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Literature Review of Environmentally Friendly Moorings – Environmental and Engineering Performance

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Executive summary

Moorings are a common infrastructure used to secure vessels in shallow water and are widespread across estuaries in New South Wales. Most mooring designs cause damage to marine habitat. There are alternatives to current designs that are less destructive, however very few of these 'environmentally friendly' moorings are in use. In this report, we undertook a review of the published literature pertaining to environmentally friendly moorings (EFMs), to better understand the current market availability and status of EFMs, the science used to assess their performance and to identify EFM designs for in-water trial. We took a multi-disciplinary perspective around the known potential of EFMs both from environmental, engineering, and socio-economic fields and provide a gap analysis to indicate where future research is required.

The review included a systematic search of peer-reviewed scientific literature and "grey literature" (non-peer reviewed documents which are not published in recognised scientific journals e.g., reports, websites) connected to EFMs, and similar terms. This returned 163 primary results, which we have condensed to 78 relevant items. Of these, 52 sources are in the scientific literature (1 in review) whilst 26 are grey literature.

It is evident that Australia has a long, active, and globally significant history of research on EFMs. The earliest primary publication to document mooring damage to seagrass meadows was published in Western Australia in the late 1980s. A more recent publication on EFMs in Jervis Bay, NSW in 2013 is internationally influential and widely cited (67 citations).

Environmental

Across the literature most studies on moorings generally, and EFMs in particular, look to identify and/or quantify the problem of mooring impact on the environment. There has been a strong focus on the conservation of seagrass meadows, and to a lesser extent, non-vegetated habitats, fish communities, and biophysical processes such as sediment resuspension. There is also separate literature on damage to corals and anchor damage. While the problem is well defined there are very few performance assessments of EFM deployments.

While there was only incremental progress in the field of EFM science for the first 20 years of its inception, in the last 5 years there has been an upsurge in interest and EFM development. The interest in EFMs has also spread more widely from Australia to a range of other countries. There are a small number of trials on the environmental effects of EFMs, but these have produced mixed results. Despite the increasing implementation, EFMs are still a tiny fraction of all moorings globally and there are considerable knowledge gaps and challenges to utilising EFMs for conservation or mitigation. The variation in the impacts reported suggest EFMs have issues with effectiveness based on location, design, perceptions, servicing and implementation.

A rapidly increasing body of literature documents the high carbon sequestration potential of coastal vegetated habitats, including seagrasses. Within this literature moorings have been linked to degradation of these marine or 'Blue Carbon' sinks. Many nations, including Australia, are seeking to manage coastal vegetation to help meet their climate change mitigation targets. The

Australian Government, through the Clean Energy Regulator, has recently developed an exposure draft for Blue Carbon sequestration methods, based on a national-scale prediction of contemporary and future Blue Carbon storage. One proposal is better management of physical disturbances to seagrass and seagrass soils to avoid greenhouse gas emissions. Seagrasses and other sub-tidal ecosystems may also be resilient carbon sequestrators in the face of climate change compared to inter-tidal ecosystems such as saltmarsh and mangroves.

The role that moorings can play more generally in hydrodynamics, erosion, and resuspending contaminated sediments, especially within urbanised estuaries has also been a recent area of active research. Edge effects can cause increases in erosion from currents and waves, with mooring scars eventually merging and causing the collapse of seagrass meadows. This collapse may also occur in other habitats. There is also the negative effect of microbial priming, which increases the release of greenhouse gases from disturbed sediments.

There is an extensive grey literature, especially from New South Wales and Queensland, reviewing EFM designs and mooring management. Many of the EFM systems provided in these reviews are now out of date, due to EFM systems no longer being commercially available. We provide a current review of availability in our engineering section. It is surprising that with such a long and widespread period of development, EFMs are only very minor components of Australian mooring fields. A notable exception includes a well-developed EFM program in Moreton Bay, Queensland, facilitated by Healthy Land and Waters (a not-for-profit organisation which is a partnership between governments and various institutions). Since 2009 this has led to the installation of hundreds of EFMs, financed through an environmental offsetting program.

Another successful EFM roll-out example, although on a smaller scale, is the installation of 20 EFMs in Port Phillip Bay, Victoria, managed by Parks Victoria. These moorings are hired to the public for cost recovery. No significant EFM roll-outs have occurred in other Australian states with the limited exception of some trial and localised EFM deployments in NSW, TAS and WA.

Environmental Protection Agencies in SA and WA also recommended ‘environmentally friendly’ designs for new mooring installation, but there are no apparent schemes to facilitate these recommendations.

Engineering

Despite EFMs being widely recommended in the scientific literature, only a small fraction of published studies (4 out of the 78 primary sources) define what an EFM is or suggest specific mooring designs. There are very few peer-reviewed, independent engineering papers that describe EFMs or their designs. Most information pertaining to EFM engineering specifications appears in grey literature or as part of manufacturer’s literature. Recent CSIRO research, however, has suggested that chain catenary moorings (also known as block and chain, traditional moorings, chain moorings or chain swing moorings) may experience higher peak tension loading than EFMs when subjected to extreme weather.

We could find no engineering standards for EFMs either in Australia or internationally. The only engineering advice we found for swing moorings in Australia is a recently published (2020) Darwin

Ports standard for traditional chain catenary moorings, which includes a private mooring equipment guide for small vessels (<6m – 15m). A review of mooring management conducted in 2014 by the Gold Coast Water Authority found that no Australian insurers had developed any manufacturing or installation guidelines for boat moorings. Instead, insurance to mooring providers was based on risk and claim history alone.

While there is considerable evidence around failures of chain moorings, especially for offshore applications, there is no relative comparative assessment of failure rates between chain moorings and EFMs. There are also few studies of the engineering performance or servicing of EFMs. Some manufacturers provide 'pull test' results, however this only assesses the instantaneous holding power of the anchor. These tests provide no understanding of a mooring system's dynamic performance in dampening forces on the vessel in different environmental conditions or how the mooring wears over time. Recent CSIRO research suggests that EFMs may wear and require different servicing to traditional chain moorings, and vessels attached to EFMs may also move differently in exceptionally light wind conditions.

Several studies highlighted issues with improper installations and biofouling resulting in the failure of the EFMs to halt benthic scarring. Unlike traditional chain moorings, EFMs have two distinct functions: safely securing vessels and removing impacts on the seafloor. This increases the complexity of the EFM design compared to the chain mooring. It also tightens the allowable engineering tolerances of EFMs compared to chain moorings. EFMs hence need to be more precisely 'tuned', especially with increased 'mid-water' componentry.

EFMs were assessed into 6 categories with 19 individual solutions discovered, containing a mix of both manufacturer and generic solutions (built from independent components). The method of dissipating mooring forces was found to vary across the range of EFMs. While chain moorings all work using the mass of the mooring chain to dampen the vessel's dynamic forces by converting kinetic energy into gravitational potential energy, EFMs work using elasticity (whole or partial), displacement, substitution, gravitational potential energy, springs or a combination of these methods. This finding reinforces the view that widespread adoption of EFMs will require considerable consultation with strong engineering technical input.

Gap analysis

Our review revealed potential insights and explanations for the lack of EFM uptake on a larger scale through gaps in knowledge. There is a considerable gap in independent engineering assessment of designs, performance, and service life of EFMs. 'Traditional' mooring designs (i.e., chain catenary moorings) appear to have been locally developed through long-term trial and error methodology and hence may have strong cultural connections. Alongside this gap in engineering knowledge, there is a lack of understanding of social attitudes, perspectives of the safety of EFMs and economic drivers for uptake. Lack of stakeholder knowledge and confidence about EFMs by regulators, waterway managers, mooring contractors and vessel owners may consequentially present challenges for progressing EFM uptake in the medium term.

Without building stakeholder confidence, through demonstrated examples of engineering robustness, it may be difficult to convince stakeholders to adopt EFMs. Many papers call for top-down policy direction to address damage from moorings; however, several international studies (from the USA and Italy) identified conflict between government agencies and the boating community, as well as enforcement issues after banning of mooring and/or anchoring.

Despite the relatively comprehensive impact studies documenting damage caused by chain catenary moorings, very few studies have assessed EFM performance in an experimental setting with robust scientific design. Aspects of robust designs which are often missing include: experimental manipulations, lack of the baseline data or the 'before' component of Before After Control Impact (BACI) designs, low replication, and a lack of generality from results due to studies being highly localised. Additionally, non-vegetated habitats have been largely overlooked, despite the high biodiversity and ecosystem services that they can provide, and that most moorings occur in these habitats.

Recommendations

We recommend that future research of EFMs should take a multi-disciplinary approach rather than exclusively focusing on environmental impact considerations. The following areas of research and activity should be considered:

1. Engineering and servicing assessments of EFMs to clearly define and independently assess performance beyond commercial testing provided by manufacturers, including both modelling and instrumenting vessels to assess dynamic behaviour.
2. Studies of perceptions and socio-economic drivers of important stakeholders (a funded study of licensee perspectives is currently underway in Tasmania).
3. Development of education and outreach programs for EFMs across stakeholder groups (regulators, contractors, equipment suppliers and vessel owners).
4. Conducting EFM impact and performance studies that include a high level of replication across multiple geographic regions and follow the BACI (Before-After-Control-Impact) design framework.
5. Experimental designs that compare recovery rates of both biodiversity and biogeochemical processes, such as carbon sequestration, following replacement of chain catenary moorings with EFMs.
6. Research that occurs over multi-year time scales, at a high species biodiversity resolution, across multiple habitat types (both vegetated and non-vegetated benthic habitats) and depth ranges.

1 Background

Over the last century, increased installation of chain catenary moorings (also known as block and chain, traditional moorings, chain moorings or chain swing moorings) to secure vessels, particularly in the shallow waters of urbanised estuaries, has resulted in significant loss of coastal marine habitats both in Australia and globally. Unlike intermittent or ‘pulse’ benthic disturbances such as trawling, temporary anchoring, or storms, which can allow for ecological recovery, chain moorings are a form of ongoing or ‘press’ disturbance which permanently changes the habitat (Herbert et al., 2009). In many urban areas there is a high demand for moorings (Hedge et al., 2017; MAST, 2016). Chain moorings traditionally use, as part of their design, an anchor connected to a heavy chain and then to a lighter thrash chain to provide anchorage and shock absorption for the vessels in response to weather and currents. Unfortunately, chains are highly destructive to the seabed, destroying biodiversity, habitats for endangered species, nursery areas for commercially and recreationally important fish; while also increasing erosion (Glasby and West, 2015; Hastings et al., 1995; Unsworth et al., 2017; Walker et al., 1989).

Mooring chain scouring the seafloor creates a ‘scar’ in the habitat, which is especially noticeable in seagrass meadows but occurs in all habitat types. This mooring scar phenomenon was first reported in Australia in the 1980’s (Walker et al., 1989), although aerial photographs captured the initial formation of mooring scars from as early as the 1940s (Fig. 1). Despite the long history of mooring impact research and consideration of EFMs, which in Australia dates to at least 1995 (Hastings et al., 1995), only limited progress has been made in reforming mooring management and transitioning to EFM designs on a large scale.

Figure 1 Aerial imagery of Manly Cove, NSW from (a) 1943, (b) 2010, and (c) 2016 shows ‘scars’ created by swinging mooring chains in a *Posidonia australis* meadow. Scars have expanded and merged over time, heavily fragmenting and then collapsing the meadow.

Source: www.nearmap.com.au; Copyright © 2016 Nearmap Australia Pty Ltd

In dense moorings fields, the increased number of scars also create more habitat edges, which are vulnerable to erosion, partly due to decreased wave attenuation (Colomer et al., 2017; Evans et al., 2018; Hastings et al., 1995). This can result in habitats continuing to fragment even if no new moorings are installed. This cumulative effect of mooring scar damage over time, whereby individual mooring scars expand and eventually merge, dramatically fragments the habitat (Glasby and West, 2018) and can cause complete habitat collapse.

In NSW, as of December 2020, the number of (available, occupied, and offered) private and commercial mooring leases is 22,810. This comprises 17,819 Private Mooring Leases, and 4,991 Commercial Mooring Leases (Transport for NSW, 2020). This includes a subset of moorings that are impacting the seagrass, *Posidonia australis*, which has locally endangered populations. Estimates of total current disturbance by chain moorings in NSW are 3,014,731m^2 of which 223,824m^2 is disturbance to seagrass (7.4%); this comes with the proviso that the estimate does not include legacy effects from old scars (Glasby and West, 2018). While there has been a particular focus of research from the impact of moorings on seagrass meadows, other soft sediment habitat types are increasingly also being considered (Cullen-Unsworth and Unsworth, 2016; Glasby and West, 2018; Unsworth et al., 2017); and there is a separate literature on damage to corals.

Besides habitat and biodiversity considerations, vegetated coastal ecosystems effected by moorings can also sequester substantial amounts of carbon per unit area, which can be up to 50 times more than terrestrial forests (Mcleod et al., 2011). When first deployed, chain moorings release a plume of organic carbon into the water column, making it susceptible to mineralisation, conversion to CO2 by organisms, and subsequent emission into the atmosphere. The plume can also form carbonic acid, which contributes to ocean acidification. As the mooring chains continue to swing around the block on the seafloor, they inhibit both plant and most other benthos biomass growth. This undermines any sediment stabilisation, which is an important requirement for natural carbon capture and sequestration (Bedulli et al., 2020).

While chain moorings are the most common way of securing vessels, there are currently no Australian Standards for mooring designs, though Darwin Ports does provide advice for traditional chain catenary moorings for small vessels. There are also no standards for EFMs, and while these systems have been on the market for many years, they have had limited take up by the public.

Recent CSIRO and University of Tasmania engineering modelling has indicated that working load limits (WLL) for traditional chain catenary mooring designs may often be exceeded when wind gusts reach extreme but expected levels (Lynch et al., 2020, Wong et al. submitted). Due to lack of elasticity, chain mooring designs can experience high shock loading, with load peaking to more than twice the WLL in extreme weather. Comparatively, modelled EFM designs rarely exceeded the WLL, or only by a minor amount, even in extreme conditions. These results are like both modelling and field validation of coastal oceanographic moorings by Paul et al. (1999), whose chain mooring design recorded a much higher tension load than non-chain mooring alternatives. This increase in load created a high fatigue environment which potentially reduced the life expectancy of deployed oceanographic instruments (Paul et al., 1999). With changes in the global climate, extreme wind and wave conditions may become more frequent (Meucci et al., 2020), potentially increasing failure rates of chain moorings.

2 Scope and Aim

The scope of this report is single-point, swing moorings, especially the commonly deployed chain catenary moorings (commonly known as block and chain moorings in NSW), and various 'environmentally friendly' alternatives. Single point swing moorings are comprised of three essential components: an anchor, a rode, and a floating buoy. The rode component on a chain catenary mooring is a heavy chain that sits on the seafloor, attached to a lighter thrash chain connected to a buoy or a line to a buoy. The anchor of a chain catenary mooring is usually a 'dead weight' such as a concrete block or railway wheel, hence they are commonly referred to as 'block and chain' moorings. Swing mooring designs with alternative rode styles, which do not contact the seafloor (e.g., buoyant elastic rodes instead of chain) are known as environmentally friendly moorings (EFMs), eco-moorings, environmentally sustainable moorings, conservation moorings, or seagrass friendly moorings. EFMs can also be associated with a particular type of anchor system, usually screw or helix anchors that are buried into the substrate. This report will use the term EFM to describe any mooring system with a rode which does not directly contact the seafloor, irrelevant of anchor choice.

The aim of this literature review is:

1. To assess the current state of scientific assessment for environmental impact of both chain moorings and EFMs.
2. To evaluate the performance and market availability of different EFM systems.
3. To identify and provide recommendations on EFM systems for in-water trials.

3 Review of literature

3.1 Methods and metadata

We undertook a systematic search of the primary literature for environmentally friendly moorings (EFMs) and similar terms, with Scopus, a peer-reviewed literature database, and Google Scholar (see bibliography for all results reviewed). Google Search was also used more generally to discover grey literature (reports, websites) both for Australia and Internationally. Synonyms to 'EFM', including 'advanced mooring system, 'conservation mooring', 'eco mooring' and 'seagrass-friendly mooring' were included in this search, however all environmentally friendly mooring designs will be referred to as EFMs in this section.

Scopus and Google Scholar searches returned 126 primary literature results, which we condensed to 66 relevant papers. Within the Australian grey literature, we found 30 results, which included information from all states. Internationally we found 33 grey literature results across multiple countries (Vietnam, Sweden USA, NZ, France, China, Italy, Spain, Dubai, and Greece). Despite EFMs being widely recommended in the scientific literature, only a small fraction of published studies (4 out of the peer-reviewed 66 sources) defined EFM system components.

There were 24 studies found that experimentally investigated the environmental impacts of swing moorings (see bibliography).

3.2 Environmental

3.2.1 Benthic impact

It is well established that chain catenary moorings cause environmental damage to benthic habitats (Cullen-Unsworth and Unsworth, 2016; Evans et al., 2018; Glasby and West, 2018; Unsworth et al., 2017). These impacts are particularly well documented for seagrass, though other habitats have also increasingly been considered (Cullen-Unsworth and Unsworth, 2016; Glasby and West, 2018; Unsworth et al., 2017) and there is a separate literature on damage to corals. In Australia, a seagrass of particular concern is *Posidonia australis* (see Demers et al., 2013; Glasby and West, 2018; Hastings et al., 1995; Walker et al., 1989) followed by other seagrass species such as *Amphibolis spp, Zostera muelleri* subsp. *capricorni* and *Halophila ovalis* (Bedulli et al., 2020). Seagrass are distributed in shallow, protected bays, which are also preferred places of refuge for boats and coastal infrastructure.

The focus on seagrass may be due to their known importance for provision of habitat, wave attenuation, carbon sequestration, nutrient cycling, and erosion control. The visually obvious impact that moorings have on these habitats may have also contributed to this focus. Utilisation of aerial or satellite imagery to monitor mooring scars, is a cheap method for monitoring impacts but this is less useful for detecting changes in non-vegetated habitats due to the lack of colour differentiation between disturbed versus undisturbed areas. Even in seagrass habitats, aerial mapping underestimates scar sizes in seagrass habitats by 7% (Unsworth et al., 2017) and has limited resolution beyond 6-8 metres depth (Kutser et al., 2003; Wilson et al., 2019). Moorings are often deployed beyond these depths and as chain length is multiplied by a factor related to depth, chain scars are larger for moorings in deeper water (McCandless, 2018). These limitations mean that the impact of moorings on benthic habitats could be significantly underestimated.

Of the 24 studies that experimentally investigated the environmental impacts of swing moorings (see bibliography) half were dedicated exclusively to impacts on seagrass meadows, especially *Posidonia spp*. The remaining studies included impacts to rhodolith ecology, fish behaviour, macro-invertebrate biodiversity, general habitat impact, and sediment biogeochemistry. There were 7 research studies conducted in Australia, of which 5 have focused on impacts to *Posidonia australis* meadows (Ferretto et al., 2021; Glasby and West, 2018; Hastings et al., 1995; West, 2012; Demers et al., 2013). Another study investigated the impact of moorings on sediment biogeochemistry in Posidonia meadows rather than the vegetation itself (Serrano et al., 2016). Only 1 Australian study has specifically investigated mooring impacts in non-vegetated soft sediment habitats (Macolino et al., 2019), while another investigated fish community and feeding behaviour near chain moorings (Lanham, et al., 2018).

In NSW there is a recent state-wide assessment that estimated current leased moorings were causing losses of 129,884 m^2 of *P. australis* and 93,940 m^2 of *Z. capricorni*, and disturbing 2,790,907 m^2 of non-vegetated soft sediments. It is important to note that these NSW seagrass loss estimates relate only to damage from current moorings and could be underestimated by ~41% for *P. australis* in estuaries that contain many old scars that remain after the relocation of moorings (Glasby and West, 2018).

Despite the predominance of seagrass in the literature, most moorings (88% in NSW) are in non-vegetated soft sediments (Glasby and West, 2018), and the impact of moorings on these habitats is poorly studied. Of the global studies that have occurred in non-vegetated habitats, all found some impacts from moorings. For example, the diversity of Rhodoliths, which are a calcareous algae resembling coral, and the communities they support, is negatively impacted by moorings (Gabara et al., 2018; Tompkins and Steller, 2016). Damage from long-term moorings also leads to decreased biological productivity in these communities (Dolinar et al., 2020) and changes in macro-invertebrate communities (Herbert et al., 2009; Maluleke, 2017; McCloskey and Unsworth, 2015; Ostendorp et al., 2009).

Over time impacts from moorings accumulate in seagrass habitats (Glasby and West, 2018) with movement of chains and anchors expanding impacts, as scars merge due to erosion, and this can lead to collapse of the seagrass meadows. This accumulation effect potentially occurs in other habitats. Recent research has also identified that chain catenary moorings can decrease fish abundance in their direct proximity (Lanham et al., 2018).

While there are extensive studies of impacts from moorings, performance assessment of EFMs or other mitigations are much rarer. One documented example of EFM performance, in this case for conserving seagrass habitats, is from Jervis Bay, NSW (Demers et al., 2013) and this is internationally influential and widely cited (67 citations). A recent review by Broad et al. (2020), however, identified issues with the scientific methods around the assessment of impacts from moorings and anchor damage. Until recently, studies rarely included any experimental manipulation or baseline data (the 'before' part of Before After Control Impact designs). Luff et al. (2019) did consider these scientific design elements in a recent small-scale EFM experiment, though with extremely low replication (1 mooring vs 1 EFM) and generality (one location).

A recent article that is still in preprint (i.e., not yet peer reviewed) by Seto et al. (2023) has added increased replication and generality. They conducted two experiments, one with 5 chain moorings against 15 EFMs across two harbour locations with an additional treatment of eelgrass (a type of seagrass, *Zostera marina*) being replanting. A separate time-series experiment tracked eelgrass recovery over five years following deployment of 21 EFMs at three harbours. Finally, additional EFMs where added to the study to bring the total to 52 EFMs to monitor the rate of retention of gear. Though a relatively robust study, controls (unimpacted eelgrass) were only included in the last monitoring period, and only at one site and were immediately adjacent (1m) to scars. There were also only a limited number of chain controls. Baseline data was not collected prior to deployment of EFMs, with the study starting at deployment. Data was transformed rather than distribution appropriate models used to analyse data.

EFMs allowed for recovery of eelgrass but additional planting did not have any additional affect, but this may have been a function of low replication for this part of the study. The magnitude and rate of eelgrass recovery following conversion to floating rode systems was contingent on the location (e.g., site specific environmental conditions) and the size of the scar associated with the mooring. Eelgrass recovery was inversely correlated with exposure and tidal range, and positively correlated with original scar size. While most scars started to revegetate within two years of mooring conversion, few experienced complete recoveries, with a two-meter denuded halo persisting around mooring anchors five years post conversion.

A potential drawback for undertaking more robust scientific approaches is the need to collect long-term data sets, which has resulted in a reliance on historical aerial imagery or non-manipulative observational approaches to assess recovery effects. Attempts to monitor recovery over shorter time periods (~12 months) have detected little recovery (see Herbert et al., 2009) in some habitats. This may be particularly acute for *P. australis*, with long term datasets suggesting recovery can take decades after mooring removal (Glasby and West, 2018). For these habitats, recovery trajectories may be accelerated by active restoration in addition to EFM installation, as has been successfully demonstrated in recent trials in Port Stephens, NSW (Ferretto et al., 2021). Other habitats, including different species of seagrasses, may have faster recovery trajectories following removal of the press disturbance of chain moorings alone.

The next stage of EFM benthic impact research is to move from descriptive to experimental studies of how recovery occurs after chain catenary mooring removal and replacement with EFMs. This work should be done at: large scales, over multi-years, with high species biodiversity resolution, and across multiple habitat types and depth ranges.

3.2.2 Carbon and biogeochemistry interaction

It is well established that vegetated coastal or 'Blue Carbon' ecosystems such as tidal marshes, mangrove forests and seagrass meadows, are efficient carbon sinks (Duarte et al., 2013; Fourqurean et al., 2012; Mcleod et al., 2011). Globally, despite only covering <2% of the world's ocean surface these ecosystems account for just under 50% of the total carbon burial and sequestration in all marine sediments (Duarte et al., 2013; Duarte et al., 2005). Seagrass ecosystems have outstanding sequestration capacity, storing a large fraction of their substantial production and are responsible for about 15% of the carbon storage in the ocean (Duarte, 2002; Fourqurean et al., 2012).

Quantifying the impact of mooring damage to seagrass meadows and Australia's Blue Carbon storage capacity is a recent and active area of research. For instance, baseline estimates of seagrass extent, and soil carbon stocks, accumulation rates from different seagrass habitats and comparisons to denuded areas (Bedulli et al., 2020; Serrano et al., 2016) have recently been published for areas in WA. In NSW there has been a recent state-wide estimate of mooring damaged to seagrass and other habitats, estimates of rates of increase of damage and the negative effects of increased depth and boat length (Glasby and West, 2018).

Some seagrass species form long-lasting meadows, with meadows of the long-lived *Posidonia oceanica* dated to >4000 years old (Duarte, 2002), while sediment cores taken from *P. australis* meadows in Australia date back 3200 years (Kaal et al., 2019). Damage by moorings therefore not only effects the current carbon burial capacity of seagrasses it also releases back into the atmosphere considerable amounts of carbon dioxide from ancient carbon stocks (Marbà et al., 2015).

Many nations, including Australia, are seeking to manage coastal vegetation to help meet their climate change mitigation targets (Young et al., 2021). The Australian Government through the Clean Energy Regulator and the Emissions Reduction Fund has recently developed an exposure draft for Blue Carbon sequestration methods based on a national-scale prediction of contemporary and future blue carbon storage (Kelleway et al., 2020). One part of this proposal is better management of physical disturbances to seagrass and seagrass soils to avoid greenhouse gas emissions from what should be hotspots of carbon sequestration.

Seagrasses and other sub-tidal ecosystems may also be resilient carbon sequestrators compared to other marine ecosystems. Carbon stocks in mangrove/tidal marsh ecosystems are likely to experience declines under predicted climate change scenarios (19% of ecosystems area is predicted to have an increase in soil carbon stocks, while 38% of ecosystems area is predicted to have a decrease in soil carbon stocks), but most seagrass areas are likely to have increased soil carbon stocks (56% increase, 7% decrease) (Young et al., 2021).

Most Blue Carbon research and national scale predictions are focused on seagrass meadows, salt marshes and mangrove forests, which undoubtedly sequester disproportionately high levels of carbon. However, most of the seafloor is covered by non-vegetated soft sediments, which also act as long-term carbon stores, although less per unit than vegetated areas (Bulmer et al., 2020). The organic carbon in these sediments is largely derived from coastal and marine vegetation, and sequestration rates are usually lower in coarse, high sand sediments compared to siltier areas (Phang et al., 2015). The impact of mooring scour on sediment composition is not well understood but sediment grain is coarser within the scars (Hedge et al., 2017; Herbert et al., 2009). It is likely that the disturbance cause by mooring scours would result in the loss of carbon in non-vegetated habitats, like the process known to occur in vegetated habitats.

Mooring chain scour also results in erosion and resuspension of nutrients and sediments, which has consequences for sediment composition, carbon storage capacity and other biogeochemical processes (Sagerman et al., 2020; Serrano et al., 2016). This increased suspension may contribute to water quality declines (Unsworth et al. 2017). There is also the possibility of the release and bioavailability of contaminants, such as heavy metals and organometallic compounds (Eggleton and Thomas, 2004) from mooring scours. Few studies, however, have directly observed these effects, and we could find no studies that investigated sediment recovery trajectory after mooring removal and replacement with EFMs.

The proximity of coastal habitats to runoff and disturbance also creates ideal conditions for soil organic matter or microbial “priming”. Priming in the case of moorings impacts involves a change in rate of organic matter decomposition. This enhances remineralisation of sequestered carbon as previously buried and anoxic substrates are exposed to oxygen and microbes. Priming can result in a 2–3-fold increase in carbon released from sediments (Trevathan-Tackett et al., 2018).

The environmental conditions of habitat edges differ to the conditions found within habitat areas, and this can alter their biodiversity (Carroll et al., 2019). Generally, having numerous habitat edges can result in overwhelmingly negative effects on biodiversity if they are subject to hydrological fragmentation (Yeager et al., 2020). These edge effects mean that the cumulative impacts of many moorings within a mooring field can be greater than the sum of individual scars. In fully or over-subscribed mooring fields, where multiple scars combine, the extent of damage may disrupt self-reinforcing feedbacks (Seto et al., 2023) that are needed to promote aquatic plant growth.

3.2.3 Environmentally Friendly Moorings as a management tool

Some broad trends are evident in the results of this literature review; Australia has a long and active history with EFMs, with our earliest primary publication being from Western Australia (Walker et al., 1989). A more recent publication on EFMs in Jervis Bay NSW (see Demers et al., 2013) is internationally influential and widely cited (67 citations). While there was only incremental progress in the field of EFM science for the first 20 years of its inception, in the last 5 years there has been an upsurge, particularly in the international literature (Byrnes and Dunn, 2020; Macolino et al., 2019; Ouisse et al., 2020, Unsworth et al. 2022).

Although the maximum potential long-term biodiversity conservation and carbon benefits of replacing chain catenary moorings with EFMs can be estimated with existing information, this assumes that the EFMs work as management tools. A common consensus found across mooring impact literature is that EFM designs should be implemented to manage and mitigate environmental damage. However, few large-scale EFM roll-outs are well documented in the literature and there is also limited documenting of any failures or successes of EFMs, replacement or offsetting schemes.

A recent review by Broad et al. (2020) identified that few studies included any experimental manipulation or Before After Control Impact (BACI) designs, which are the most robust forms of science. Partial exceptions include Luff et al. (2019), who did consider these scientific design elements in a recent small-scale experiment in the UK but with no replication (1 mooring vs 1 EFM), and Ostendorp et al. (2009) who monitored impact over a two-month period, in Germany. Both studies observed a positive effect of EFMs, but more robust data is needed. A larger scale study, which included 11 EFMs and three locations (two in the UK and one in Puerto Rico), for a simple EFM, made of rope and useful for mooring light small vessel in mild summer conditions (Unsworth, et al., 2022), found significant recovery of seagrasses.

Across the UK trials of EFMs, which are also called Advanced Mooring Systems (AMS), have occurred since 2007 with approximately 45 installations of vessel moorings and 21 navigation moorings across 11 sites (Maclennan, 2022). Most of these moorings have been installed since 2020 and include Seaflex, Hazelett, Stirling, Safemoor and Sealite gear.

Another, rare, recent example of a large scale roll out of EFMs is from the grey literature. In 2014 - 2015 the Massachusetts Port Authority's mandated and sponsored conversion of 285 block and chain mooring systems to EFMs (called conservation mooring systems), in six harbors as offsetting mitigation for permitted impacts to seagrass in other areas. Mooring conversions to EFMs were fully subsidized at $3,320 per conversion (Seto et al., 2023). These EFMs generally restored the eelgrass but location and depth impacted on effectiveness. Sheltered and low energy harbours correlated with increased eelgrass recovery while very shallow moorings were less effective as it was difficult to keep mooring gear off the bottom. Continued scour impacts have also been observed following installation of EFMs in Australia and the United Kingdom (Egerton 2011, Demers et al. 2013) but performance improved with mooring depth.

Both engineering and perception issues also impacted on the effectiveness of the Massachusetts trial. Improperly installed systems uprooted the eelgrass, EFMs which were installed without subsurface buoys sank, resulting in the bottom shackles scouring the seafloor. Rodes which were improperly sized led to tangles, dragging, and further scour to the bottom and biofouling also sank the rodes, again leading to damage to the bottom. Finally, as subsidies were not continued and some owners and mooring contractors' perceptions were that EFMs were less safe, retention illegally dropped off in three harbours.

Grey literature reviews of EFMs have occurred multiple times in both NSW and QLD in attempts to initiate programs. Currently across the Australian Commonwealth, the most well developed EFM programs are in Queensland, through Healthy Land and Water, a Southeast Queensland (SEQ) not for profit natural resource management organisation and in Victoria, though Parks Victoria. These programs support more than 230 moorings in SEQ through an environmental offsetting program (Mooney et al., 2020), while Parks Victoria manages tens of public moorings, which they hire out to the public for cost recovery. No significant EFM roll-outs have occurred in other Australian states with the limited exception of some trial and localised EFM deployments in NSW, TAS and WA. Environment protection agencies of SA and WA recommended 'environmentally friendly' designs for new mooring installations, but do not define a particular design. Except for SEQ, it is noted that despite such a long period of development, EFMs remain a very minor components of Australian mooring fields.

3.3 Engineering

The following section is a detailed summary of all the EFM solutions found during our review. The different systems are grouped into categories depending on their method of converting and damping the energy acting on the mooring (see Appendix A for further information on mooring physics).

It should be highlighted that some systems have been more thoroughly observed than others in the literature, and that an absence of issues found on a system is not necessarily an endorsement; conversely, negative observations on a system do not necessarily mean that these issues occur at a higher rate than on traditional chain mooring systems. There was no literature found that defines true long-term operational challenges with reliable data for any of the mooring systems described. As such, the assessment is mostly qualitative, and workmanship or operational issues are addressed across all EFMs broadly. Design issues that are directly inherent to a particular design or mooring category are highlighted within their section.

Several literature sources have already compared some cost and operational findings of these systems at length, though may be out of date; as such, costing information is not summarised in this report (Bowman, 2008; DEEDI, 2011; Egerton, 2011; Marina Projects, 2011; RPS APASA, 2014; Urban Harbors Institute, 2013).

3.4 EFM Solutions

3.4.1 Buoyancy/Displacement Systems

Buoyancy/Displacement Systems work partially in an inverse manner to gravity systems. They convert kinetic energy into buoyant potential energy, working to pull a buoy down in the water column, in which time damping occurs mostly through viscous drag and friction forces. Moving the buoy (or other submerged object) laterally in the water column will also induce drag forces on the buoy, helping to slow down the system displacement and reduce the loading on the mooring system due to vessel displacement.

EzyRider (Advanced Mooring Technology)

The EzyRider system is a combination elastic and buoyancy system but is categorised here due to it being quite different from other elastic systems. The surface buoy moves along a stainless-steel shaft that at the top end is attached to the vessel pendant line, and at the bottom end is attached to a suspended chain that runs down to the anchor. The buoy keeps the system suspended. Elastic rubbers are connected to the base of both the buoy and the shaft (Figure 2). As the mooring tilts over, the buoy rises relative to the shaft and elongates the elastic, acting similarly to other elastic systems. However, the system is designed to limit the travel of the elastic rubbers; when the buoy hits the top of the steel shaft its travel is stopped, and any further tilt over on the mooring will submerge the buoy, further dampening the energy in the mooring system. This approach is quite unique, and there are no other systems with a similar arrangement. Another feature is that the elastic connections do not form part of the structural integrity of the system, and if they break the mooring is not lost. We speculate that this was an important design feature when the system was first designed (~1999) when elastomeric risers did not have broader scale use as they do today.

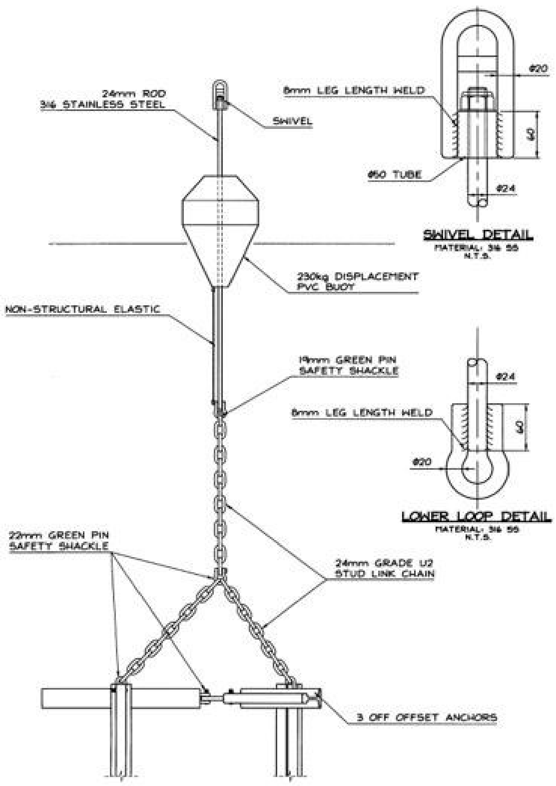


Figure 2 EzyRider Mooring System

Source: ezyridermooring.com; Copyright © Advanced Mooring Technology

Another point of difference with other elastic systems is that the EzyRider needs to be installed in a relatively taut configuration for the surface buoy to function effectively after full engagement of the elastic. The engagement of the buoy as a submerged object is more effective the more vertical the mooring is in the nominal state. This system appears to be quite sensitive to the depth of water; it has been deemed not suitable for areas with large tidal ranges and has had installation issues because of this in Australia (DEEDI, 2011; Egerton, 2011). Biofouling has also hindered the unique design aspect of this system previously, preventing the buoy from moving along the shaft (DEEDI, 2011). It is unknown whether either of these aspects have been addressed since the time of that report, though they are quite inherent to the design.

The EzyRider website claims that over 450 units have been installed around Australia, though this claim is quite old, appearing elsewhere as well (Bowman, 2008). There is evidence of installations in most areas of Australia.

At least one source incorrectly states that the cyclone mooring configuration (see 3.4.5) is similar to the EzyRider system – this is quite misleading. EzyRider sells an Offset Anchor System that has three embedment legs but is in no other way similar to a cyclone mooring configuration, and ecological or engineering results for cyclone moorings should not be ascribed to the EzyRider system, or vice versa.

It is not clear whether the EzyRider system is still commercially available – the company did not reply to our contact. The mooring system is quite unique and would be challenging to adequately analyse for the purposes of giving assurance to stakeholders. An alternative approach, such as a testing regime, could possibly address these concerns.

Subsurface Buoy System (generic)

Egerton (2011) developed an EFM proposal for a Welsh Council for trials off the coastal village of Porth Dinllaen and refers to two very similar (if not identical) systems: one called the 'Harmony System' and the other a 'Traditional Style with subsurface buoy and high tensile rope'. The Harmony anchor system is the steel coil anchor itself, and is specifically targeted for Posidonia meadows, to minimise any damage to the leaves or the plant rhizomes (Francour et al., 2006).

The subsurface buoy mooring system consists of an all-rope rode with a subsurface buoy that helps dampen the system as it moves under the vessel's motion. No sizing guidance for such a system was found and as such it was not included in the Porth Dinllaen trials.

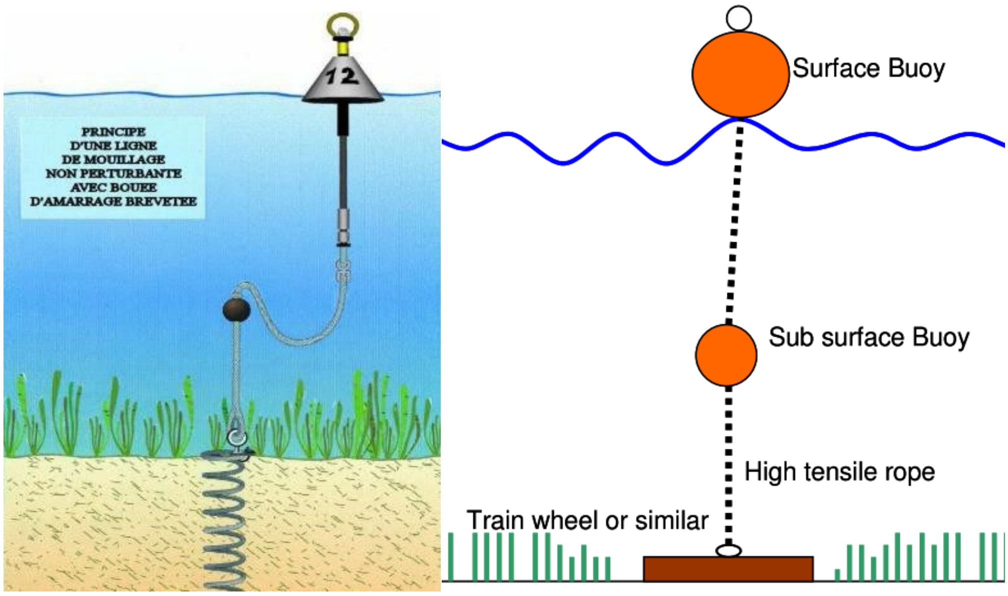


Figure 3 Harmony System / Traditional Style with subsurface buoy and high tensile rope

Source: Egerton 2011

Pacific Marine Group has installed a system they call the Grouted Screw System (DEEDI, 2011; Pacific Marine Group, 2017) with a similar layout, though it incorporates the anchor into the 'system' as well ('grouted anchors' are also detailed in Francour et al. (2006)). These have been installed extensively around the Whitsundays area, though there is no independent reporting available on these installations.

In the field of oceanographic moorings, the subsurface buoy configuration is quite common, usually going by the name of inverse catenary mooring (Grosenbaugh, 1996), S-tether mooring or slack mooring.

Whilst standard sizing guidance is not currently available for such a system, engineers routinely size these systems for bespoke applications in the marine science field (Martini et al., 2021), and assessing them for recreational vessels would be quite straightforward. Egerton (2011) specifically identifies this mooring type as possibly the cheapest solution available, but with no engineering guidance chose not to pursue it.

3.4.2 Chain Substitution Systems

Chain substitution systems typically replace the chain component of a catenary mooring with a neutrally or positively buoyant section. As such, they remove the mass in the system that makes gravity systems work, without replacing it with something equivalent to dampen shock loads. They can be used in very benign environments (and have had usage in coral beds in highly protected areas) but should not be considered for broad scale adoption due to the lack of shock absorption. Due to this, only a cursory overview of the systems described in the literature is given, with no further assessment.

Halas Mooring (generic)

The Halas system has been used extensively throughout the Florida Keys, named after the Florida Keys National Marine Sanctuary employee, John Halas, who pioneered the system. Over 100 moorings have been installed in the sanctuary alone, with reference to further installations worldwide (Reef Relief Founders, 2011; RPS APASA, 2014). The system has been used only with embedded anchors, due to it being targeted at coral areas. It is mostly an all-rope system, with a small weight used to ensure there is no floating line. Although not stated, the use of the weight implies that all the rope components are positively buoyant.

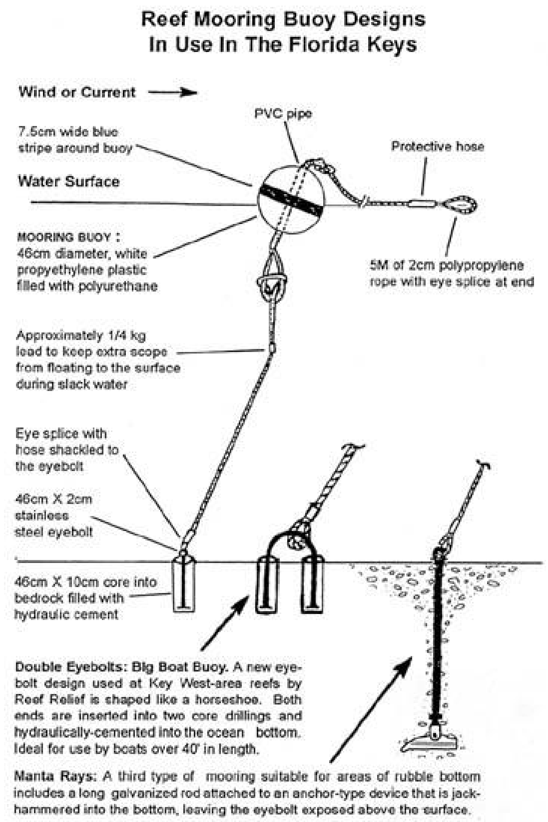


Figure 4 Halas Mooring System

Source: reefrelieffounders.com/key-west-reef-mooring-buoy-program.html

Literature on the system indicates that it is for solid substrates only, with the unique anchoring (Figure 4) considered part of the whole system, though for this assessment we are considering the mooring components only. There was minimal operational evaluation and no engineering data found on the system.

Sealite Synthetic Mooring (Sealite)

The Sealite Synthetic Mooring is a neutrally buoyant mooring strop intended to fully replace chain in a mooring system, being connected directly from an anchor to the moored item. It contains a nylon core surrounded by a vulcanised rubber casing. Its most common application is to moor Aids to Navigation, which do not require as much damping capability as small vessels.

Lynch et al. (2020) assessed the use of an entire mooring rode made from the Sealite (Black Snake) mooring strop for mooring vessels. It found that whilst shock loads were reduced in extreme weather compared to a traditional chain mooring, the loads were still higher than the safe working loads limits of the strop for the conditions assessed. In summary, the strop converts some of the vessel's kinetic energy into elastic energy, but not enough. Sealite do not claim this system to be highly elastic, but as a chain replacement. In the mooring of Aids to Navigation, Parks Victoria and Sealite have claimed quite long service usage of the strops compared to chain. This knowledge informed its usage as a component of the CSIRO ES Mooring (see 3.4.4).

Since the strop is not highly elastic it is not intended to be used taut and requires a large scope. Concerns have been raised about the possibility of the strop floating on the surface and being potentially cut by surface vessels (Steinbrecher and Lewandowski, 2018), which needs to be addressed if used. Evidence from CSIRO trials indicate the opposite, that biofouling may drag the strop to the bottom of the water column (Lynch et al., 2020).

3.4.3 Elastic Tether Systems (whole)

Elastic tether systems dampen the kinetic energy of a vessel by transferring it into elastic potential energy in the mooring rode. The longer the period of extension and contraction, the more energy can be dissipated. These systems are easy to analyse and determine their ability to moor a vessel securely, as long as the elastic behaviour of the components are known. If the manufacturer does not have this data available this can easily be found by bench testing. These systems can be utilised in either taut or slack configurations, though are often promoted to be used as taut due to the benefit of increased mooring density. In a taut configuration, they either require a permanent anchor (such as a screw or auger anchor) that provides high holding power in a more vertical direction or a large deadweight anchor that relies purely on its weight as it will receive less benefit from friction/embeddedness with the seafloor compared to longer scope moorings. However, all these systems can be used at longer scopes with lighter deadweight anchors.

Whole elastic systems are where the entire mooring rode stretches under load. It is not clear whether there is a preference for this type of system compared to a partial elastic system (see 3.4.4) in terms of mooring performance. One area where whole elastic systems may be unfavourable, compared to partial elastic systems, is the inability to lift the anchor using the rode itself, as there may be increased operational risk due to the stored energy within the rode if used as a lifting device.

Elastic systems (whole and partial) have been used in a variety of other applications such as pontoons/docks, wave monitoring buoys, navigational buoys and oceanographic buoys (Urban Harbors Institute, 2013). Suppliers of these systems have likely been able to gather operational feedback over a larger volume of units than other more targeted systems.

Eco-Mooring Rode (Boatmoorings.com)

The Eco-Mooring Rode is a single elastic rode with a high-stretch capability to lower mooring loads. It is available in a range of different diameters and lengths, and engineering data is also available to customise as needed. Typically, a small section of chain is used near the connection with the anchor, requiring a small float to raise this off the seafloor, though the company now sells the 'Eco-Mooring Shallow Water Tackle' which eliminates the need for chain near the anchor and incorporates a float around the mooring line (Figure 5).

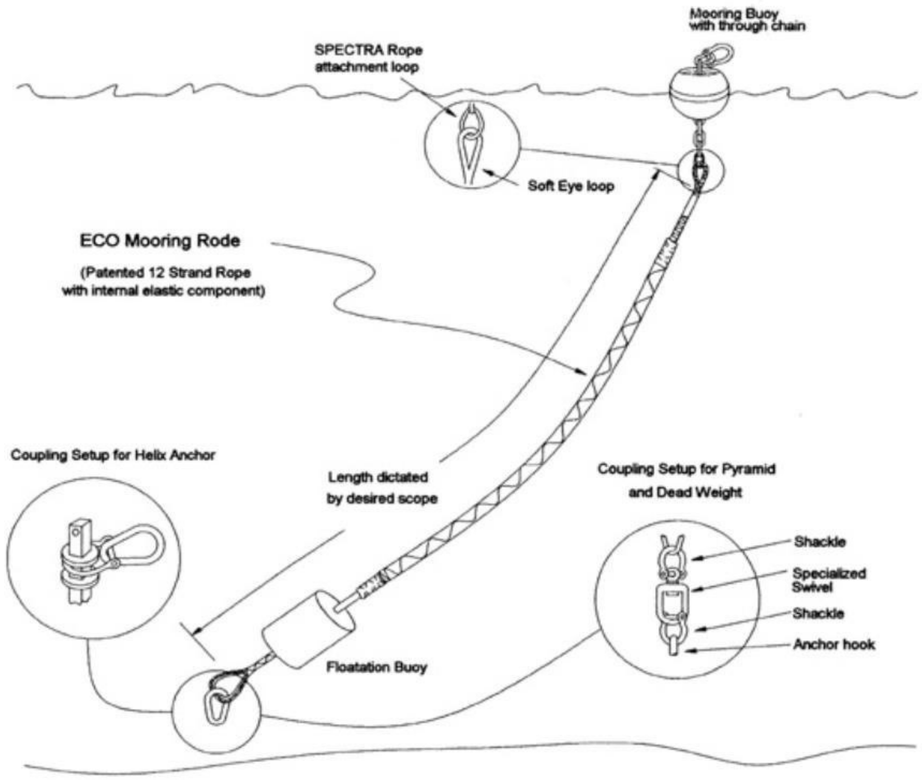


Figure 5 Eco-Mooring Rode Shallow Water Tackle

Source: boatmoorings.com; Copyright © Boatmoorings.com

Egerton (2011) specifically recommended the Eco-Mooring Rode (along with the Harmony system) due to its capacity to handle large tidal changes, a focus of the study in Porth Dinllaen, as well as relatively cheap unit prices (Urban Harbors Institute, 2013).

As of 2020, a variation of this system is being installed in Moreton Bay (under a different brand name, Enviromooring, from Waters Marine Pty Ltd). Though the exact numbers are unknown from the literature, the total number of EFMs installed in Moreton Bay is over 230 (Healthy Land and Water, 2020). The system was not originally installed when the Moreton Bay EFM trials were initiated, with prior reports not referencing the system (DEEDI, 2011; SEQC, 2015).

Boatmoorings.com is US based and it appears to have broad usage, though total numbers are unknown. It was included in the only known US review of EFMs for recreational vessels, in Massachusetts (Urban Harbors Institute, 2013). The manufacturer was approached for further information, but we did not receive a reply.

StormSoft Elastic Boat Mooring

The StormSoft elastic boat mooring features a 5 ft stretch component that utilises a small float to remain clear of the seafloor. It is then spliced into a longer section of rope to make a single piece mooring rode. The system is described as allowing limited stretch for shock loads (Steinbrecher and Lewandowski, 2018).

The StormSoft system is documented as being used for at least 10 years in Florida as of 2013 (Urban Harbors Institute, 2013) and trialled more recently in Tampa Bay for an EFM buoy mooring trial (Steinbrecher and Lewandowski, 2018). However, the StormSoft website (stormsoftboatmooring.com) is no longer online, and no engineering or other support data for the system was found.

3.4.4 Elastic Tether Systems (partial)

Elastic tether systems that utilise partial elastic components typically have a short section of a highly elastic component in combination with a positively or neutrally buoyant rope section, with all being lifted off the seafloor, often with the aid of subsurface flotation. The elastic component can have high elongation itself, improving the ability to dampen the energy in the mooring system, without changing the overall scope of the mooring significantly due to it being short in length.

Combinations that have been identified for use in the literature utilise the highly elastic components both near the anchor and near the surface buoy, with most manufacturers showing both configurations being possible. The CSIRO Environmentally Sensitive Mooring specifically uses a strop as a lifting device before connection to the elastic component, to facilitate anchor deployment and recovery using a service vessel and without divers. In this configuration, the elastic component can be brought on board the service vessel prior to lifting the anchor.

All these systems, like whole elastic systems, can easily be modelled and analysed for expected performance.

CSIRO Environmentally Sensitive Mooring (generic)

The CSIRO Environmentally Sensitive (CSIRO ES) Mooring is designed as a 3:1 scope mooring that can be installed with a deadweight anchor and utilise existing mooring operator’s infrastructure. It utilises a Sealite Black Snake strop at a 2:1 ratio to the water depth, combined with a nylon rope section to add elasticity to the mooring system. In terms of the different elastic systems covered, it is the lowest stretch solution. From a build perspective, it can be made from components that are available through any marine chandlery.

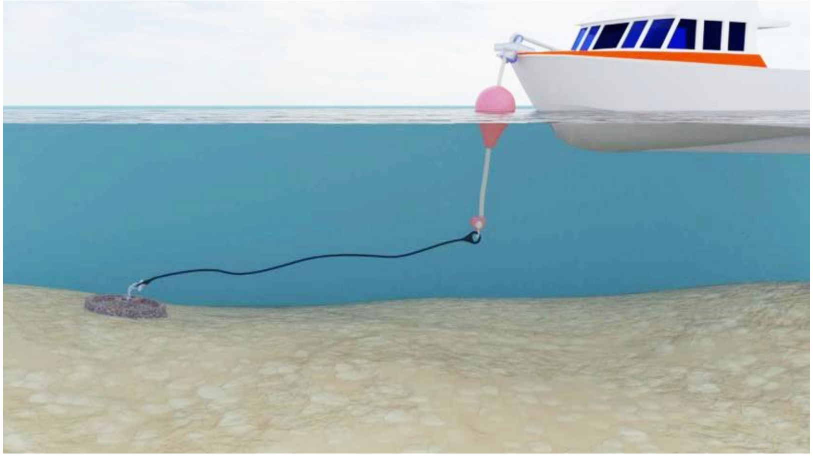


Figure 6 CSIRO Environmentally Sensitive Mooring

Source: CSIRO; credit – Derek Fulton

Lynch et al. (2020) showed that this system reduced peak loading in extreme conditions compared to a traditional chain mooring and the Sealite Synthetic Mooring configuration. In calmer conditions there is a higher load on the mooring compared to chain moorings. The design is different to other all rope solutions in that the nylon rope was explicitly sized to the stretch properties required to allow the system to function effectively under extreme conditions. Several rounds of servicing on this system have been undertaken that suggest that this EFM may have wear areas and rates that differ to traditional chain moorings. It is currently being trialled in Tasmania and operational results (see 3.5) are similar to other EFM systems (Wong et al. submitted). The paper also documents the engineering approach and potential differences in mooring behaviour between EFM and traditional chain moorings in light wind conditions.

Hazelett Elastic Mooring Rode (Hazelett Marine)

The Hazelett Elastic Mooring Rode is made from a polyurethane elastomer with pressed polyethylene thimbles, with no metallic components. It is available in four lengths and at two load ratings; to increase the load rating, multiple rodes are connected in parallel using Hazelett's Dockmaster System to suit requirements (Figure 7), before stepping up to the higher load rated elastomer. As such, unique sizing requirements for load and elongation can be achieved.

Figure 7 Hazelett Dockmaster System

Source: hazelett.com; Copyright © 2019 Hazelett Marine

One of the attractive features of the Hazelett rode is that it starts taking on load quickly with elongation, but then has a long extension as it nears the peak of its working load limit (see Appendix A.2). In theory, this feature should provide one of the lowest loadings of all the available systems in extreme conditions, whilst also having good calm condition performance as well with minimised vessel movement. Full engineering data and sizing tools are available from Hazelett's website. There are also claims that the rode's snapback (its unloading and reduction in length) is quite gentle, though this is unsubstantiated (Hinz, 2001).

The system is shown with the elastic rode always installed directly to the anchor. The company was contacted for comment on this aspect (along with other queries sent to all manufacturers) and have indicated that a system set up with the elastic rode connected to the surface buoy can be accommodated.

Like the Eco-Mooring Rode, it is US made, appears to have broad uptake, and was included in the Massachusetts review (Urban Harbors Institute, 2013) and reported to be in use in the Isle of Man (Egerton, 2011). First documented evidence of usage comes from 2001.

Marine Flex Elastic Mooring (Marine Flex)

The Marine Flex system uses rubber cords connected to a composite end housing. More cords can be added to match the needs of the mooring system, allowing tailored sizing.

The company has a long history that started with their own anchoring system and installing other EFM products. Their EFM system has been on the market since at least 2014 according to their own literature. No external engineering reviews of EFMs have investigated their product. The company supplied proprietary engineering data with claims of superior performance compared to competitors in terms of the elastic behaviour of their product, though this requires more interpretation outside the scope of this report and is not included in Appendix A2. Engineering support is available from the company to size their systems to specific applications.

The Marine Flex units can also contain a by-pass system that prevents over-extension of the rubber cords.

Safe-Moor

Safe-Moor is a mooring tether comprised of nylon, rubber and aramid (Kevlar) for the tether, and stainless-steel terminations. Tethers come in two lengths and can be suited to individual requirements by running multiple tethers in series and/or parallel using Safe-Moor's custom modular connectors. All necessary engineering information is on their website.

The company was founded by staff at Woods Hole Oceanographic Institute and have been deploying their elastomer technology on oceanographic moorings for over a decade (SafeMoor, 2020). There is no literature available on mooring vessels though this is an advertised use from the company. Safe-Moor did not respond to requests for further information.

Figure 8 Safe-Moor mooring tether

Source: safemoor.com; Copyright © 2020 SAFE-MOOR

Seaflex Mooring System (Seaflex)

The Seaflex Mooring System is one of the oldest systems on the market, with the company installing their first system in 1975 and clearly demonstrating a strong track record. Their units are predominately for floating dock applications (Urban Harbors Institute, 2013), though they have a strong history for swing mooring usage as well. Seaflex units contain multiple rubber hawsers connected at two end plates; the system also has a safety bypass system that takes up load before the hawsers reach their elastic limit (Figure 9). The unit can be scaled to unique load/displacement requirements by adding hawsers and increasing length as needed.

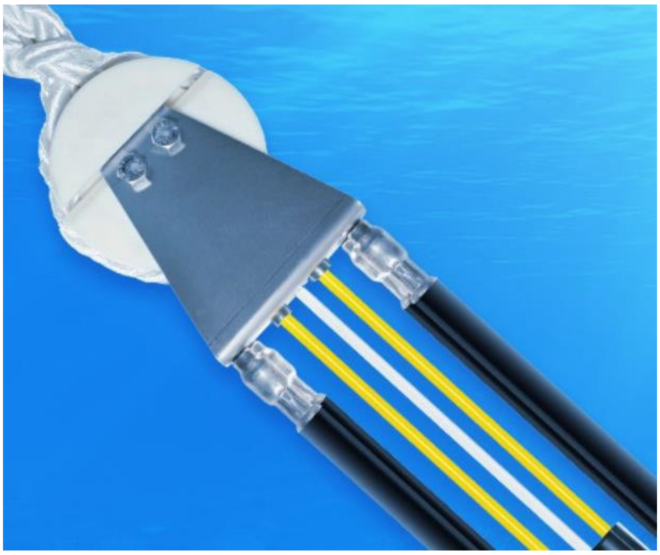


Figure 9 Seaflex Mooring

Source: seaflex.com

Several sources report both positive and negative results of the system, though the sources are nearly a decade old, with correspondence included from the company that they were addressing all issues (Bowman, 2008; DEEDI, 2011; Egerton, 2011). As mentioned above, rates of issues with any moorings have not been assessed as part of a systematic review, and the Seaflex mooring has been one of the most trialled EFMs.

Tevi (2021) and Stone (2022) reported favourable simulation results for the Seaflex that were comparable to their baseline chain catenary mooring, in terms of mooring loads under various environmental conditions. The elastic system was able to dampen loads in roughly the same manner with a much smaller watch circle. These two papers are based on the same simulations, though present slightly different datasets for results and discussions.

Like Marine Flex, engineering support is available from Seaflex to size their systems, though engineering data is proprietary (supplied to the author for analysis purposes). Also similar are claimed performance gains from the unique elastic properties of their system. The company was very responsive to queries.

Superflex Mooring System (www.supflex.com)

The Superflex Mooring System is similar to the Safe-Moor design, with multiple rubber components being used in parallel to achieve the required strength necessary for the mooring line. Superflex targets mostly large floating structures, and as such will not be considered for further investigation or usage. Only a single report contained evidence of deployment of the system (Steinbrecher and Lewandowski, 2018).

3.4.5 Gravity Systems

Gravity systems are those that use the mass of the mooring chain to dampen the dynamic forces created when a boat moves due to wind, current and wave forces, by converting kinetic energy into gravitational potential energy (i.e., it lifts a portion of the chain). As such, this category encompasses traditional block and chain moorings that are being targeted for replacement with EFMs. The systems described here therefore tend to be most closely aligned with existing chain moorings in terms of hardware and operational techniques (though cyclone moorings, as described below, are unique in their anchoring). Traditional chain mooring systems tend to be a long scope (typically 3:1) in order that the displacement of the vessel does not lift all of the available chain mass lying on the seafloor, otherwise damping is exhausted and shock loading occurs on the mooring system (Urban Harbors Institute, 2013). Scopes may be reduced in more sheltered areas when increased field density is desirable and in deeper water (Poiraud et al., 2008).

Gravity systems have predominantly used deadweight anchors, with the chain providing additional holding power and being used as the lifting device for retrieval and deployment of the anchor. However, they are not limited to this and can utilise fixed anchor points from screw anchors.

Cyclone Mooring (generic)

The cyclone mooring configuration (sometimes referred to as a multiple anchor single point mooring) is a chain catenary system that has three anchors instead of one. The anchor chains come together to a single point before the chain riser extends to the surface buoy. It is made from generic components and can utilise permanent or temporary anchors.

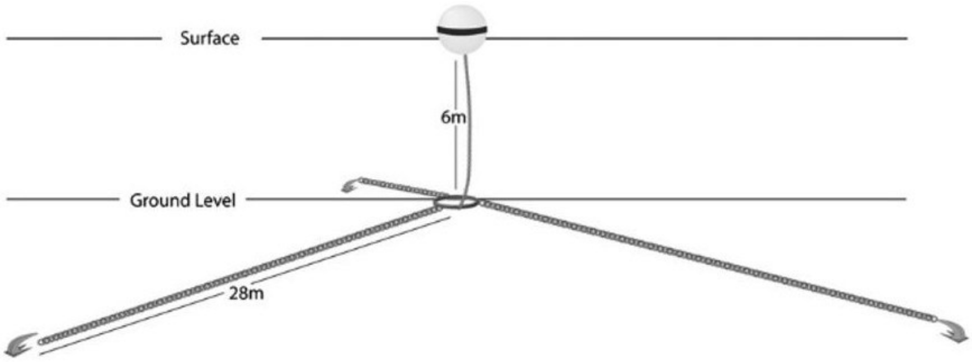


Figure 10 Cyclone Mooring schematic

Source: Demers et al. 2013; Copyright © 2012 Elsevier Ltd

This design therefore does not have the swing of a traditional single point mooring; however, it still has heavy anchor chain impacting the area. There is evidence that this mooring configuration should not be considered environmentally friendly (Demers et al., 2013; Hastings et al., 1995) though this contrasts with earlier literature (Walker et al., 1989).

The consistency as to what constitutes a cyclone mooring configuration has not been made within the previous three sources, or from other sources. No firm sizing guidance has been found; the issue of whether the ground chains are taut or slack, embedded or suspended is also not clear. Additionally, the analysis required to size this system is slightly more complicated than a system with components all serially connected, and so more specialised advice/analysis is needed for potential owners/operators than for other systems.

The system is more expensive than a traditional chain mooring due not only to the increased chain costs, but the multiple anchors and the operational requirements to place them correctly.

We are sceptical of the damping capability of this system compared to a 'standard' chain catenary mooring. The separate anchor chains are more restricted in how much they can rise in the water column (if at all), and therefore it is unknown how much of the vessel's kinetic energy can be transferred into potential gravitational energy before shock loading occurs. Shock loading would be spread between two anchors, which is considered a benefit of this system, however we consider it undesirable to reach shock loading in any mooring system due to vessel hardware concerns.

ECOMOORING (eco-mooring.com)

The ECOMOORING is a system with a suspended chain between a primary and secondary buoy. Only a schematic of the solution is available on the company's website (now obsolete).

It has been confirmed with the company owner that only a few initial trial versions of the system have been manufactured, without extensive testing at this stage. More information is required to assess whether the system can be adequately analysed using traditional mooring analysis methodology. No further assessment has thus been done given the bespoke nature of the system and its infancy, though it is a novel and unique approach which may merit further investigation in the future.

Stirling Advanced Mooring System (generic)

Luff et al. (2019) presented the Stirling Advanced Mooring System (SAMS), a chain catenary mooring with floats attached to the ground chain that lift it up out of the water column and prevent scouring of the seabed. This approach is unique, with no evidence found of similar approaches in the literature. The configuration is intended to address issues with other EFMs in high tidal zones.

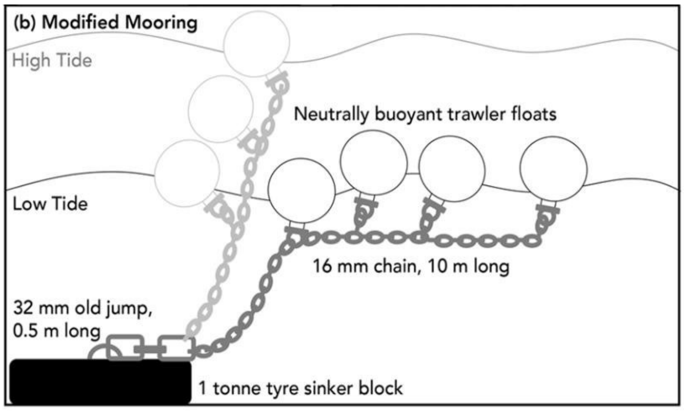


Figure 11 Stirling Advance Mooring Systems (SAMS) schematic

Source: Luff et al. 2019

A unique aspect of the system and its main characteristic is the ability to retrofit existing moorings for a relatively cheap price and using existing operational techniques. The system is made from commercially available non-proprietary components. Both deadweight and screw anchors can be utilised, though in practice it would be likely that most would use deadweight anchors.

As far as can be determined, the system has only been tested in a small number of cases and does not yet have a large uptake. This solution is relatively new, with results describing the ecological benefits of the configuration in comparison to a traditional block and chain mooring. Whilst it defines the chain components used in the mooring set up (and in the comparison 'traditional' set up), it does not establish the sizing of the flotation components, nor the performance of the system from an engineering performance perspective. The adaptation for the single mooring in the study cost £120, with foreseeable future hardware and maintenance costs comparable to an existing mooring system. The mooring configuration also met the current insurer's existing policy requirements. The trial involved the conversion of a single block and chain mooring to the SAMS configuration for assessment.

Tevi (2021) and Stone (2022) assess the engineering performance of the SAMS system using engineering modelling with the Orca Flex FEA software package, considered the gold standard in mooring analysis. The key finding of these reports is that the SAMS system leads to increased loads throughout the mooring system compared to a traditional chain mooring under all conditions and vessels analysed. With a lower gravitational potential energy being able to be transferred due to the partial lifting of the chain, less dampening of the mooring forces will be accomplished with this arrangement.

Both reports argue for sizing optimisation to be undertaken for the SAMS system, and to replicate the analytical work with field trials to verify the analyses. The sizing and analysis of the SAMS configuration would be a relatively simple process if this configuration is pursued for further investigation.

3.4.6 Spring/Shock Absorber Systems

Spring systems, or shock absorbers, work by compressing a spring as the mooring line is extended. One half of the system pulls through the other half to compress the spring material, similar to the compression of a shock absorber, though this system is extending whilst compressing the spring. The SeaSpring (described further below) shows this mechanism well (Figure 12).

Figure 12 Marine SeaSpring relaxed (left) and extended (right)

Source: tfimarine.com

These components are used similarly to the small elastic components in the partial elastic tether systems, though they typically have a shorter working length. Since engineering data has not been found (or received) for any of the systems described below, it is difficult to assess the working loads and characteristics of these systems. Both the Seaflex Spring and the SeaSpring appear to be largely targeted towards the offshore wind market, where increased engineering investment for a single installation can be easily justified.

Similar to elastic systems, spring systems can be modelled in engineering software that allows non-linear spring rates to be incorporated into the definition of the mooring components. It is not clear on these systems (with the exception of the SeaSpring) how larger or smaller vessels are handled – each solution seems to have only one configuration, and no load/elongation data is available to assess.

Seaflex Spring (Seaflex)

The Seaflex Spring is quite similar to the SeaSpring in both the way it works, and its targeting and adoption within boat moorings, which appears to be minimal at best. Seaflex is largely known for their Seaflex Mooring System, and the market positioning of the Seaflex Spring is not clear; it is advertised on their website primarily for pontoons, but also mentions mooring vessels. Seaflex confirmed that the SeaSpring makes up only around 3-4% of their production (in terms of units manufactured) compared with the Seaflex Mooring System. No engineering data is available for the system.

Seagrass Friendly Moorings – Mooring in a Bag (On Water Marine Services)

On Water Marine Services currently advertises the Mooring in a Bag system under the broader name of the Seagrass Friendly Mooring. It consists of a UV stabilised polypropylene/polyethylene riser connected to a foam filled buoy that also houses a shock absorber. A pickup line is attached to the top of the buoy (Figure 13). The system can be installed with a range of anchor types.

Figure 13 Mooring in a Bag from Seagrass Friendly Moorings

Source: seagrassmooring.com.au; Copyright © 2021 On Water Marine Services Pty Ltd

This system seems to have replaced the original Seagrass Friendly Mooring system (see below) at some stage, though when is not clear. Most literature up to 2013 refer to the original system, though Bowman (2008) refers to the 'cheaper design' of the Seagrass Friendly Mooring. Starting with SEQC (2015) there is clear mixed referencing to these systems (this report contains a picture of the Mooring in a Bag system), and it is difficult from this time to discern in the literature which system is being referred to.

We did not receive a response from a request for information from the supplier. According to Healthy Land and Water the company has been sold recently, and Healthy Land and Water are not currently using their product in Moreton Bay.

Seagrass Friendly Moorings – Original (On Water Marine Services)

The Seagrass Friendly Mooring system is one of the earliest known Australian designs to be used throughout Australia. No evidence was found of use of the system internationally. The original system used a custom helix anchor, with the shock absorber contained in a stainless steel housing connecting directly to the anchor post and able to pivot to face any direction.

This system has been extensively used in Moreton Bay, though the exact numbers of this and the superseding system is difficult to determine, being mixed with other EFMs. The total number of EFMs installed in Moreton Bay is over 230 (Healthy Land and Water, 2020). At least 45 have also been installed in Port Stephens – Great Lakes Marine Park for marker buoys and light duty boat moorings (Bowman, 2008). There are also installations in Jervis Bay.

Again, no response was given from On Water Marine Services on this system, and it is believed to be obsolete based on their current website.

SeaSpring (TfI Marine)

TfI (Technology from Ideas) Marine manufacture the SeaSpring, mostly targeting the Floating Offshore Wind Technology (FOWT) sector. Their website (https://www.tfimarine.com/) lists their smallest unit (D200) as applicable to small vessel mooring systems, though no literature was found demonstrating this application; case studies available on the site only target FOWT applications.

The company was contacted for input with no reply. The different available units suggests that an appropriately sized unit could be found for different vessel sizes if the engineering data was available.

3.5 Engineering/Operational Considerations for EFMs

3.5.1 Engineering Data and Analysis

Almost all real-world trials of EFM point to a lack of engineering and operational support in the system design and deployment. There are numerous reports of components not being at the right length for the application, lines that were meant to be taut but were slack, systems that were undersized or oversized for the application, etc. (DEEDI, 2011; Egerton, 2011; Steinbrecher and Lewandowski, 2018; Urban Harbors Institute, 2013).

Some reports have included anchor pull tests as part of their assessment, though only one report (Urban Harbors Institute, 2013) correctly identifies that different mooring systems will react different loads back to the anchor for the same vessel and environmental conditions, and as such a pull test is only a good test of the anchoring system itself.

Engineering data from different manufacturers is also not to any standard, and comparisons across systems is difficult to make for non-technical stakeholders. The few reports that have been able to assess engineering performance adequately, have shown that some EFM systems are able to dampen loads as effectively or better than traditional chain moorings (Lynch et al., 2020; Tevi, 2021) and more engineering investigations should occur to assess other available EFMs.

3.5.2 Engineering and Operational Benefits of EFMs

There are potential benefits to using EFMs from an operational and owner's perspective. The two main ones are lower ongoing maintenance costs due to the longer service life of many synthetic components compared to chain and the reduction in shock loading on vessels in extreme conditions, a major contributor to broken moorings (Lynch et al., 2020; Sealite, 2019; Tevi, 2021; Urban Harbors Institute, 2013). These benefits require broadscale communication with stakeholders to increase take-up and dispel misconceptions around EFMs and their suitability.

3.5.3 Engineering Issues to be addressed

There are several issues reported in the literature on EFMs that should be addressed with additional engineering support and operational expertise. These issues are relevant to all types of moorings, including chain moorings, but should be a particular focus of any trials due to slight differences. These include:

- Designing out the potential for floating components in the mooring system
- Reducing excess vessel motion by ensuring a properly damped system

- Reducing electrolysis/corrosion issues by matching the anodic index of metals appropriately, and the proper use of anodic protection
- Reducing chafing of rope components over bow rollers
- Having robustness in the mooring system and guidelines for operators to modify systems appropriately for unexpected changes, like water depth and tidal variation

3.6 Mooring Trial Criteria

The following criteria were used to assess whether a mooring system should be considered for future trials:

Shock Capacity

Any replacement for chain moorings should have a similar or better capability to withstand shock loading, with any systems that have a lower capacity being deemed unsuitable for trials. Shock loading can result in vessels breaking free of their moorings, for example with shock loads being higher than the capability of mooring cleats that hold the mooring to the vessel.

Anchoring Flexibility

The ability to anchor the mooring system with both deadweight and permanent (screw) anchors allows flexibility for multiple environments, operators, regulations and client preferences.

Engineering Methods and Data

We have made every effort to determine how the system would be analysed in standard mooring analysis software, and whether the necessary information is available from the manufacturer. Additional testing could be conducted to gain this information but would be an increased cost, and it is the authors' view that this responsibility should be with the manufacturer.

Track Record & Availability

Evidence of existing usage or a track record of performance or engineering study is required. For bespoke manufactured systems, we also required confirmation from the manufacturer that they are still manufacturing a viable product.

Large tidal range or flooding

Engineering analysis of mooring configurations should assess tidal or flooding extremes for the given configuration and environmental conditions. It is interesting therefore that few papers in the literature have addressed options to solve highly variable depth range issues for EFMs.

Combinations of floating and sinking components can be used to ensure that 1) mooring components are not hitting the seafloor, and 2) mooring components are not floating on the surface. The Stirling Advanced Mooring System provides an example of this approach using subsurface flotation, but we are concerned that this system lacks shock absorption. The CSIRO ES mooring is another system that uses sinking line and sub-surface floatation to cope with varying water depths.

3.7 Mooring Trial Recommendations

All EFMs were assessed to the above criteria and a breakdown of the assessment for each EFM is shown in Table 1. The following are recommended for preliminary analysis and trials:

- CSIRO ES Mooring
- Hazelett Elastic Mooring Rode
- Marine Flex Elastic Mooring
- Seaflex Mooring System

Whilst these four systems all come from a single category of EFMs (partial elastic tether systems), this category is viewed as including the most flexible systems in terms of operational parameters, and these EFMs have sufficient difference in their elastic properties and build philosophy as to provide a point of differentiation in any testing.

A further step before testing these systems would be to verify analytically if any of the benefits of displacement systems (i.e., submerged buoyancy) can be added to the above four EFMs before physical testing.

Table 1 Environmentally Friendly Mooring Assessment

Category	Product / Type	Shock Capacity	Anchoring Flexibility	Engineering Methods & Data	Track Record & Availability	Recommend for Trial	Rationale
Buoyancy/ Displacement	EzyRider	?	N	N	?	N	Unique and difficult to assess. Learnings are not as translatable to other systems. Bespoke anchoring system.
Buoyancy/ Displacement	Subsurface Buoy System	?	Y	Y	Y	Y	In combination with CSIRO ESM and potentially other EFMs. Needs further analysis to confirm effectiveness.
Chain Substitution	Halas Mooring	N	Y	Y	Y	N	No shock absorption.
Chain Substitution	Sealite Synthetic Mooring	N	Y	Y	Y	N	Insufficient shock absorption as a complete rode.
Elastic Tether (whole)	Eco-Mooring Rode	Y	?	Y	Y	N	Lifting anchor and highest stretch of all solutions are both concerns. If concerns were dispelled could reconsider.
Elastic Tether (whole)	StormSoft Elastic Boat Mooring	Y	?	?	?	N	Unclear who manufacturer is. Stormsoftboatmooring.com is no longer online.
Elastic Tether (partial)	CSIRO Environmentally Sensitve Mooring	Y	Y	Y	Trials only	Y	Known results, comparison point for longer stretch solutions.
Elastic Tether (partial)	Hazelett Elastic Mooring Rode	Y	Y	Y	Y	Y	Load/elongation profile is very appealing.
Elastic Tether (partial)	Marine Flex Elastic Mooring	Y	Y	Y	?	Maybe	Evidence of prior use not found in primary literature. Engineering data supplied for analysis.
Elastic Tether (partial)	Safe-Moor	Y	Y	Y	?	Maybe	Developed from an offshoot of WHOI, with history of elastomers in oceanographic moorings. Evidence of prior use not found in literature. Contact with company not established.
Elastic Tether (partial)	Seaflex Mooring System	Y	Y	Y	Y	Y	Longstanding product/track record. Engineering data supplied for analysis.
Elastic Tether (partial)	Superflex	Y	Y	Y	?	N	Not targeted for small vessels.
Gravity	Cyclone Mooring / Multiple Anchor Single Point Mooring	?	N	?	Y	N	Unproven, possibly detrimental environmentally.
Gravity	Ecomooring	?	Y	?	N	N	Not in production.
Gravity	Stirling Advanced Mooring System	N	Y	Y	Trials only	N	Shock absorption results in Tevi show further engineering development is needed.
Spring/Shock Absorber	Seaflex Spring	Y	Y	?	?	N	Not targeted for small vessels.
Spring/Shock Absorber	Seagrass Friendly Mooring - Mooring in a bag	Y	Y	?	?	N	No engineering information from supplier to model.
Spring/Shock Absorber	Seagrass Friendly Mooring - Original	Y	N	?	?	N	Bespoke anchoring system.
Spring/Shock Absorber	Tfl SeaSpring	Y	Y	?	?	N	No engineering information from supplier to model.

4 Conclusion

Potential reasons for a lack of more general uptake of EFMs may be due to their unknown engineering integrity, as well as their potential to cause collisions in mix fields due to differing behaviours between EFM and chain catenary mooring designs (Lynch et al 2020; Wong et al submitted). Other barriers to uptake may include previous design failures, complex deployments and servicing, perceived higher capital and servicing costs, or market and/or warranty failures with servicing restrictions related to propriety products. These barriers, however, have mostly been identified by this study's authors from limited qualitative conversations with stakeholders.

There is a general lack of quantitative understanding of social and economic attitudes and drivers around and toward EFMs. A partial exception to this is a recent assessment of behavioural and social responses by UK power boat owners to an EFM trial in England (Parry-Wilson et al., 2019). This study, however, was very small scale and only investigated attitudes towards public moorings which are seasonally made available to boaters. A larger scale social and economic study is currently underway with Tasmanian mooring licence holders.

Many of the descriptive papers of damage call for top-down policy direction to address damage from moorings (Glasby and West, 2018; Parry-Wilson et al., 2019). However, studies from the USA and Italy (Kelly et al., 2019; La Manna et al., 2015), described that when a policy was introduced, such as banning mooring/anchoring, it caused conflict between government agencies and the boating community, as well as enforcement issues. Mandating for EFMs has occurred in some jurisdictions. In Portland, Maine, USA, any new mooring installed in seagrass must be an EFM and all moorings in seagrass must either be converted to a EFM or removed (Portland Harbour Board, 2023).

In addition to the gap in social science and economic understanding, there is a significant lack of research into EFM engineering, dynamic performance, and servicing, despite the varied range of systems available. In this literature review, no EFM standards were found, and EFMs were only classified as such by the manufacturer. Despite EFMs being widely recommended in the scientific literature, only a small fraction of these (3 out of the 65 sources) define what an EFM is or suggest specific mooring designs.

While EFMs have the potential to provide significant ecological restoration, biodiversity conservation and mitigation of climate change via carbon sequestration, there are no clear pathways to provide market-based or other incentives for uptake.

There may be considerable challenges in progressing EFM uptake in the medium term due to lack of knowledge and understanding by boat owners and contractors around the engineering, cost, usability, and maintenance.

We suggest that future research of EFMs should take a multi-disciplinary approach rather than exclusively focusing on environmental impact considerations. Considering the gaps in the current literature, this should include:

1. Engineering and servicing assessments of EFMs to clearly define and independently assess performance beyond commercial testing provided by manufacturers, including both modelling and instrumenting vessels to assess dynamic behaviour.
2. Studies of perceptions and socio-economic drivers of important stakeholders (a funded study of licensee perspectives is currently underway in Tasmania).
3. Development of education and outreach programs for EFMs across stakeholder groups (regulators, contractors, and vessel owners).
4. Conducting EFM impact and performance studies that include a high level of replication across multiple geographic regions and follow the BACI (Before-After-Control-Impact) design framework.
5. Experimental designs that compare recovery rates of both biodiversity and biogeochemical processes, such as carbon sequestration, following replacement of chain catenary moorings with EFMs.
6. Research that occurs over multi-year time scales, at a high species biodiversity resolution, across multiple habitat types (both vegetated and non-vegetated benthic habitats) and depth ranges.

Appendix A Mooring Physics – Energy, Work and Comparing Elastic/Spring EFMs

A.1 The Mooring System and Forms of Energy

To understand how effective EFMs may be from an engineering perspective, it's important to understand the role of the mooring system with relation to the energy within the system. In addition to the requirement to hold a vessel on station, the mooring system must take the kinetic energy of the vessel (motion due to waves, wind and current forces) and dissipate that energy into another form to dampen the motion of the vessel. For example, on a traditional chain mooring, the kinetic energy of the vessel is transformed into gravitational potential energy in the mooring chain (the mooring chain mass is lifted), which then transmits back into kinetic energy as the chain drops and pulls back on the vessel. Over this period of transformation, kinetic energy of the water is also created (surrounding water is being displaced by the mooring) with viscous drag and friction created during these transformations, helping to dissipate the overall energy in the mooring system. If energy is not dissipated effectively, then large forces can be transmitted fully along the entire mooring line. For a chain mooring, this occurs when the chain is fully lifted or untrenched off the bottom and there is still kinetic energy that needs to be reacted. This now taut configuration results in shock-loading, and high mooring line loads are experienced along all points of the mooring system, on the vessel deck hardware, the mooring rode components and on the anchor.

The entire interaction is somewhat more complex than this, but this basic explanation provides context for further discussion on each of the categories of moorings and why they should (or should not) be considered effective in mooring a vessel safely. The definitions below should assist in this understanding:

Kinetic Energy – *"the kinetic energy of an object is the energy that it possesses due to its motion."*

Gravitational Potential Energy – *"associated with gravitational force, as work is required to elevate objects against Earth's gravity. The factors that affect an object's gravitational potential energy are its height relative to some reference point, its mass, and the strength of the gravitational field it is in."*

Elastic Potential Energy – *"is the potential energy of an elastic object that is deformed under tension or compression. It arises as a consequence of a force that tries to restore the object to its original shape. If the stretch is released, the energy is transformed into kinetic energy."*

Damping – *"is an influence within or upon an oscillatory system that has the effect of reducing or preventing its oscillation. In physical systems, damping is produced by processes that dissipate the energy stored in the oscillation."*

Examples of damping include:

Viscous drag – *“a liquid's viscosity can hinder an oscillatory system, causing it to slow down”*

Frictional losses – *“friction dampens the system and can cause the oscillations to gradually decay in amplitude towards zero or attenuate.”*

Heat dissipation – *“A shock absorber does this by converting the kinetic energy of the shock into another form of energy (typically heat) which is then dissipated.”*

Another form of energy that can be described is *buoyant potential energy*. When a buoyant object displaces a body of water, the work required to pull that buoy down (or raise the water up) is a form of potential energy. Just like gravitational potential energy, this is energy in a stored manner – if we let a submerged buoyant object free it will accelerate and rise to the surface, just as a suspended object that contains gravitational potential energy will accelerate and fall to the ground when dropped.

A.2 Elastic Properties of EFMs

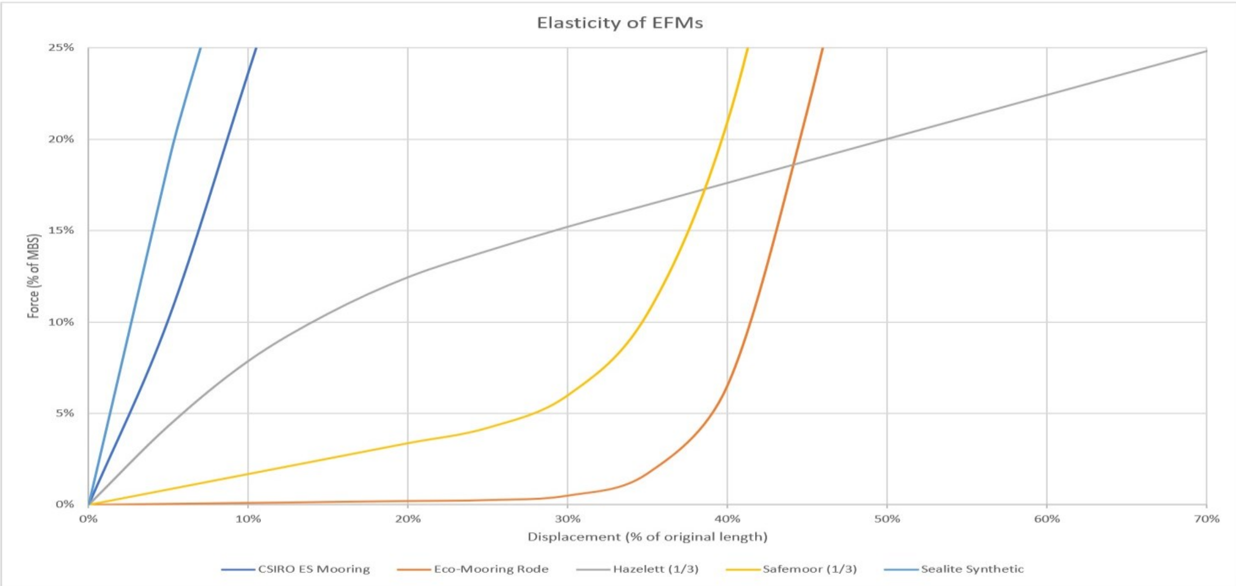
The concept of energy in physics also relates to a concept called *work*. Work is a measure of the energy transferred from one form to another, and for elastic or spring systems this is effectively force x displacement. When looking at force/displacement graphs of different elastic or spring tethers (Fig. A.1), the area under the curve represents the work done. A tether that produces more work will dampen forces better.

Literature that discusses the ‘high buffering capability’ of chain moorings are effectively talking about this same concept, the amount of work a chain mooring can do. The force required to displace a chain mooring and continually lift it higher and higher represents a lot of work being done on the chain and is why it performs so well from an engineering standpoint.

Figure A.1 graphs the force versus displacement for various EFMs, with both expressed as percentages of maximum breaking strength and original length, for comparative purposes. For the partial elastic systems, it has been assumed that the elastic component makes up 1/3 of the mooring system, with a relatively rigid component making up the other 2/3 – please note that this might be different for different systems, and so this is preliminary only.

As you can see in the figure, the systems that we have data on work in very different ways, and more should be done to investigate the optimum configuration for each and compare their ‘buffering’ capability. As an example, the behaviour of the Hazelett Elastic Mooring Rode looks quite advantageous – it requires a relatively high force at an early displacement, and then a continued high force to increase the displacement. A lot of work is thus performed.

We can also compare the long stretch of the Eco-Mooring Rode to the short stretch of the CSIRO ES Mooring. Whilst the Eco-Mooring Rode stretches substantially more, it’s not doing that much more work – it stretches ~30% before really starting to react any force. It likely creates, however, more problems in a mixed mooring field due to its high stretch without significant gain.



Apx Figure A.1 Elastic Properties of Different EFMs

(All data sourced from company websites, with reinterpretation for comparison)

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