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REVIEW

A review on the interactions between engineering and marine life: key information for engineering professionals

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Abstract

Marine life both affects and is affected by coastal, marine and offshore engineering. As engineering projects have become larger, more frequent and more complex, hence has the number and type of interactions with marine life. Engineers are looking for more information about these interactions so they can better mitigate against any harmful effects to marine life and enhance any positive impacts. This review aims to fill this purpose, giving professional engineers a broad understanding of the impacts that marine engineering projects can cause to marine life and to suggesting some "best practice" mitigation strategies. The review considers the interactions between engineering projects and marine life from three perspectives with a specific example given in each case. First, potential mitigation measures are discussed in the context of offshore windfarms. Secondly, the issue of engineering noise affecting marine species in different ways. Lastly, the engineering solutions employed in the "Great Barrier Reef (GBR) Restoration Project" is exampled. Environmental Impact Assessments used by managers must reference up-to-date and detailed data from biological surveys so that local species that are vulnerable to the specific engineering activities can be identified. The mitigation activities must include acoustic mitigation, be scalable and affordable. This review highlights the need for engineers to liaise closely with marine scientists and biologists to ensure that solutions are appropriate and do not have unexpected or indirect consequences to marine life.

Keywords Environmental impact assessment · Mitigation for engineering projects · Offshore wind · Hydroacoustics · Bioacoustics · Great barrier reef

1 Introduction

Marine life both affects and is affected by coastal, marine and offshore engineering. For example, offshore industrial activities, including oil and gas exploration, wind farm construction, pipelaying and commercial shipping have resulted in increased noise in the sea, which can impact marine animals (Hawkins 2014). The opposite affect is the issue of marine growth on offshore platforms, aquaculture pens and offshore wind structures which can cause issues for offshore engineering projects due to increased structural loading. In addition, marine growth on moving marine assets (such as vessels) causes the movement of species from one biogeographical region to another (Apolinario and Coutinho 2009).

As engineering projects have become larger and reached further into the oceans (Bugnot et al. 2021), so has the number and type of interactions with marine life (Patten 1994; Southall et al. 2017; Bahtiarian 2022; Galparsoro et al. 2022; Zulkifli et al. 2022). This includes different types of interactions that could be categorized as; intentional direct, unintentional direct and unintentional indirect. Unintentional direct interactions include whale and sea bird strikes and acoustic disruption (Hawkins and Popper 2017). Unintentional indirect interactions are caused by processes, such as marine pollution (Gall and Thompson 2015), marine debris (Laist 1997), invasive species from ballast tanks (Nature 2019), ocean warming and ocean acidification (Dove et al. 2020).

Currently, the local authorities around the world are considering whether our goal as engineers should be to produce minimum harm to marine life or zero harm. This is fuelled by

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public demand (social media), the need to comply with various Health and Safety Management systems (for zero harm to employees) and innovation partnerships such as the Zero Harm Innovation Partners Program (Chesworth 2015; Rightship 2024). From the perspective of marine policy-making, the emergence of new technologies is significant both as ways to improve our understanding of marine pollution events (Anthony et al. 2023) and as an enabler to move from minimum harm to zero harm. In addition, previous studies have highlighted the need for marine hazard impact mitigation to include the effect of natural hazards (such as extreme climate hazards, geological hazards and biological hazards) (Sallares and Gonzalez 2021). This could make zero harm difficult to achieve and even more difficult to prove.

Marine renewable energy development can have both positive and negative impacts on marine environments, so careful planning and management are necessary to mitigate negative impacts and promote biodiversity (Copping et al. 2014). The current and future generations of engineers are working in a world where climate change and environmental impact are at the forefront of decision making. With this and the growth of unintentional interactions (Lebreton et al. 2018; Machernis et al. 2018), there is a great need for marine engineers to increase their understanding of these issues. This will enable better mitigation of the negative effects of engineering projects on marine life and mean that future engineering projects are intentionally designed to aid the needs of local marine life.

For this to happen, engineers must liaise closely with marine scientists and biologists to ensure that solutions are appropriate and do not have unexpected or indirect consequences on marine life. For example, well-meaning attempts to improve natural ecosystems on land have sometimes had unintentional indirect consequences such as the introduction of rabbits, foxes and cats to Australia (Calver et al. 1998; Alves et al. 2022).

There are many aspects to the interactions between engineering projects and marine life. The topic could be considered from the perspective of: different types of engineering project, different types of impacts or in terms of ecosystem types. In this review, all three of these perspectives are considered using a specific example in each case. First potential mitigation measures are discussed in the context of offshore windfarms. Secondly, the issue of acoustic output by engineering projects is presented showing the different ways that a single interaction can affect different marine species. Lastly, the engineering solutions employed in the Great Barrier Reef (GBR) restoration project is exampled. The purpose of this review is to give professional engineers a broad understanding of the impacts that marine engineering projects can have on marine life and to suggest some "best practice" mitigation strategies.

2 Methodology

This manuscript is based on the presentations given during the "Engineering and Marine Life" afternoon lecture at ASME's 42nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2023) in Melbourne, Australia. As such, papers were selected for inclusion based on those referenced in the original presentations.

2.1 Marine life interactions with offshore wind farms

To reach the European Union's goal of carbon neutrality by 2050, offshore wind energy (OWE) will need to account for at least 50% of the total energy supply (European Commission 2019). OWE companies are acting quickly to plan and build large numbers of offshore renewable energy structures to meet this target (Lee and Zhao 2022). With approximately 100,000 additional offshore wind turbines expected to be built and deployed into the offshore environment to reach this target, the effect on marine life must be considered.

Offshore wind farms (OWFs) can have both positive and negative effects on marine life (Galparsoro et al. 2022). The positive impacts include the increase in fish and invertebrate abundance. The effect has been to increase around OWFs (Glarou et al. 2020) due to the use of OWF structures as refuge and overall habitat enhancement (the reef effect). However, the local negative impacts often outweigh any local positive effects.

The harmful effects of OWFs on marine life vary depending on a number of engineering factors and biological variables. The engineering factors include: the size of the individual turbines, the overall size of the farm, the number of additional offshore structures, the position (nearshore / offshore) and geographical location (Bergström et al. 2014). In addition, different impacts are seen at installation, operation and decommissioning stages of engineering projects. As it stands, the decommissioning phase is the least well documented due to the relative immaturity of the OWE industry (Topham et al. 2019). The impacts include direct interactions with turbines and indirect effects such as changes in habitat availability due to alterations to the local seabed or migration rerouting that increases the fatigue of young animals and can contribute to death.

Direct impacts are easier to monitor and have been documented in a number of the previous studies (Welcker and Nehls 2016; Vallejo et al. 2017; Wilber et al. 2018), however, these impacts are too often considered in isolation. In a review of 158 separate studies considering the ecological impacts of offshore wind farms, Galparsoro et al. (2022) highlighted the need to investigate multiple interactions been OWE related activities and marine ecosystems so that a more holistic and cumulative understanding can be developed. They showed that the highest negative impacts reported in the literature

Table 1 OWF engineering activities that can produce negative effects on marine life with potential mitigation measures

Activity	Potential Negative Impact	Mitigation Measure
Activities involving the use of lubricants and other liquid pollutants including vessel fuel oil	Pollution (e.g. oil spills and overboard discharge)	Real-time monitoring of vessel and equipment activities using vessel tracking services (VTS) as Martínez de Osés and Uyà Juncadella (2021) suggested on a global scale
		Spill prevention using vessels with hull explosion prevention technology, static electricity prevention strategies and implementing human factors governance (Zhang et al. 2021)
		Spill detection could involve image processing, biomonitoring, spectroscopy and/or microscopy (Anthony et al. 2023)
		Spill response procedures must be immediate and effective (Dhaka and Chattopadhyay 2021)
		Spills must be followed up with accident reports so that they can be learned from within a "no blame" culture (Dhaka and Chattopadhyay 2021)
Structures on seabed	Habitat disturbance	Windfarm siting based on the local biodiversity studies so that seabed structures are placed to actively avoids key habitat areas, as exampled by Lloret et al. (2022) for the Mediterranean Sea
		Need to protect against excessive scouring and erosion with seabed mitigation such as burying cables, mattresses etc. Some methods of scour protection are described by Whitehouse et al. (2011)
Turbine farm position	Turbine blade collision	Bird and bat detection methods should be used to monitor local populations (Croll et al. 2022)
	Migration rerouting	Windfarm siting to avoid all known migration routes (Croll et al. 2022)
Construction	Noise impacts	Mammal monitoring with schedule adjustments to avoid times when vulnerable mammals (and other vulnerable animals) are present. Plus the use of quieting technology and best practices (Chou et al. 2021)
		In addition, the use of acoustic deterrent devices (ADDs) could be deployed (Verfuss et al. 2016)
Vessel operation	Vessel impacts	Reducing speed within the OWF and promoting awareness of vessel operators (Marine Mammals Management Toolkit 2023)
		Following avoidance and reporting guidelines such as those set out for the Oil and Gas industry working in the Gulf of Mexico (United States Department of the Interior Bureau of Ocean Energy Management Gulf of Mexico Regional Office 2016)
Operation of OWF	Permanent change of water quality (e.g. due to increased turbidity or increase in pollutants) and ambient underwater noise	Monitoring of water quality and underwater ambient noise. This could be carried out using a variety of unmanned vehicle platforms as suggested by Yuan et al. (2023)
		Positioning OWF outside high biodiversity areas containing sensitive or threatened species and habitats as summarised for the Mediterranean Sea by Lloret et al. (2022)
		Design choices that prevent certain chemical elements (e.g. some green, long-term, environmentally friendly antifouling technologies are described by Tian et al. (2021))
		Blade colouring techniques could be employed at sea, as is suggested by May et al. (2020) for on shore turbines

are: the death and injury of birds, fish, some invertebrates and marine mammals, the distribution and abundance of birds, the behaviour of birds and marine mammals (due to changed migrations and movement) and the changes observed in ecosystem structure, functions and processes (including biodiversity and abundance). It should be noted that death and injury were caused by different mechanisms of harm such as blade strikes on birds and vessel strikes or construction activities on marine mammals. A more recent study by Rezaei et al. (2023) highlighted that the construction process (including the increase in vessel traffic associated with construction and pile driving operations) produced the highest level of disturbance due to underwater noise, magnetic field generation (during operational tests) and the re-suspension of seabed particulate matter. Rezaei et al. (2023) state that measuring EMF emitted by offshore wind farm cables is still limited by technological capability and the majority of the results that they considered came from laboratory-based experiments and mathematical models as per Gill and Desender (2020). They highlighted that different biological effects may occur over different areas and time scales and that different organisms respond differently to different disturbances.

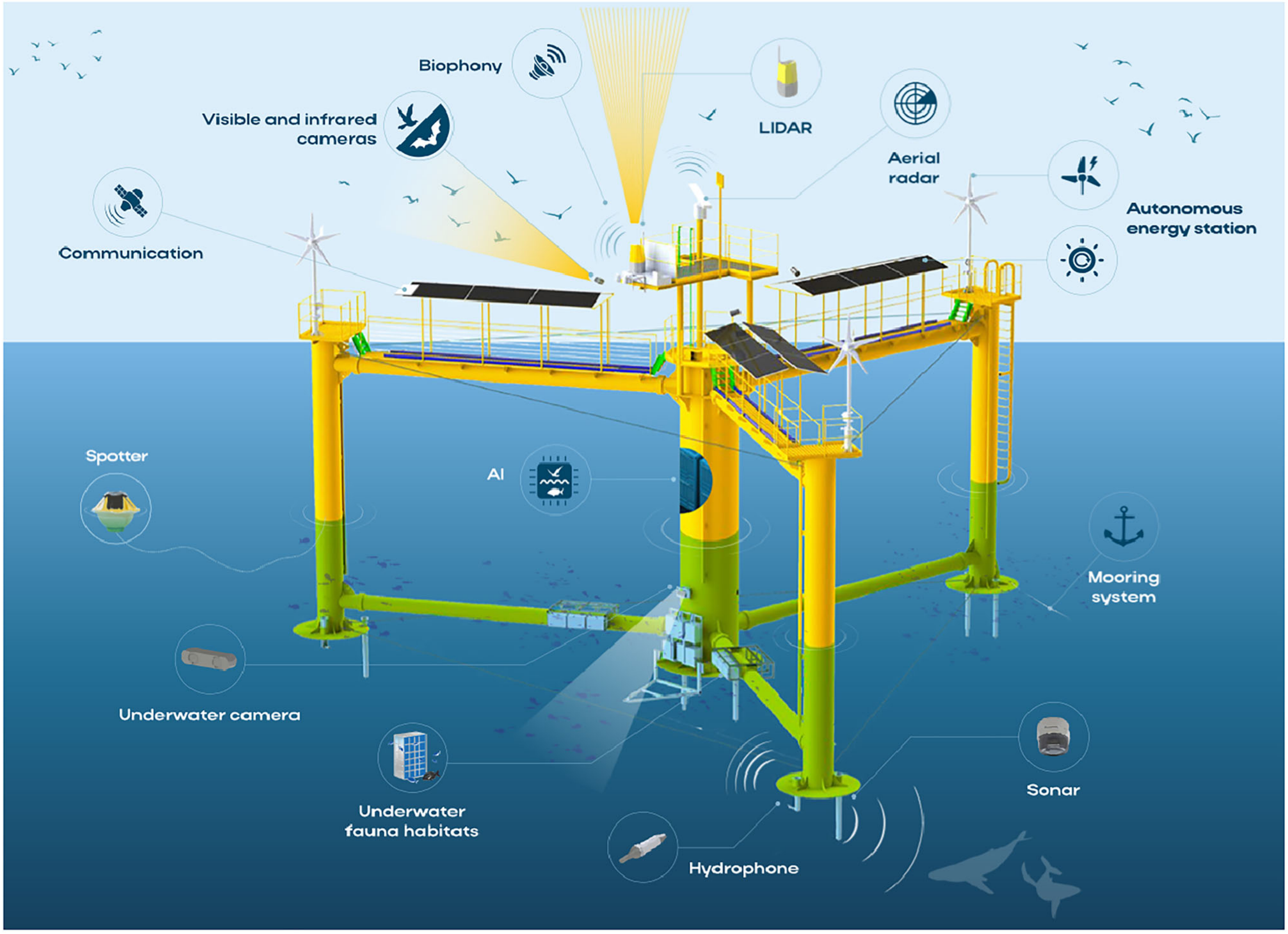

Fig. 1 The OCG-Data (product of Ocergy) is an example of an assessment data buoy

The OWE industry can learn from this by considering the engineering sources of each of these impacts and mitigating for them. This method is exampled for six engineering sources of negative impact in Table 1.

There are still significant gaps in our understanding of environmental impact (Cook et al. 2018) and individual projects require local data collection and analysis to enable Engineering Managers to assess potential interactions between devices and marine species as well as non-direct impacts. Projects such as the BLUE ORACLE project, funded by French government organization ADEME, is an example initiative that aims to collect more local environmental data more reliably using site assessment data buoys (e.g. Figure 1). The project aims to demonstrate the feasibility to combine logistics and means of measurement during ocean data campaigns for the characterization of resources and aerial and underwater biodiversity, where multiple shorter campaigns are otherwise used. The "*OCG-Data*" buoy has the capability to detect bats, birds, marine animals, fish and nutrients as well as local environmental information (including wind, waves, current, salinity, temperature etc.) and noise data and to process that data over an extended measurement campaign.

Windfarms should meet noise impact requirements which are normally set out by regulatory or planning authorities and often refer to directives such as the European Union (EU) Marine Strategy Framework Directive (European Commission 2008). However, many operating wind farms have noise outputs that are just above ambient noise and therefore monitoring noise can be a complex task. Lenchine and Song (2016) explored a variety of methods that could be used for assessing wind farm noise as explored in the next section.

2.2 The impact of engineering produced underwater noise on marine life

Anthropogenic activities in the sea can create noise sources that have either prolonged or transient impacts on marine life (NOAA 2018). Long term noise sources include commercial shipping (which are intermittent, loud noises), pump noises, offshore energy facilities (which are consistent low

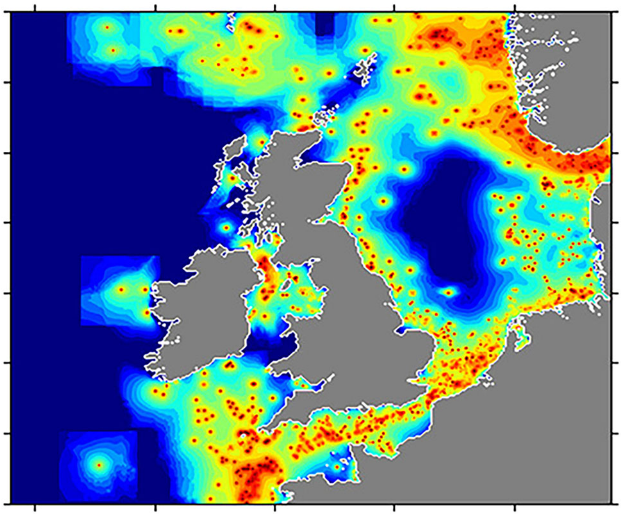

Fig. 2 Ship noise map reproduced from Farcas et al. (2020). (No scale provided)

noises) and short term noise sources may include construction projects, exploration tests and sonars from moving vessels. Excessive noise impact has to be understood in the context of the ambient underwater noise that consists of natural non-biological and biological noise sources and adds to the noise levels that marine animals need to tolerate (Wenz 2005).

Typical sound levels and frequencies depend on type of the noise source, proximity to the source and other factors, underwater noise levels may easily exceed 200 dB for some of activities (Molnar et al. 2020). Anthropogenic noise has different dominant frequencies that covers a wide frequency span. For example, the major spectral content of construction and ship noise is typically made up of relatively low frequencies < 1 kHz, whilst sonars cover a very broad frequency span (depending on application) that can be as high as 200 kHz (Deng et al. 2014). As such, anthropogenic activities may interfere with the sensory systems of marine species and thus evoke various physiological and behavioural reactions.

Farcas et al. (2020) modelled and published a ship noise map (validated using hydrophone measurements) which is reproduced in part in Fig. 2. This illustrates the hot spots around the UK and Northern Europe clearly following commercial shipping, ferry and fishing routes. Underwater noise can be assessed and described using a variety of acoustic descriptors including peak levels (Eq. 1), effective levels (Eq. 2) and sound exposure levels (Eq. 3). Peak levels are typically used to characterise impact from impulsive noise, like strikes during impact pile driving, whilst effective levels are used for relatively steady noise. Sound exposure level is typically used to characterise cumulative impact over certain period, as this descriptor considers exposure duration. In general, if the noise is loud enough, then it has the potential to cause physical damage (tissue damage and hearing shift or loss) however, the amplitude, frequency, and duration of underwater noise exposure significantly affects the impact type and level.

$$L_{peak} = 10log_{10}\left(\frac{p_{peak}^2}{p_{ref}^2}\right) \quad (1)$$

$$L = 10log_{10}\left(\frac{p_{rms}^2}{p_{ref}^2}\right) \quad (2)$$

$$SEL = 10log_{10}\left[\int_0^T \left(\frac{p(t)^2}{p_{ref}^2}\right)dt\right], \quad (3)$$

where p is the acoustic pressure, p_{ref} is the reference sound pressure in water (1 μPa), p_{rms} is the root mean square pressure over measurement period and p_{peak} is the peak pressure (the maximum value measured). All pressures must be input using the same units so that the levels are unitless. The timeframe that the noise levels are measured over needs to be appropriate for the noise output. For example, it could include 30 min worth of specific pile driving noise data or 24 h of general marina construction noise.

Marine species have a range of hearing mechanisms with different hearing sensitivities that have been characterised for some species (NOAA 2018; Southall et al. 2019; Southall 2021) but not for all species. There is no agreement on number of different fish species living in the world's oceans. Typically their number is estimated as tens of thousands different fishes. Some of these species have swim bladders that participate in the hearing process, some are sensitive to particle motion induced as sound waves travel through seawater (Sigray and Andersson 2012) and some to fluctuations of water pressure (Popper et al. 2014). Stated typical frequency spans for hearing of marine cetaceans are: low-frequency (7 Hz-35 kHz), high-frequency (150 Hz-160 kHz), very high-frequency (275 Hz-160 kHz). Other species also may have a wide typical hearing range, for example sirenians: 250 Hz-72 kHz, phocid carnivores: 50 Hz–86 kHz and other carnivores: 60 Hz-39 kHz (NOAA 2018). As such, most anthropogenic noise has the potential to impact at least one of these groups (Lenchine 2023).

Marine organisms close to an area characterised by high noise levels (as defined by Eq. 1–3 or other methods) may experience a range of effects depending on the species, their proximity to the noise impact and its amplitude and frequency. Close to the noise source there is a near field potential for death, physiological effects, impaired hearing, masking and behavioural response. Further from the noise source, temporary hearing impairments and detrimental behavioural responses may occur. Behavioural responses to noise can range from minor to severe depending on the noise level, sensitivity of species to noise and other factors (Hawkins and Popper 2012). Behaviour responses can include group or individual avoidance of a sound source (Hawkins 2014), impaired social communication during aggressive and reproductive encounters (Butler and Maruska 2020), brief separation of mother and calf (Vergara 2022), and cessation of vocal behaviour (Dunlop 2019).

When regulators are considering what effects should be targeted to specify acceptable levels of acoustic impacts for marine engineering projects, it is typical to use temporary hearing threshold shift (TTS). TTS refers to the effect of sudden or cumulative noise exposure that causes a temporary loss of hearing sensitivity. There are no standardised approaches to set criteria and thresholds however research outputs and reports exist that can be used to guide the setting of acceptable levels of noise if the presence of certain species is known (Popper et al. 2014; NOAA 2018; Southall et al. 2019). It is suggested that qualitatively similar weighting functions exist (Eq. 4) for groups of marine species (NOAA 2018) and these frequency and amplitude profiles can be used to set noise criteria where a local species list is known for an area (from biological surveys). Where biological surveys have not been conducted, are not up-to-date, or were only conducted for a short period, then the presence of the most sensitive marine life should be assumed and the most conservative weighting should be used to identify TTS zones (Lenchine 2023).

$$W_{aud} = C + 10log_{10}\left(\frac{\left(\frac{f}{f_1}\right)^{2a}}{\left(1+\left(\frac{f}{f_1}\right)^2\right)^a\left(1+\left(\frac{f}{f_2}\right)^2\right)^b}\right), \quad (4)$$

where f- is the frequency within the hearing range, f_1 is the low frequency cut-off, f_2 is the high frequency cut-off, C- is the weighting function gain, a is the low frequency exponent and b is the high frequency exponent.

Results from a recent and thorough biological survey should be referenced in all environmental management documents along with information on the particular species present in the construction or operation area of a project. This information should be used alongside data on the local background noise to assess the noise tolerance of the local marine species. An example workflow could be:

– Review results of a local, recent and thorough biological survey
– Identify the most sensitive/ protected species
– Review information about background/ambient underwater noise
– Analyse hearing thresholds and auditory functions
– Use envelopes of auditory functions if information is not sufficient
– Identify noise impacts relevant to the project
– Suggest project noise criteria.

There are some shortcomings to this approach as it may lead to "safe distances" being made larger than necessary due to a lack of data. However, this precautionary approach is always recommended to prevent inadvertent negative acoustic impact on local marine species.

Some of the factors that affect sound propagation in seawater include salinity, temperature, chemical contents, wave frequency/amplitude, physical properties of the seabed and depth. There are multiple methods used to compute the propagation of sound underwater. Ray theory solvers are generally applicable for high frequency or deep water regimens however they do not take into account the ray transmission into the sediment or diffraction. Parabolic solvers are applicable to low frequency, ducted or deep water regimens while normal mode solvers are used to compute noise propagation for low frequency, shallow water areas with layered sediments. Commercially available software such as dBSea (dBSea 2023) can aid in predictions. Safe separation distances from sensitive species should be predicted considering the most appropriate simulation method, source levels, noise propagation modelling and comparing predictions with identified criteria. Once this is completed, noise mitigation measures should be considered if necessary. When choosing safe separation distances, cumulative noise impacts could be more critical than peak noise levels.

There are multiple mitigation measures that could be implemented either separately or together. Operational methods tend to be based on the reduction in the intensity of noise output whilst observers are used to ensure that noise is stopped if sensitive species are detected within the high exposure area.

The Government of South Australia recently updated Underwater Piling and Dredging Noise Guidelines (Department for Infrastructure and Transport 2023). The document contains recommendations to minimise underwater noise impact and suggests a number of noise mitigation measurements. They can be summarised as follows:

- Avoid conducting noisy activities during times when marine mammals are likely to be breeding, calving, feeding, migrating or resting in biologically important habitats located within the potential noise impact footprint.
- Use low noise construction methods where possible.
- Presence of marine mammals should be visually monitored by suitably trained crew members (Marine Mammal Observers (MMOs) or Passive Acoustic Monitoring technicians (PAMs) for at least 30 min before the commencement of the piling procedure.

- A soft-start piling procedure should be used where necessary. This involves gradually increasing the piling impact energy over a certain time period. Visual observations of marine mammals within the exclusion zone should be maintained by MMO and/or PAMs throughout the start period.
- If a marine mammal is sighted within the observation zone operations should be placed on stand-by.

Mobile noise sources (such as vessels, dredging operations etc.) can be more difficult to mitigate against however similar MMO and/or PAM mitigation measures, as described above, can be employed.

Local marine life should be considered as a holistic ecosystem where potential underwater noise impact is considered for all of the species present in the affected ecosystem. Acoustic mitigation must be included as one of many environmental impact mitigation measures to reduce negative impacts of engineering projects on marine life. However, engineering can also be the solution to restore marine communities and habitats from the after effects of unintentional indirect impacts. This is exampled in the next section.

2.3 Engineering solutions for marine life on the great barrier reef

The Great Barrier Reef (GBR) is one of the largest ecosystems on Earth comprising some 3,000 reefs across 345,000 km^2 of ocean (Hutchings et al. 2019) along 2,000 kms of the East-Australian coast (Hopley 1982). It supports an estimated 600 species of corals, 1,500 species of fish, six of the world's seven species of sea turtle, the main population of the endangered dugon and generates nearly 6 billion dollars in economic activity each year (Deloitte Access Economics 2013).

Like reefs world-wide, it is under a range of threats, especially due to changing thermal conditions as a result of Climate Change. Unusually warm waters lead to corals becoming 'bleached', (which happens when coral become stressed and expel the symbiotic algae from their tissues) and this leaves the coral vulnerable to disease and mortality. Mass coral bleaching events were recorded on the GBR in 1998, 2002, 2006, 2016, 2017 and 2020, or an average of every 4.4 years (McWhorter et al. 2022) with another event predicted for the austral summer of 2023–24. The speed and scale of these disturbance events means that much of the GBR is now in a disturbed or recovering state which may impact the long-term sustainability of the system.

In the face of such rapid and widespread change, our ability to measure and understand this change may itself be a limiting factor to how we respond. Traditional science involves a slow process where the focus is on robust defendable conclusions that typically take years of data to develop. By the time the data is collected, analysed, and reported the system being studied may have already changed. In addition, to ensure robust defendable outcomes the data used by scientists typically has a large number of constraints around how it is collected, the methods used, the qualifications and training of those involved and the provenance of the data.

The scale and complexity of the changes being seen are increasing. Coral bleaching is no longer a local phenomenon but impacts large parts of the world at any one time (Oliver et al. 2018). To make this more complex, the impact and recovery of the bleaching event is highly variable at small scales and can be linked to multiple other factors such as water quality (MacNeil et al. 2019).

The net result is that the current scientific method and model provides a limited ability to respond to these complex, rapid and large-scale events. As such the fundamental science model, which revolves around robust defendable conclusions, may be an impediment to dealing with rapid large-scale complex changes. Engineering, and technology in general, provides one pathway to speed up data collection, to allow for new forms and sources of data to be used with confidence, and for actional outcomes to be delivered aligned to management and intervention needs. Engineering, and technology can be used to develop science grade data collection methods that can be used by technical users to collect data of sufficient quality and provenance that they have value in delivering outcomes. This is to explicitly get around some of the issues with Citizen Science by filling the gap between using simple off the shelf systems and bespoke highly complex systems.

Some areas that need to be re-considered by project managers in the context of environmental monitoring include:

- The fundamental scientific model and how scientific knowledge is delivered
- The scaling of data collection and analysis
- Dealing with data that has higher levels of uncertainty and lower level of robustness
- Shortening the path from scientific understanding to actionable outcomes and strategies

As an example of best practice, the Australia Institute of Marine Science (AIMS) has been investigating solutions that scale the data collection capacity and that shorten the path from scientific understanding to management action. For example, the AIMS Long-Term Monitoring Program (LTMP), currently use Manta Tow and Photo Transect survey methods (Miller et al. 2009) to monitor the health of the GBR.

While this is considered to be the best example of a reef monitoring program globally, it only surveys approximately 3% of reefs and of the reefs surveyed less than 2% of the reef area is actually surveyed (De'Ath et al. 2012). The more

Fig. 3 The transom-mounted ReefScan system (Australian Institute of Marine Science 2023)

Fig. 4 CoralAUV Platform (Australian Institute of Marine Science 2023)

data available, the better mitigation and restoration can be designed for the specific species, habitats and behaviours observed on the reef (and the more likely that surveys will observe rare behaviours such as mating, spawning or migration events).

The AIMS program uses a small team of highly trained scientists supported by sophisticated research vessels and infrastructure. To increase the area surveyed or to reduce the time between surveys requires a massive ongoing funding investment. As a result, this model of monitoring doesn't scale.

In response to this limitation, AIMS is developing a suite of semi-autonomous and autonomous monitoring platforms that capture high resolution spatially located images. These platforms achieve a number of things:

- The data collector needs to be technically trained but not scientifically trained and this significantly increases the number and type of people that can collect data (including rangers, traditional owners and NGO's).
- A single team can undertake a number of surveys in parallel, providing a force multiplier effect.
- Collection of images provides a multi-purpose data set that can be mined for other data in the future as well as providing a permanent visual record.
- Looking to the future, a fully automated platform may further scale the activity and potentially allow for surveys in areas where human safety concerns are currently limiting.
- The simplicity and reliability of the developed systems mean that they can be used in developing areas where access to science-grade resources is current limited.

To this end, AIMS has developed a simple transom mounted camera system that attaches easily to any small vessel, such as a fishing boat, with work underway to apply this to monitoring in the Philippines and Vietnam (Fig. 3). AIMS is also developing Autonomous Surface Vessels (ASV's), or self-driving boats, suitable for use in dynamic environments such as around reefs. These are branded under the 'ReefScan' name and use a common open architecture based on machine vision cameras, the use of the open Robot Operating System (ROS) and commonly available components.

A core part of the ReefScan system is the inclusion of a GPU computer (NVidia Jetson™ based computer) that allows real-time Machine Learning (ML) models to be run so that the system can know what is in each image as it is collected. This can be used both to inform the operator or to implement adaptive sampling where the behaviour of the platform changes based on the real-time analysis of the collected images. For example, if the area being surveyed is mostly sand the platform may speed up, if a target item is detected then the platform may go into a different survey mode. The use of real-time ML also shortens the analysis time so that the survey outcome is available immediately on completion.

A number of other platforms are also being developed including a smart towed camera-sled system that implements depth and altitude hold (terrain following) as well as active collision avoidance and an Autonomous Underwater vehicle (AUV), the CoralAUV, that is suitable for deeper water work beyond the normal limits of diver-based surveys (Fig. 4). ML models (such as implemented via the ReefCloud (www.reefcloud.ai) platform developed by AIMS) can analyse each image and produce a summary of percentage benthic cover estimates for each reef or reef segment. This allows analysis of thousands of images to be analysed per minute. The ReefCloud platform is currently being made available to support a range of monitoring work.

Engineering advances are allowing us to develop force-multipliers that increase the speed and scope of data collection while maintaining data quality and provenance, that increase our ability to analyse the data collected and to deliver actional outcomes to managers. Technologies such as autonomy, Artificial Intelligence and increasing availability of high-quality sensing systems together allow us to build new solutions.

For a marine research agency such as AIMS, the move to new science models, adoption of new technologies and developing new ways of delivering impact are all challenges. This is pushing scientific research agencies down a more technical approach as they look for solutions that scale the response to the scale of the issues. In the forefront is the need to develop human-centric solutions, to translate the latest science into actionable outcomes and to build trust in the information provided by autonomous collection and analysis. Engineering is a key component of this, enabling faster environmental data collection that can be translated into useable information by decision makers.

3 Conclusions

Climate change and environmental impacts are at the forefront of political decision making, necessitating a deeper understanding among engineers of the interplay between engineering projects and marine life throughout project life cycles. This review has highlighted interactions between marine life and offshore wind projects, the impact of underwater noise on marine life and provided mitigation strategies as well as an example of engineering solutions for the restoration of marine life. Future endeavours must foster closer collaboration between marine engineers and marine scientists to safeguard the future of the marine environment while ensuring the feasibility of marine engineering projects. It is imperative that these solutions are not only scalable but affordable, given the limited timeframe available for their development, validation and implementation.

For some areas, such as coral reefs, the increasing pace of change is forcing a major re-think about the role of engineering solutions in science. This includes devolving data collection to autonomous collection platforms, use of Machine Learning to analyse the data and increased use of new technologies to deliver new sets of solutions. As such, the power of engineering solutions should be applied to scale up and speed up environmental data collection and thus enable more specific mitigation procedures to be designed and implemented.

The symbiotic relationship between marine engineering and marine life is undeniable. As the footprint of anthropogenic activities in marine environments are expanded, it is our responsibility to ensure that engineering projects not only coexist with but also contribute positively to the preservation and restoration of marine ecosystems.

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Author contributions T. Dobson wrote the introduction, section1, conclusion and abstract. V. Lenchine produced the content for section 2 and S. Bainbridge produced the content for section 3. All authors edited and reviewed the manuscript.

Declarations

Competing interests This manuscript is based on presentations given during the "Engineering and Marine Life" afternoon lecture at ASME's 42nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2023) in Melbourne, Australia. The presenters received financial support to attend the conference however no funding was received to assist with the preparation of this manuscript. Valeri Lenchine is the Technical Director for Noise and Vibration at GHD. Scott Bainbridge leads the Technology Development Engineering team at AIMS.

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