research into best-practice MER
51 and evidence-based management (Nichols and Williams, 2006; Kemp et al., 2012; Hallett et al.,
52 2016; Hedge et al., 2017), there are at least seven important characteristics that define effective
53 marine MER: (1) Having clear management objectives (e.g., related to conservation of biodiversity,
54 sustainable harvest of natural resources, or threat reduction) and monitoring objectives (i.e., to
55 measure key indicators related to management objectives); (2) Having robust monitoring program
56 design, with targeted monitoring data to assess progress towards objectives and evaluate
57 management effectiveness; (3) Having the capacity to incorporate various data sources (e.g.,
58 quantitative and qualitative monitoring data, traditional ecological knowledge and expert
59 judgement); (4) Undertaking routine evaluation and reporting of monitoring results; (5) Producing
60 accessible reporting for public outreach (e.g., report cards), which demonstrates progress towards
61 achieving objectives and provides access to more detailed monitoring and evaluation reports; (6)
62 Allowing for adaptation in response to changing environmental conditions and management needs
63 (i.e., adaptive management); and, (7) Securing long-term funding for MER activities that extend
64 beyond political cycles.

65 Despite the growing political and social imperative for MER, and the rise in MER approaches
66 employed around the globe, there are some persistent challenges to implementing and undertaking
67 successful marine MER activities. There are institutional challenges, such as: a lack of stability in
68 resources to fund MER activities through time, which means that the time-frame of many important
69 ecological changes will not be detected by MER activities (Duarte et al., 1992; Ferraro and
70 Pattanayak, 2006); a continued failure to set clear management, monitoring and evaluation objectives
71 (Kemp et al., 2012; Fox et al., 2014); and, persistent difficulties in accessing fit-for-purpose
72 environmental monitoring data, successfully evaluating different types of monitoring data, and
73 “closing the loop” to ensure the results of monitoring and evaluation informs evidence-based
74 management (Fox et al., 2014; Addison et al., 2015). Scientific challenges also exist that limit the
75 ability of marine MER activities to inform evidence-based management, which include the challenge
76 of monitoring extensive, remote environments, poor scientific understanding of large-scale
77 ecological processes and interactions, uncertainty in the attribution of cumulative impacts of threats,
78 and in understanding the effectiveness of management interventions (Cvitanovic et al., 2015;
79 Addison et al., 2017). Some of these persistent challenges represent the reality of organisational
80 constraints that MER practitioners must work within, whereas other challenges are being addressed
81 by scientific advancements and sharing best-practice lessons (Ferraro and Pattanayak, 2006;
82 Cvitanovic et al., 2015; Addison et al., 2017). However, there are emerging challenges in the field of
83 evidence-based marine management that are yet to be comprehensively addressed in the peer-

84 reviewed literature, and require inter-disciplinary solutions to help progress marine monitoring,
85 evaluation and reporting activities.

86 Today's practitioners involved in marine MER work across the science–management–policy
87 interface, and include scientists, decision-makers (i.e., managers and policy-makers), and knowledge
88 brokers from government agencies, non-governmental organisations (NGOs), academic institutions,
89 and consultancies. This diversity in practitioners means that historically some marine MER
90 challenges have been slow to overcome, as communication and collaboration has been limited across
91 the science–management–policy interface. However, this diversity in practitioners means that a
92 range of technical, managerial, and political skills can be used to advance MER in the face of
93 emerging challenges in this evolving area of evidence-based marine management (Thébaud et al.,
94 2017).

95 A diverse group of marine MER practitioners from universities, government agencies, and
96 consultancies, came together at the 2015 Australian Marine Sciences Association conference to
97 discuss the emerging challenges and novel solutions for marine MER. This group of practitioners
98 shared common ground in wanting to share experience and expertise to improve the management and
99 protection of the marine environment. Here we synthesise the discussions, identifying three critical
100 and emerging challenges facing today's marine practitioners. We then propose solutions to these
101 challenges and in doing so offer a vision for a new wave of marine MER within evidence-based
102 management.

103 **2 Emerging challenges facing marine MER**

104 *Emerging challenge 1: Integrating environmental, social, and economic MER*

105 Traditionally, marine MER activities have focussed on assessing the environmental variables in the
106 marine environment across the water quality, fisheries and biodiversity management sectors (e.g.,
107 FAO, 2003; Hering et al., 2010; Tett et al., 2013; USEPA, 2015). Monitoring and evaluating
108 environmental variables, such as water quality, habitat quality, ecosystem condition, and species
109 abundance have come with a range of challenges, which include understanding and assigning
110 causality of complex interactions in marine ecosystems, and developing suitable indicators to cut
111 through the complexity and deliver simplified measures of environmental change (McQuatters-
112 Gollop, 2012; Constable et al., 2016; Stuart-Smith et al., 2017). However, social and economic
113 aspects of marine systems are increasingly being considered in the management of the marine
114 environment, with the recognition that true sustainability needs to balance these aspects with the
115 often opposing needs for ecological sustainability (Thébaud et al., 2017).

116 The social and economic dimensions of marine systems are vitally important to consider as humans
117 have a range of connections, dependencies, and conflicts with the environmental dimension of
118 marine systems (Marshall et al., 2016). For example, people can be financially and culturally
119 dependent on the marine environment, which means that society and economy can draw direct
120 benefits from oceans (e.g., community wellbeing, and livelihoods dependent on natural resources),
121 but this dependence can also impact marine ecosystems (e.g., through unsustainable resource use;
122 Marshall et al., 2016). Consideration of socio-economic and environmental dimensions is critical for
123 evidence-based management, as these dimensions are often competing, thus trade-offs between
124 dimensions will be made – whether decision-makers deal with trade-offs transparently or not.
125 Integration in evaluation (e.g., through modelling) or reporting (e.g., through dashboards or
126 integrated reporting) allows for interdependencies, interactions, and feedbacks between critical
127 environmental, social and economic indicators to be explicitly considered. For example, integrated
128 modelling of Essential Ocean Variables in the Southern Ocean is helping scientists and decision-
129 makers explore and understand ecosystem dynamics in light of human pressures and physico-
130 chemical properties, to help attribute drivers of change and make predictions about future changes
131 that may require management (Constable et al., 2016).

132 Integrating the environmental, social, and economic dimensions within marine MER activities
133 requires a great breadth of technical skills and knowledge, and the data generated from these
134 different spheres do not necessarily lend themselves to integration. To date, the best efforts that have
135 been made to incorporate environmental, social, and economic assessments within reporting
136 programs have involved a silo approach. This is where environmental, social, and economic
137 monitoring data are evaluated and reported separately, with some attempt to synthesize these during
138 the reporting phase – often just verbally. Examples of these evaluation and reporting approaches
139 include the Great Barrier Reef Outlook Report (GBRMPA, 2014), marine assessments by the
140 Intergovernmental Panel on Climate Change (Pörtner et al., 2014), and the World Oceans
141 Assessment (United Nations, 2016), and the French marine protected areas dashboard (Agence des
142 aires marines protégées, 2014).

143 There are very few examples of integrated assessments of environmental and socio-economic
144 factors, such as where evaluations enable trade-offs between environmental, social, and economic
145 variables (but see: Weijerman et al., 2015 for a coral reef example). Beyond the challenges of
146 integrating the evaluation of these different components, reporting this variety of information
147 presents further challenges such as ensuring integrated reporting is factually reliable, aligned with
148 management objectives, and communicates key messages clearly and simply to a broad range of
149 audiences including the general public, marine managers, and politicians.

150 *Emerging challenge 2: MER and the world of big data*

151 The collection, analysis, storage, and visualisation of data are fundamental to marine MER. Early
152 marine monitoring programs faced the challenges associated with intensive data collection and
153 analysis, which due to resource constraints, often focused on a limited number of metrics over a
154 small number of sites. Since then, an increased focus on marine management has fuelled the need for
155 a greater diversity of information about marine systems (Ducrotoy and Elliott, 1997). Subsequently,
156 marine monitoring programs have become more complex, looking at additional physical, chemical,
157 and biological factors, often with an increased volume of data collected through monitoring and
158 generated from modelling (De Jonge et al., 2006).

159 Increases in data volume and complexity have also originated from advances in monitoring
160 technology (Vitolo et al., 2015). Modern in-situ, continuous, and remote sensing technologies (e.g.,
161 long-term deployed probes, autonomous systems, and higher resolution satellite imagery) offer
162 increasingly larger volumes of information for scientists and environmental decision-makers (Kogan
163 et al., 2011). Improvements in technology also extend to loggers, autonomous vehicles, telemetry
164 networks, and databases, and this is revolutionising the way data is collected, transmitted, and stored.
165 Rapid data availability brings a range of advantages to managers, and can enable dynamic ocean
166 management where responses to changes in monitored social and environmental variables can be
167 made in near real-time (e.g., in fisheries management in Australia and the U.S.A, and marine
168 conservation management in the USA; Maxwell et al., 2015).

169 Despite the benefits of big data, this new world also presents a number of challenges for marine
170 management organisations. Additional human capacity and expertise is required to ensure data
171 quality can be assured for decision making purposes (e.g., daily checking of data plots, regular
172 cleaning and maintenance and validation against samples to achieve the required data quality). Many
173 organisations have also found that their systems, designed to process and store relatively simple and
174 discrete monitoring data, have proven unsuitable in the face of institutional changes and rapidly
175 evolving technologies. These systems lack the required architecture, complexity and processing
176 speed for handling the volumes and variety of new data. For example, datasets may now include
177 images, audio, video, and spatial data, along with the traditional environmental variables stored as
178 numbers and text characters, and qualitative data in the form of expert judgement and traditional
179 knowledge. The outputs of modelled data add another challenge as they can easily take up terabytes
180 of storage and are not always recognised as valuable datasets requiring appropriate metadata and
181 management in their own right.

182 There are a range of technologies now emerging for processing large datasets, such as more flexible
183 web-based and geo-spatial databases that can facilitate large volumes of heterogeneous
184 environmental data (Vitolo et al., 2015). However, the increasing scope of data collected and the
185 potential future purposes for which it will be used, means that established tools and processes for
186 collecting, storing and analysing datasets may become increasingly bespoke, particularly if the trend
187 for repurposing data continues (e.g., the use of artificial intelligence and machine learning to extract
188 new information from existing databases). The need for ever more sophisticated data processing
189 makes it even harder to meet the open data standards, which are needed going forward to make data
190 accessible and synoptic analyses possible.

191 ***Emerging challenge 3: The challenge of uncertainty throughout MER activities***

192 Uncertainty is a pervasive challenge for marine practitioners across all stages of marine MER.
193 Uncertainty is the incompleteness of knowledge, or lack of certainty in understanding and managing
194 marine systems. Drawing on uncertainty research (Regan et al., 2002; Kujala et al., 2013), we
195 classify three (non-mutually exclusive) types of uncertainty relevant to marine MER activities: 1)
196 epistemic uncertainty - the gaps in knowledge or lack of certainty in socio-ecological system
197 understanding (both current state and future regime shifts), uncertainty in the measurement of
198 ecosystems, and uncertainty in model representation; 2) linguistic uncertainty - vagueness or
199 ambiguity in terms, expressions or concepts used to develop objectives, select indicators and
200 interpret monitoring results; and, 3) decision-making uncertainty – subjective judgment and human
201 preferences that can influence or bias indicator or model parameter selection, choice of normalization
202 of monitoring data, and model interpretation (Table 1).

203 Uncertainty is present across all stages of marine MER, and can influence activities such as: setting
204 management objectives (e.g., influenced by linguistic uncertainty, where a vagueness of terms used
205 in management objectives can have very different meanings to different people); monitoring program
206 design (e.g., influenced by epistemic uncertainty, where information gaps, lack of certainty about
207 ecosystem processes, and natural variation will influence monitoring program design); model design
208 and parameterisation (e.g., influenced by epistemic and decision-making uncertainty, where
209 subjective human judgement can influence the type of model and parameters included in models;
210 Table 1).

211 Models and the modelling process are themselves important sources of uncertainty, but, if used
212 appropriately, they offer opportunities to explicitly consider and account for uncertainty by exploring
213 and clarifying epistemic uncertainty in system understanding, monitoring program design, and
214 decision-making rules. Another key opportunity for better dealing with uncertainty is improving
215 decision-making processes using participatory methods and approaches to elicit expert judgement to
216 reduce subjective bias, linguistic uncertainty and decision-making uncertainty (see further discussion
217 in Solution 1 and 3). Despite opportunities and methods to robustly consider and account for
218 uncertainty, scientists and managers alike commonly fail to account for uncertainty. Common traps
219 evident in environmental science and management include: completely ignoring the influence of
220 uncertainty in monitoring data and in decision-making, addressing an incomplete set of more trivial

221 uncertainties in models, believing that models represent the truth, and failure to set unambiguous
222 objectives (Milner-Gulland and Shea, 2017).

223 An emerging issue for marine MER activities is how to address uncertainty in reporting of
224 monitoring results, as this is subject to epistemic, linguistic and decision-making uncertainty (Table
225 1). Report cards are a common output of MER activities, which often include ratings of condition of
226 environmental or socio-economic indicators to reflect the status and trends in environmental and
227 socio-economic attributes (e.g., GBRMPA, 2014; Carey et al., 2017). Report cards help simplify
228 complex monitoring information for public reporting to a broad audience ranging from scientists, to
229 policy-makers and the general public. They commonly present colour coded condition assessments
230 of environmental or socio-economic indicators. Whilst these reporting formats provide clear and
231 simple messages, this perceived simplicity can be misleading as uncertainty associated with
232 environmental or socio-economic attributes can be completely hidden, and ecosystem complexities
233 (e.g., multi-state systems) can be over-simplified. The failure to explicitly communicate uncertainty
234 in report cards can arise from: i) the motivation to present simple results in report cards (i.e., hiding
235 error bars), and ii) the incorrect treatment of uncertainty in underlying models used in evaluations
236 that are presented in report cards (i.e., epistemic uncertainty not incorporated into model parameters).
237 Either way, the outcome of failing to deal with uncertainty can mean that readers, including
238 managers, policy-makers, and the general public may be misled by interpreting results with false
239 certainty (e.g., with a water quality report card: Queensland Audit Office, 2015).

240 **Table 1.** A taxonomy of uncertainty affecting marine monitoring, evaluation and reporting.

Type of uncertainty	Issue	Various stages of MER that can be influenced by uncertainty						
		Setting management objectives	Indicator selection	Monitoring program design	Model design & parametrisation	Interpretation of monitoring data and model outputs	Reporting monitoring results	Evidence-based management
Epistemic uncertainty	<i>Gaps and lack of socio-ecological system understanding</i> e.g., information gaps and lack of certainty about ecosystem processes, such as ecosystem interdependencies, interactions, and feedbacks between variables.	•	•	•	•	•	•	•
	<i>Natural variation, measurement or systematic error</i> e.g. the natural variability of socio-ecological systems, and the uncertainty that arises from monitoring (i.e., measurement error) and modelling these systems (i.e., systematic error).			•	•	•	•	•
	<i>Model structure uncertainty</i> e.g., representation (or lack of representation) of socio-ecological variables in models.				•	•	•	•
Linguistic uncertainty	<i>Vagueness or ambiguity in terms, expressions or concepts</i> e.g., vagueness and ambiguity in the description of management objectives; ambiguity in indicator selection (based on different interpretation of objectives); and ambiguity of ecosystem concepts in reporting of monitoring results.	•	•	•	•	•	•	•
Decision-making uncertainty	<i>Subjective judgement and uncertain preferences</i> e.g., the human values and subjective judgment that can influence or bias decision-making (i.e., in indicator or model parameter selection, choice of normalization of monitoring data, approach to weighting or aggregating indicators (e.g., in composite indicators or multi-objective models), and in the interpretation of model outputs).	•	•	•	•	•	•	•

242 **3 Solutions for a new wave of marine MER to support evidence-based management**

243 The field of MER has evolved considerably over the last decade, but addressing the challenges we
244 have outlined above requires innovative solutions. We believe the solutions proposed here will assist
245 with developing and sustaining MER activities so that they meaningfully inform the development of
246 policy and implementation of evidence-based management of the marine environment. Marine
247 practitioners with a diverse range of expertise will need to effectively collaborate across the science–
248 management–policy interface to implement the recommended solutions. Thus, we cannot stress
249 enough the human dimension of our solutions, in the form of effective collaboration and enabling
250 political conditions, and their critical role in the implementation of these solutions to support a new
251 wave of marine MER and evidence-based management.

252 *Solution 1: Integrating modelling and monitoring to maximise MER activities in evidence-* 253 *based management*

254 An integration of data and models should be at the core of MER activities. Data-integrated modelling
255 applications have been extensively used in this context in some marine sectors, like fisheries
256 management (Link et al., 2002; Collie et al., 2014), and are a core component of adaptive
257 management (Addison et al., 2013), but uptake has been less widespread in other marine sectors. In
258 some cases this may be because marine monitoring data have not been available or adequately
259 targeted to address marine management needs (Fox et al., 2014; Hedge et al., 2017), but in other
260 cases it may be because marine practitioners have not been aware of, or have not had access to, the
261 full suite of models that could support management decisions, and may not have considered
262 modelling as complementary to monitoring.

263 Models are abstractions of real world phenomena that can help make environmental and socio-
264 economic processes easier to understand. One model will never suit all applications; rather a toolbox
265 of models of different types, complexity and scope are often required to support environmental
266 management (Table 2). Models can span a range of complexity from simple conceptual models that
267 help formalise and clarify our understanding of how systems work (e.g., used in the scoping and
268 monitoring phases), to statistical models that help interpret monitoring data and quantify patterns and
269 associations in systems (e.g., used in the evaluation and reporting phases), through to mechanistic
270 models that can mathematically represent real-world processes (e.g., used to inform the management
271 response phase). A toolbox of models can assist with integrating multiple lines of evidence (e.g.,
272 expert judgement, traditional knowledge, and monitoring or research outputs), reducing or
273 highlighting epistemic or linguistic uncertainty, evaluating alternative decision scenarios, and
274 clarifying cause-and-effect relationships for marine practitioners to better understand and manage
275 marine systems. Furthermore, spatially explicit and dynamic mechanistic models (e.g.,
276 oceanographic / hydrodynamic models, and species distribution models) can allow us to evaluate
277 processes and environmental condition on scales that are much larger than can generally be achieved
278 though monitoring alone.

279 Models are not a panacea, and on their own cannot drive marine MER activities towards more robust
280 evidence-based management. If not well understood, model outputs can easily be misinterpreted and
281 used incorrectly to inform decision-making. For example, a recent study of papers reporting marine

282 socio-ecological model forecasts found that the majority (90%) failed to account for uncertainty in
283 the interpretation of model outputs, which can have profound effects on decisions based on model
284 outputs (Gregr and Chan, 2014). For models to be useful in evidence-based management, they
285 require effective collaboration between marine practitioners to ensure that models are developed
286 within existing management frameworks, and that models of appropriate scope and complexity are
287 used to address management questions (Addison et al., 2013; Cartwright et al., 2016). Examples
288 where models have been integrated into management frameworks, include: the use of fisheries
289 models to set catch limits worldwide (Tittensor et al., 2017); the use of statistical models within an
290 adaptive management process for protected areas in Australia (Carey et al., 2017); and the Atlantis
291 model, which is a representation of the management strategy evaluation cycle (including a full end-
292 to-end ecosystem model) and is used operationally to inform marine ecosystem management
293 decisions in both Australia and the U.S.A. (Fulton et al., 2011).

294 Developing “toolboxes” of models will help marine practitioners explore how to better understand
295 the system they are managing, use existing monitoring evidence to test their understanding, and
296 subsequently in management, potentially identify where more or different monitoring and evaluation
297 techniques are required. Model toolbox (or ensemble) approaches are also essential for overcoming
298 the emerging challenge associated with integrating environmental, social and economic aspects of
299 MER (Emerging challenge 1; e.g., previously called for in marine natural resource and conservation
300 management (Melbourne-Thomas et al., 2011; Long et al., 2015; Marshall et al., 2016)). There are
301 currently relatively few examples where models have simultaneously incorporated environmental
302 and socio-economic variables in evaluation and reporting stages of MER. However, some notable
303 examples that are emerging include: conceptual models to define complex socio-ecological systems
304 (e.g., conceptual models developed by stakeholders for Australian marine park management, to
305 explore and document perceptions of critical ecological and socio-economic values and pressures in
306 marine systems; Bryars et al., 2016); through to more complex, dynamic whole-of-ecosystem models
307 to test and predict ecological and socio-economic dynamics (e.g., ecosystem models used to inform
308 ecosystem-based management, such as Atlantis (Fulton et al., 2011), Ecopath with Ecosim (Heymans
309 et al., 2016), and CORSET (Melbourne-Thomas et al., 2011)).

310
311 Integration of environmental and socio-economic variables in evaluation and reporting stages of
312 MER does not solely rely on a one-way process of feeding data into models. There are also exciting
313 developments in platforms (models with user-friendly, visual displays) that can process and display
314 environmental and socio-economic data in an interactive dashboard. Such models are important to
315 support interpretation and uptake for more rapid and effective evidence-based management. For
316 example, the dynamic ocean management applications outlined in Maxwell et al. (2015), such as the
317 Turtle Watch program in Hawaii that displays information on temperature fronts and satellite
318 tracking of loggerhead sea turtles to help guide reduced turtle bycatch in local fisheries.

319
320 The toolbox of models approach we propose to support MER activities will also help address the
321 emerging challenge of big data, as statistical models become critical for dealing with increasing
322 volumes of data and modelling complex natural system patterns (Spiegelhalter, 2014; addressing
323 Challenge 2). For example, Markov, Bayesian and dynamic modelling are being used to help predict

324 (and not just observe) species distributions, population dynamics, and inform biodiversity
 325 management, by drawing on increasingly larger datasets (Gimenez et al., 2014).

326 The use of multiple modelling approaches can also help support marine managers in clarifying
 327 uncertainties in interpreting monitoring data (helping overcome Challenge 3; Table 2)). For example,
 328 a diverse set of qualitative models was used to explore and test sources of epistemic and linguistic
 329 uncertainty associated with the system dynamics of Australia’s commonwealth waters, where the
 330 level of system knowledge varied greatly between environmental assets. This allowed the selection
 331 of asset-specific indicators to inform monitoring program designs (Hayes et al., 2015).

332 Finally, using a toolbox of models is also a good way to explore model structure (epistemic)
 333 uncertainty (Challenge 3), by considering variability of outcomes from different modelling
 334 approaches. Importantly, this requires that there is actually structural diversity among the models,
 335 and the same assumptions and flaws are not present in all models and simply being represented in
 336 different ways (Gegr and Chan, 2014).

337 **Table 2.** Types of models and their application through the different stages of marine monitoring,
 338 evaluation and reporting activities.

MER phase	Qualitative and conceptual models	Statistical models	Dynamic and mechanistic models
Monitoring	<ul style="list-style-type: none"> Assist with indicator selection (e.g., conceptual and systems models) 	<ul style="list-style-type: none"> Understand patterns and interactions when selecting indicators (e.g., statistical analysis of historic data, or meta-analysis of published results) Inform monitoring program design (e.g., power analysis using baseline monitoring data or published results) 	<ul style="list-style-type: none"> Inform indicator and target selection (e.g., ecosystem models) Inform monitoring strategy (e.g., observation models) Inform monitoring program design (e.g., model evaluation of monitoring strategies)
Evaluation	<ul style="list-style-type: none"> Understanding surprises (e.g., conceptual models) Distinguishing mechanisms of change 	<ul style="list-style-type: none"> Understand patterns of monitored indicators (e.g., statistical analysis of monitoring data) Support model choice where alternative models exist 	<ul style="list-style-type: none"> Extrapolating monitoring data over larger scales (with accompanying estimates of uncertainty)
Reporting	<ul style="list-style-type: none"> Displaying ecosystem interactions between threats, ecosystem status and management responses (e.g., conceptual models) 	<ul style="list-style-type: none"> Display temporal or spatial patterns in monitored indicators (e.g., statistical model outputs) 	<ul style="list-style-type: none"> Display modelled results

339

340 ***Solution 2: Working effectively in the world of big data***

341 Some of the most prevalent opportunities that have arisen for marine monitoring programs over the
 342 last decade have come through improvements across the data life-cycle. Of particular note are

343 advances in the technology and systems for data collection, transmission, management, processing,
344 and analysis. These advances have opened doors for novel and more cost-effective monitoring
345 techniques, which are seen in regional and global collaborative projects dedicated to observing and
346 measuring ocean attributes (IFSOO, 2012; Meredith et al., 2013; Constable et al., 2016; IMOS,
347 2016). Combining some of these technologies offers a previously unheard-of range of options
348 available to MER practitioners to collect high-quality data, that capture daily, seasonal, annual and
349 event-based environmental variability, and in some cases, inform real-time marine management
350 (Maxwell et al., 2015; Edgar et al., 2016). It is not just technology that is contributing to the big data
351 era – people are too. The management of big data requires new collaborations between marine
352 practitioners and data scientists with expertise in programming languages and packages like R and
353 Python. These new collaborations are making it possible to manage and analyse extremely large,
354 complex data sets to inform marine evidence-based management.

355 Citizen science offers another area of growth for marine data collection and analysis (Gimenez et al.,
356 2014). Citizen science uses volunteers to collect and/or analyse data, and cost-effectively increase
357 research capacity and potentially fill data gaps (e.g., in scientific monitoring programs) over large
358 geographic areas (Bird et al., 2014; Vann-Sander et al., 2016; Stuart-Smith et al., 2017). Many
359 citizen science programs are beginning to supplement traditional modes of field data collection with
360 mobile phone apps, which are a versatile data collection tool supported by mobile capabilities like
361 GPS, camera, clock, and data storage (e.g., Marine Debris Tracker, 2017; Project Seagrass, 2017;
362 Secchi Disk, 2017). There have sometimes been concerns over the quality of citizen science datasets
363 (Vann-Sander et al., 2016). Data quality is not an issue confined to citizen science, however, and
364 there is growing recognition of effective ways to tackle issues of data quality, which include
365 adequate training of data collectors, quality control mechanisms for collected data, and statistical
366 consideration of data quality or observer error during analysis and interpretation (e.g., as addressed
367 in the Reef Life Survey citizen science program; Edgar and Stuart-Smith, 2009; Bird et al., 2014).
368 Collaboration between marine practitioners and new partners, like citizen scientists, are opening up
369 new opportunities to bring additional information into marine MER activities.

370 Improved modes of data collection form only part of the digital age innovations for marine MER,
371 and in response to the rise in big data, non-relational databases are now emerging to help deal with
372 the ever-increasing volume of complex and varied data (Vitolo et al., 2015). A crucial aspect of these
373 databases is metadata, which allow data to be more confidently used in the future, potentially in ways
374 not envisaged by the original collector, and as more powerful and innovative analytical techniques
375 are developed (e.g., Seeley et al., 2009). A vast array of modelling techniques matched with online
376 technologies now exist to support the processing of large and multidimensional datasets (Maxwell et
377 al., 2015; Vitolo et al., 2015).

378 It is impossible for MER practitioners to be experts in the varied fields required to be able to
379 effectively interpret and most effectively apply data from varied sources to management processes.
380 Thus, collaboration is key to fully utilise the increasing volume and variety of data available to
381 inform marine MER. Many bespoke data management solutions are emerging (Vitolo et al., 2015),
382 but the next step for marine MER practitioners will be to share and create best-practice data
383 management and sharing standards in the world of big data.

384 Digital datasets, especially those available online, now offer marine practitioners access to a wealth
385 of information that would have been previously inaccessible. Examples include the Ocean
386 Biogeographic Information System, the Australian Ocean Data Network and a variety of government
387 data portals. This increased accessibility becomes even more valuable when we consider MER
388 practitioners looking to work across environmental, social, and economic spheres. While this sort of
389 data sharing and accessibility is yet to be uniformly adopted by individuals or organisations (Huang
390 et al., 2012), it is at least recognised that there is a growing trend for MER practitioners willing to
391 share their data (Wallis et al., 2013). Furthermore, governments are embracing open access data and
392 requiring publicly-funded institutes to make their data accessible to the public. The next challenge to
393 be tackled is how to encourage and facilitate the sharing of environmental data collected by industry,
394 such as commercial fisheries and proponents undertaking environmental impact assessment, where
395 access to these data is commonly restricted by commercial-in-confidence clauses. Responsible and
396 effective use of shared monitoring data will require: strict data quality assurance/quality control
397 (QA/QC) procedures to ensure the quality of data prior to sharing (Addison, 2010), standardised
398 metadata specifying essential details of the data to minimise potential for mis-use (Vitolo et al.,
399 2015), approaches to protect commercial-in-confidence elements, and a robust data sharing policy
400 that benefits both the user and data provider by supporting the ongoing funding of the monitoring
401 (Juffe-Bignoli et al., 2016).

402 ***Solution 3: Approaches to evaluate, account for, and report on uncertainty in MER***

403 Environmental management is subject to diverse sources of uncertainty (e.g., epistemic, linguistic
404 and decision-making uncertainty), which affects all stages of marine MER (Challenge 3; Table 1).
405 During the evaluation phase, a range of models can be used to help interpret patterns in
406 environmental condition (Table 2), and statistical models have the functionality to robustly explore
407 and account for epistemic uncertainty. As mentioned in Solution 1, model simulations, sensitivity
408 analysis or Bayesian methods can help account for epistemic uncertainty and in the interpretation of
409 environmental patterns detected in statistical models (e.g., Spiegelhalter, 2014; Milner-Gulland and
410 Shea, 2017). Similarly, statistical power analysis can help practitioners understand and account for
411 epistemic uncertainty associated with natural variation, measurement error, and modelling
412 approaches (Gimenez et al., 2014; Milner-Gulland and Shea, 2017).

413 Mechanistic models can be used to make predictions about environmental responses to a range of
414 management interventions, and test the effect of epistemic uncertainty associated with model
415 parameters (e.g., using Monte Carlo simulation) – helping identify parameters that may need
416 additional data and testing to help understand natural system dynamics (Fulton et al., 2011; Heymans
417 et al., 2016). Finally, model inter-comparisons and ensemble approaches (e.g., using statistical
418 models to combine outputs from multiple mechanistic models) can account for structural uncertainty
419 associated with individual models, by considering whether structurally distinct models give
420 consistent or divergent results, and thus can help resolve epistemic uncertainty in system
421 understanding and model representation.

422 Models cannot, however, directly address linguistic and decision-making uncertainty. Instead, this is
423 where the human dimension of decision-making dominates, and where structured decision-making

424 processes and expert elicitation methods can be used to reduce the influence of linguistic and
425 decision-making uncertainty in objective setting, indicator development and monitoring design. For
426 example, structured decision-making in addition to objectives hierarchies can be used to ensure
427 management objectives and indicators are carefully defined prior to monitoring (Addison et al.,
428 2013). When expert judgement is used (e.g., to inform quantitative model parameters), more
429 structured methods of elicitation can be used to minimise subjective bias and linguistic uncertainty
430 (e.g., the four-step elicitation and Delphi procedure used to elicit judgements from groups of experts;
431 Hemming et al., 2017).

432 When it comes to reporting uncertainty in socio-ecological assessments, lessons can be learnt from
433 climate reporting. In response to great public and political interest and interrogation of climate
434 change the Intergovernmental Panel on Climate Change provides guidance on reporting uncertainty
435 (Mastrandrea et al., 2010), which includes articulating confidence in the datasets used in assessments
436 as well as in the final interpretation made in the assessment. Confidence is already communicated by
437 some notable marine report cards from Australia, Europe and the USA (PIFSC, 2016; EEA, 2017;
438 Karnauskas et al., 2017). Drawing on lessons from these report cards, we recommend: 1) use of
439 categorical estimates of confidence to support condition and trend assessments made by experts or
440 estimated from monitoring data (e.g., Victorian MPA assessments include confidence categories 0-
441 25%, 26-50%, 51-75%, 76-100%; Carey et al. (2017), and State of Europe's Seas assessments
442 include high, medium and low confidence in ecological assessments made (EEA, 2017)); 2) include
443 a measure of comparability with the previous report card assessments (e.g., the Australian State of
444 Environment Report demonstrates the level of comparability between 2011 and 2016 assessments as
445 comparable, somewhat comparable, not comparable and not previously assessed; Evans et al.
446 (2017)); and, 3) allow the evidence (e.g., reports and papers) used in assessments to be accessed and
447 considered independently (e.g., the online Gladstone Harbour report card allows full interrogation of
448 supporting monitoring data (GHHP (2016)), and the Ocean Health Index online platform allows
449 users to drill down to evidence used for all assessments (OHI (2017)).
450

451 **4 Conclusion: the new wave of MER**

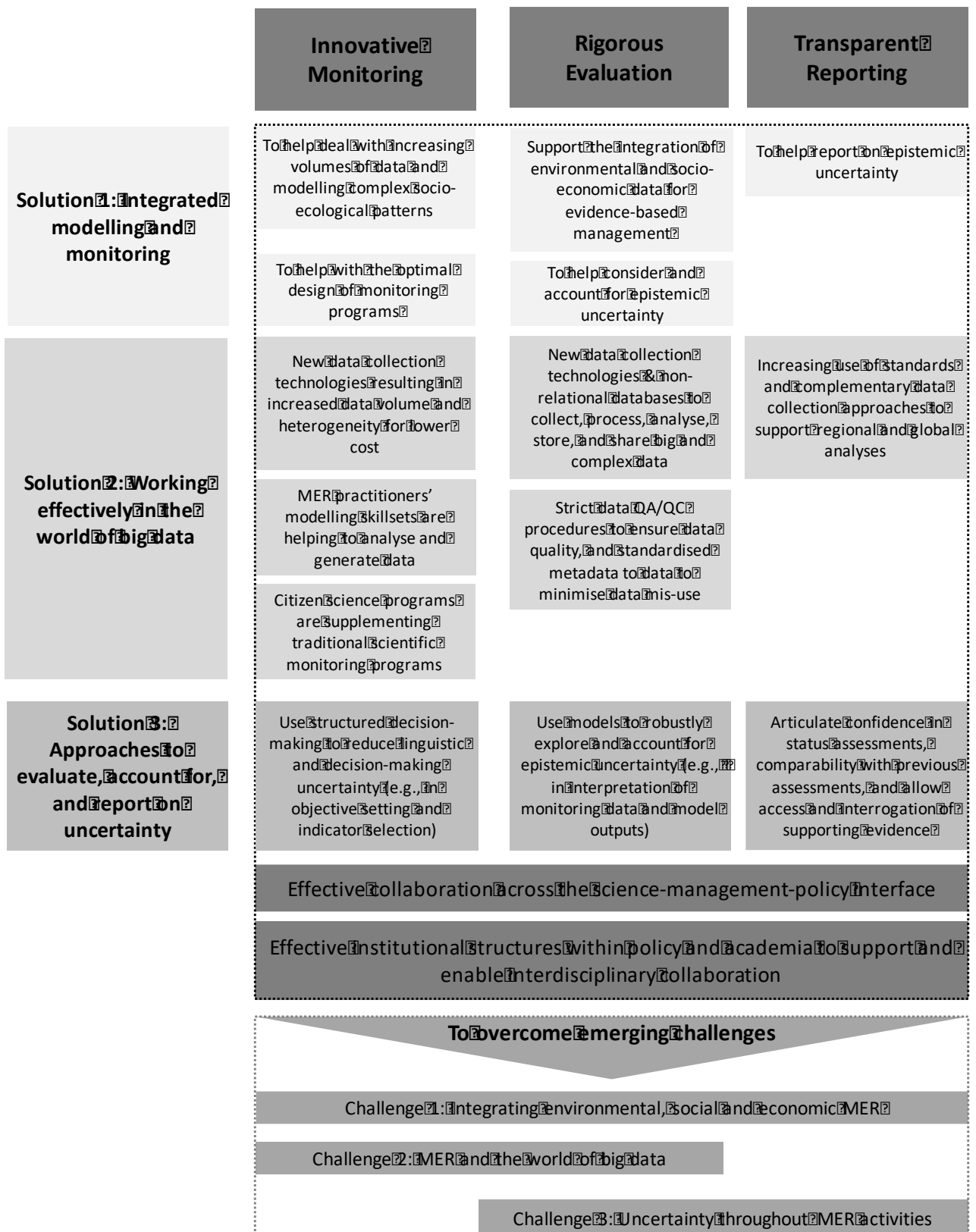
452 Monitoring, evaluation, and reporting activities help us understand environmental state and
453 pressures, evaluate management effectiveness, and provide the evidence-base to inform management
454 decisions and policy. The growing political and social imperative for MER reflected through
455 international conventions and national policy drivers means that marine MER is no longer an
456 optional activity, but a necessity.

457 As the number of marine MER approaches employed around the globe has risen, we have witnessed
458 the emergence of challenges associated with MER activities, including: 1) the need to incorporate
459 environmental, social and economic dimensions of the marine environment in evaluation and
460 reporting programs; 2) the implications of big and open data creating challenges in the collection,
461 analysis, storage, visualisation and accessibility of data; and, 3) uncertainty throughout monitoring,
462 evaluation and reporting activities that is not transparently acknowledged or accounted for. These
463 new challenges require innovative solutions to help support a new wave of MER. We have pointed to
464 key solutions that offer a vision for a new wave of more robust and transparent marine MER within

465 evidence-based management: 1) integrating models into marine management systems to help
466 understand, interpret and manage the environmental, social, and economic dimensions of uncertain
467 and complex marine systems; 2) utilising big data sources and new technologies to collect, process,
468 store, and analyse data; and, 3) applying approaches to evaluate, account for, and report on the
469 multiple sources and types of uncertainty in MER (Figure 1).

470 The successful implementation and application of these solutions requires a diverse range of
471 expertise, thus collaboration is key. Marine MER will increasingly require extensive and effective
472 collaboration across the science–management–policy interface. To facilitate the transfer of technical
473 expertise and information, newer modes of interdisciplinary collaboration and knowledge exchange
474 are required. These will help break the old model of academic scientists working in isolation,
475 employing idiosyncratic techniques that cannot be compared with other studies, with little
476 appreciation of the context and limitations of marine management, and marine managers not having
477 access to or an awareness of new scientific techniques and innovative solutions to progress evidence-
478 based management. New modes of collaboration can occur through: the establishment of boundary
479 organisations or consulting arms of universities to undertake applied research; by embedding
480 research scientists in marine management agencies to work with decision-makers or vice versa; and,
481 by employing knowledge exchange practitioners to help facilitate the multi-directional transfer of
482 knowledge and co-development of fit-for-purpose MER approaches (Michaels, 2009; Cvitanovic et
483 al., 2015). Effective institutional structures within policy (Brooks and Fairfull, 2016) and academia
484 (Keeler et al., 2017) will be critical in supporting and enabling this type of inter-disciplinary
485 collaboration.

486 While the diversity of MER activities means that there is no single successful approach to address
487 the multitude of challenges, the solutions, illustrative examples and synthesis of tools provided here
488 offer a pathway towards innovative monitoring, rigorous evaluation and transparent reporting (Figure
489 1). It will be up to marine practitioners to consider and implement these solutions and make their
490 scientific results increasingly relevant and enduring, thus improving our collective ability to more
491 sustainably manage marine resources and conserve biodiversity in the world’s oceans amidst
492 complex management challenges.



493

494 **Figure 1.** Solutions to support a new wave of MER – towards innovative monitoring, rigorous
 495 evaluation and transparent reporting. A conceptual diagram synthesizing the key recommendations
 496 made within each of the three solutions.

497 **5 Acknowledgements**

498 We wish to acknowledge all of the marine scientists and managers who presented their research and
499 shared their ideas at the Marine Monitoring Evaluation and Reporting symposium at the Australian
500 Marine Sciences Association conference in July 2015. Initial discussions with symposium
501 participants helped shape this paper, and we thank all of those involved in the symposium for their
502 contributions. PFEA and AMG thank the UK Natural Environmental Research Council for support
503 through the NERC Knowledge Exchange fellowship scheme (NE/N005457/1 & NE/L002663/1).
504 NB, PH and RDSS were supported by the Marine Biodiversity Hub, a collaborative partnership
505 supported through the Australian Government's National Environmental Science Programme
506 (NESP). RT was supported by the RJL Hawke Postdoctoral fellowship.

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