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Current extent and future opportunities for living shorelines in Australia

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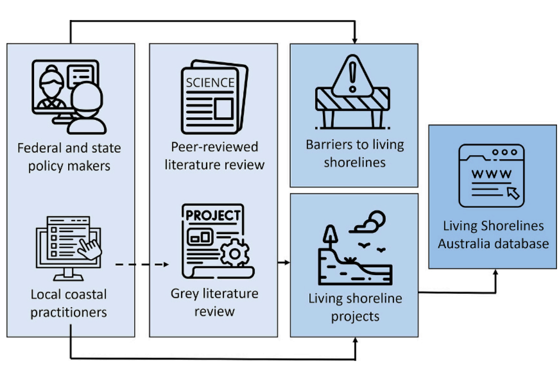
HIGHLIGHTS

- The application of living shorelines is not well-captured in scientific literature.
- Projects were extracted from a survey and interviews with coastal practitioners.
- At least 178 linear kms of living shorelines through 138 projects have been installed.
- The database contributes to knowledge sharing globally to develop best practice.

GRAPHICAL ABSTRACT



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A B S T R A C T

Living shorelines aim to enhance the resilience of coastlines to hazards while simultaneously delivering co-benefits such as carbon sequestration. Despite the potential ecological and socio-economic benefits of living shorelines over conventional engineered coastal protection structures, application is limited globally. Australia has a long and diverse coastline that provides prime opportunities for living shorelines using beaches and dunes, vegetation, and biogenic reefs, which may be either natural ('soft' approach) or with an engineered structural component ('hybrid' approach). Published scientific studies, however, have indicated limited use of living shorelines for coastal protection in Australia. In response, we combined a national survey and interviews of coastal practitioners and a grey and peer-reviewed literature search to (1) identify barriers to living shoreline implementation; and (2) create a database of living shoreline projects in Australia based on sources other than scientific literature. Projects included were those that had either a primary or secondary goal of protection of coastal assets from erosion and/or flooding. We identified 138 living shoreline projects in Australia through the means sampled starting in 1970; with the number of projects increasing through time particularly since 2000. Over half of the total projects (59 %) were considered to be successful according to their initial stated objective (i.e., reducing hazard risk) and 18 % of projects could not be assessed for their success based on the information available. Seventy percent of projects received formal or informal monitoring. Even in the absence of peer-reviewed support for living shoreline construction in Australia, we discovered local and regional increases in their use. This suggests that coastal practitioners are learning on-the-ground, however more generally it was stated that few examples of living shorelines are being made available, suggesting a barrier in information sharing among agencies at a broader scale. A database of living shoreline projects can increase knowledge among practitioners globally to develop best practice that informs technical guidelines for different approaches and helps focus attention on areas for further research.

1. Introduction

Climate change and continued coastal population growth are accelerating the demand for coastal structures that mitigate the risk of erosion, flooding and inundation (Hinkel et al., 2014; Morris et al., 2020). This coastal hazard risk has been projected to increase by up to 50 % by 2100 under future climate change scenarios, driven primarily by sea level rise and a change in the frequency and/or magnitude of storm events (Kirezci et al., 2020). Management of erosion, flooding and inundation has commonly used coastal protection structures that include seawalls, revetments and breakwaters. The use of conventional engineered structures has led to significant coastal hardening, and replacement of up to 70 % of natural shorelines in some urban areas globally (Lai et al., 2015; Waltham and Sheaves, 2015; Gittman et al., 2016; Bugnot et al., 2021; Claassens et al., 2022). Armouring of natural shorelines has considerable environmental costs as ecosystems such as saltmarshes, mangroves, seagrasses, reefs and dunes are displaced and fragmented (Goodsell et al., 2007; Gittman et al., 2016; Bishop et al., 2017). Hard structures are also non-adaptive in that they need to be maintained, replaced or upgraded at significant economic cost as the structures reach the end of their design life if damaged by storm events (Gittman et al., 2014). Although hard structures will continue to have a place in coastal protection, alternative methods that build coastal resilience and restore the function of natural shorelines should be more broadly adopted in the future where appropriate.

"Living shorelines" or "nature-based coastal defences/protection" (Bilkovic et al., 2017; Morris et al., 2018) may be important for climate adaptation and mitigation because of their ability to both reduce the risk of coastal hazards (Duarte et al., 2013; Ferrario et al., 2014) while also providing co-benefits such as carbon sequestration (Carnell et al., 2022), water filtration, biodiversity and fisheries provision, and tourism (Barbier et al., 2011; Isdell et al., 2021). Topographically complex ecosystems created by the habitat-forming species in dunes, saltmarshes, mangroves, seagrasses, and biogenic reefs provide coastal protection through wave attenuation and sediment stabilisation (Duarte et al., 2013; Morris et al., 2021a). These same coastal ecosystems already are degraded in many locations owing to habitat loss through shoreline armouring, and other stressors such as overharvesting and pollution (Beck et al., 2011; Goldberg et al., 2020). Living shorelines either restore the natural habitat alone ("soft" approach) or pair restoration with engineered structures ("hybrid" approach) for the purpose of habitat recovery, coastal protection and resilience (Table 1). Both conventional and nature-based structures may provide shoreline protection through either being able to withstand a 1-in-X annual return period environmental event, or through gradually building resilience (e.g., through shoreline accretion) over time, which then reduces the impact of the 1-in-X event. Given that natural systems can often self-repair after storm events (Gittman et al., 2014) and potentially have the capacity to adapt to changes in climate (Rodriguez et al., 2014; Sasmito et al., 2016), in addition to providing other ecosystem service co-benefits, living shorelines offer many advantages over conventional engineered structures (Feagin et al., 2021).

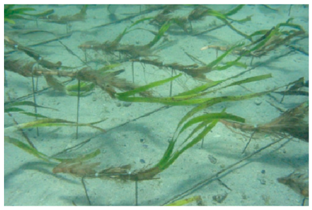
Despite the potential ecological and socio-economic benefits of living shorelines, large-scale applications (i.e., hundreds of metres at multiple sites) tend to have focused on a few regions globally (e.g., east coast United States and the Netherlands; Morris et al., 2018). One challenge to be addressed is how to translate a growing body of scientific and engineering knowledge on the performance of different shoreline protection options (e.g., Reguero et al., 2018; Smith et al., 2018; Strain et al., 2022) into effective action (DeLorme et al., 2022) across diverse types of coastlines found worldwide. Furthermore, there is increasing top-down pressure as policy changes that require greater integration of living shorelines into coastal hazard mitigation become more common (Morris et al., 2019a; Jones and Pippin, 2022). In some jurisdictions, the complexity of responsibility for shoreline protection across different levels of government can make implementation challenging especially without specific expertise (Wainwright and Verdon-Kidd, 2016; Harvey and Smithers, 2018). Furthermore, guidance is often lacking on how coastal practitioners should design and implement living shorelines (Holmes and Butler, 2021). Coastal practitioners have varied backgrounds and expertise and can include professionals from government, consulting and academia with a vested interest in the coast. Because conventional hardened structures have been used as a standard for many years, adoption of living shoreline solutions has been slow (Kabisch et al., 2016; DeLorme et al., 2022). In some cases, living shorelines have been promoted at a local scale (i.e., local government area or catchment) by individuals or organisations that have a particular interest in integrating nature-based solutions to improve coastal resilience to hazards (Morris et al., 2019a). However, without a central organisation or repository for data and/or case studies on existing living shorelines, lessons learned from local-scale projects are not recorded or shared. This lack of information transfer is also a barrier to broader uptake (DeLorme

Table 1
Examples of living shoreline methods applicable to Australia (adapted from Morris et al., 2021a). 1a © MidCoast Council; 1b © Queensland Government; 2a © Teresa Konlechner; 2b © City of Gold Coast; 3a © OzFish; 3b © Fish Habitat Network; 4a and b © Rebecca Morris; 5a © Jennifer Verduin; 5b © Estuary Care Foundation; 6a © Tristan Graham; 6b © Craig Johnson; 7a © OceanWatch; 7b © Ralph Roob; 8a © Emma Camp; and 8b © City of Gold Coast. Note the table below is to illustrate suitable living shoreline approaches, not all the included projects had a coastal protection objective.

Ecosystem	(a) Soft approach	(b) Hybrid approach
(1) Beaches	 Sand nourishment (Jimmys Beach, NSW)	 Tweed Sand Bypassing (Gold Coast, QLD)
(2) Dunes	 Dune planting and fencing (Port Phillip Bay, Melbourne VIC)	 Dune with rock core (the 'A-line', Gold Coast QLD)
(3) Saltmarshes	 Hydrological restoration and fencing (Pitt Water-Orielton Lagoon, TAS)	 Rock fillet protecting saltmarsh (NSW)
(4) Mangroves	 Mangrove planting (Western Port Bay, VIC)	 Mangrove planting in pods (Western Port Bay, VIC)

(continued on next page)

Table 1 (*continued*)

Ecosystem	(a) Soft approach	(b) Hybrid approach
(5) Seagrasses	 Seagrass transplants (Cockburn Sound, WA)	 Seagrass transplants behind bagged shell (Port Adelaide River, SA)
(6) Kelp forests	 Juvenile kelp transplants (Port Phillip Bay, VIC)	 Adult kelp transplants onto artificial reef (TAS)
(7) Shellfish reefs	 Oyster shell bags for natural oyster recruitment (NSW)	 Mussels seeded onto reef substrate (Port Phillip Bay, VIC)
(8) Coral reefs	 Coral transplantation (QLD)	 Coral transplanting on artificial reef (Gold Coast, QLD)

et al., 2022).

Most physical, ecological and socio-economic research on living shorelines has been focused in North America (Morris et al., 2018; Smith et al., 2020). Living shorelines research and implementation in Australia is in its infancy (Smith et al., 2020), with published studies focusing solely on dune management (Morris et al., 2018), yet a variety of ecosystems could be utilized for hazard mitigation (Morris et al., 2021a; Table 1). Results from recent public surveys indicate support for ecologically sustainable coastal protection approaches in Australia (Strain et al., 2019b), with the perception that living shorelines are as effective at coastal protection as conventional engineered structures (Strain et al., 2022). New policies have also prioritised living shorelines over hard protection options (e.g., New South Wales Coastal Management Act 2016 and Victoria Marine and Coastal Policy 2020; Morris et al., 2021a). Increasing social license and political support have enabled some local-scale trials (i.e., hundred metres in a few sites) of living shorelines in Australia (Morris et al., 2019a). If this protection method is to be implemented at larger scales, however, the success of living shorelines projects must be reviewed to develop best practice. Further, to support transformational change in the way communities respond to coastal hazards, potential benefits and barriers to implementation must be understood by key stakeholder groups (DeLorme et al., 2022). Here, we used a combination of stakeholder surveys and interviews and a grey and peer-reviewed literature search to: (1) develop a national inventory of living shoreline projects; and (2) determine different stakeholder perceptions of the benefits and barriers to using living shorelines in Australia.

2. Methods

Two complementary methods were used to create a national inventory of living shoreline projects in Australia: (1) surveys and interviews with coastal stakeholders; and (2) a review of published and grey literature (Fig. S1). Interviews with policy makers in State and Federal government identified the barriers and opportunities for living shorelines. Additionally, stakeholder engagement by coastal managers directly involved in the implementation and/or research of coastal infrastructure projects was determined through use of a survey and/or interviews. Human ethics approval was obtained for the survey and interviews (2021-14372-24170-5, The University of Melbourne). For the literature review, grey literature largely was obtained from the coastal practitioners through reports and information from organisation websites or media releases.

2.1. Stakeholder surveys and interviews

We interviewed twelve senior policy makers with responsibilities for coastal management at Federal and State government levels between August and October 2020. Participants were recruited through the national intergovernmental Coastal Hazards Working Group, which consisted of members nominated by all jurisdictions, the Commonwealth and the Australian Local Government Association. The 12 representatives from the state and federal government had roles related to the development and implementation of coastal policies and the provision of guidance to other coastal management agencies responsible for planning and management decisions and actions. Representatives from the following jurisdictions opted to participate in the study: Victoria (3 people); Queensland (1 person); Western Australia (2 people); Tasmania (1 person); South Australia (1 person); and Commonwealth (4 people). Interviewees were asked 14 questions across four themes (supplementary material, Table S1): (1) the interviewee's role and connection to coastal management in Australia; (2) the (organisation's) current coastal management priorities and where living shorelines fit within those priorities; (3) the policy landscape in which decisions are made about living shorelines, and barriers and enablers to living shorelines; and (4) exemplars of living shorelines in Australia and any further comments. The interviewees had prior knowledge of living shorelines through their role in coastal management and various terminologies were used during the stakeholder engagement (e.g., living shorelines; nature-based coastal defence/protection, nature-based methods) but a common definition of this approach for coastal hazard risk reduction (for which these multiple terms are used) was given to participants that aligned with that in the Australian national guidelines (Morris et al., 2021a). The interviews were conducted via Zoom, which were recorded and later transcribed using a transcription service (Pacific Transcription, Australia). The responses of the interviewees were qualitatively analysed using five themes: coastal management priorities; prior knowledge of living shorelines; position of living shorelines within priorities; barriers and enablers of uptake; and examples of living shorelines. The policy landscape of living shorelines in Australia was not a focus of this paper, and information can be found in Morris et al. (2021a).

The survey identified coastal practitioners who had implemented living shorelines in various parts of Australia. It also assessed the reasons why living shorelines had not been implemented in the jurisdictions of some respondents. The survey used both targeted (coastal practitioners known to the research team to have implemented living shorelines) and convenience sampling (all other coastal practitioners). The survey was distributed online to people aged 18 years or over, and participants were recruited via mailing lists of national coastal organisations or working groups (e.g., Australian Coastal Councils Association; Association of Bayside Municipalities; Coastal Council Adaptation Taskforce [C-CAT]; and the National Committee on Coastal and Ocean Engineering [NCCOE]), or through email lists held by the researchers. The survey was emailed to 68 people, however, the number of people the survey reached was greater than this due to forwarding of the email. All respondents were provided with access to the plain language statement which detailed the research and statement of consent before agreeing to complete the survey.

The survey was made available online through Qualtrics between 11 January and 30 June 2022. The survey included eight questions and was designed with the intention that the responses should not take more than 5 min to complete (Table S2). The survey included questions with binary (yes, no), multiple-choice, and open answers; the latter allowed participants to expand on their perspectives of the benefits of and barriers to living shorelines. Two questions within the survey identified the stakeholder type (e.g., local or state government, consultancy, university/academic) and jurisdiction; two questions identified whether the respondent (or their organisation) had used living shorelines and what type (i.e., soft or hybrid and ecosystem type; Table 1). A further three questions explored the reasons why living shorelines had not been implemented (if this was the case), whether the use of living shorelines was a priority for the individual/organisation and barriers to their use. The last two questions asked whether individuals who had implemented living shorelines would be willing to be contacted for further information about the project(s). A generalised linear model with a binomial distribution was used to test whether individuals who had implemented living shorelines (fixed, 2 levels = yes or no) were more likely to consider them a priority (fixed, 2 levels = yes or no) for future coastal management. Chi square tests of independence were used to test for an association between whether participants had used living shorelines before, and the state in which they worked and the frequency that different barriers were selected.

Where the survey identified coastal practitioners who had implemented living shorelines and had opted to be contacted, they were sent a follow-up email and provided information on the projects they had been involved in either by completing a spreadsheet or communicating the information verbally in a meeting, as well as sharing any reports or other grey or published literature, which was then transcribed to a project database (see Data extraction below).

2.2. Literature review

The literature review built on two existing databases on living shoreline (Morris et al., 2018) and beach nourishment (Cooke et al., 2012) projects in Australia. A literature search was done in Web of Science using the same systematic search terms as Cooke et al. (2012) and Morris et al. (2018) (Table S3) to account for any papers that had been published since those reviews between 2011 and 2022 and 2017–2022, respectively. We also used the reference lists of relevant papers to find additional studies and grey literature. The initial literature search identified 1095 papers for screening, first by title, followed by abstracts, for inclusion in the project database. The papers were then screened for those that reported on field-based living shoreline projects in Australia and the data for each of those projects were extracted.

2.3. Data extraction

The following information was recorded from survey respondents and grey and published literature for all living shoreline projects where available: site name; location [latitude and longitude]; approach used [soft or hybrid and ecosystem type, as before]; primary/secondary objectives of the project; coastal hazard being managed; assets vulnerable to the hazard; geographic context; project approvals required; date of project completion; shoreline length; project area; responsible organisation; funding source; project cost; whether the project was monitored; and any information/reports that resulted from the monitoring. Then, a set of ecosystem-specific variables was extracted that focused on specific details about the method used (Table S4). Only projects for which coastal protection was stated as a primary or secondary objective were included in the database. Although it is acknowledged that restoration/rehabilitation projects that do not have a coastal protection objective may have methods relevant to living shorelines, these projects were not included in the database as the aim was to increase the profile of living shorelines for coastal hazard resilience. Some projects identified through the literature did not contain all the information needed in one paper or report. In these instances, the Google search engine was used to find more information, which was frequently obtained through council or organisation websites or news articles. Occasionally, this process led to more projects being found incidentally, and these were also included in the database. Projects that were identified, but were lacking in critical information, were excluded from the database as they were not deemed fit for the purpose of providing a useful example of a living shoreline.

Projects were binned into 5-year intervals from 1970 to 2025 to reduce issues of zero-inflated data (the database included past, current and planned projects within this date range) and linear models were used to test how the number of projects using each approach (fixed; 6 levels: beach, dune, mangrove, saltmarsh, seagrass and shellfish) or in each state (fixed; 6 levels: NSW, VIC, SA, WA, QLD, TAS) varied through time (fixed; 11 levels). Chi square tests of independence were used to test for an association between the approach used and geographic context (open coast, bay [body of water partially enclosed by land directly open to the ocean], estuary [brackish mouths of rivers and streams that flow into the ocean]), primary objective (coastal protection, habitat restoration, ecosystem services, safe navigation, test methods), hazard mitigated (erosion, flooding, sea level rise [SLR], storms; selection allowed multiple options), asset protected (built, cultural, natural, private, recreational; selection allowed multiple options), whether the project was considered successful or not (no, somewhat, too early, unsure, yes) and how the projects were monitored (formal-qualitative, formal-quantitative, informal, no, unsure).

The success and monitoring of projects were categorised separately for coastal protection and habitat restoration (commonly determined through habitat establishment). Projects were considered successful if they met one of the following criteria: a) the authors determined they had arrested or significantly mitigated the coastal hazard or had established the target habitat (on the timescale or to the extent intended) based on the information provided in reports and/or publications; b) they addressed continuing erosion in a long-term sustained way (for coastal protection outcomes only e.g., sand pumping systems or tidal restoration); or c) had been explicitly referred to as successful by the organisation responsible. In most cases, multiple information lines were used to determine success (e.g., reports in addition to personal communication with responsible organisation). Success was determined relative to the goals of each project, which differed across the different projects in terms of timescales and intervention outcome. Projects were considered unsuccessful if they had not succeeded in meeting the primary goal of the project; that is, mitigating the coastal hazard, establishing the target habitat, the effects were very short term, or the organisation responsible considered the project unsustainable in the long run (e.g., some expensive sand-carting projects in areas of rapid erosion). Projects that were not monitored or did not have enough information were not assessed for success. Formal monitoring involved reporting of project outcomes, predominantly to government bodies, either through visual assessment of the site (qualitative) or measured variables (quantitative, e.g., m^3 of sand lost or gained or percent cover or density of habitat). Informal monitoring usually involved visual assessments that were not formally reported (usually community driven projects). Except for evaluating the information provided as described to categorise project success, it was not within the scope of the research to provide an assessment of the quality of the monitoring program. Research reports and a contact person/organisation where available have been provided in the project database, which enables coastal practitioners interested in certain projects to elicit more detail if required. Chi square tests of independence were used to test for an association between the type of monitoring that had been done on a project and the category assigned for success.

Project cost was adjusted from the year of completion to 2021 AUD using the online inflation converter from the Reserve Bank of Australia (https://www.rba.gov.au/calculator/annualDecimal.html; e.g., Ferrario et al., 2014) and reported for soft and hybrid approaches separately for each habitat along with the project length. The project cost was the up-front set-up or capital costs, and does not include ongoing operational costs associated with maintenance or monitoring as that information was rarely reported. Project information rarely provided a break-down of the capital costs, but would have included materials and construction, as well as potentially labour and project management costs, design fees and other investigations.

3. Results

3.1. Stakeholder interviews and survey

3.1.1. Interviews with state and federal policy makers

Coastal hazard risk management, managing development on the coast and adaptation planning were considered the priority issues for coastal policy. All the interview respondents had heard of living shorelines for hazard risk reduction, referring primarily to examples of beach nourishment and dune management, with one interviewee commenting that they had not seen many examples of other habitats such as wetlands being practiced in Australia yet. The perceived barriers to living shorelines included: few examples that could be used as precedent by coastal practitioners; limited knowledge about the costs and benefits of living shorelines as compared to conventional engineering structures; complex jurisdictional management of the coast; limited community engagement, which if increased could enhance community understanding and support for living shorelines; few workers/contractors with expertise in the delivery of nature-based coastal protection/resilience projects (Table 2). The primary incentive for implementing living shorelines identified by interviewees was the multiple benefits that could be achieved with using these interventions compared with that achieved with conventional methods (e.g., biodiversity benefit, water quality, carbon storage).

Table 2
Major barriers to living shorelines identified through the stakeholder interviews.

Barrier	Description	Example quote
Precedent	There is a lack of simple and accessible operational precedents for the use of living shorelines at scale showing coastal managers, decision makers and the broader community what can be done.	"It's a bit untested at the moment. Demonstration sites [are important] so that you can understand how [living shorelines] work in the context of other options that are out there to address the issue."
Funding	There is always a limited budget for risk reduction on the coast. A greater understanding of the cost-benefits of using living shorelines over traditional structures is required.	"[For example] beach nourishment, is always going to cost more and always becomes a longer-term project compared to a sea wall. So, people have to understand the benefit of those [projects]"
Jurisdictional	The responsible organisation for more terrestrial-based options (e.g., dunes and beaches) is often clearer than intertidal or subtidal options as management of the land-sea interface can be complex and multi-institutional.	"Who is responsible for building it? Some of [the options] will be in subtidal waters. They're probably not subject to local government having tenure or vesting in the area."
Community	Community engagement to increase understanding and support of living shorelines, including private coastal landowners who are investing in protection options.	"[We need] that education or information piece of having people understand what the advantages, cost, benefits, risks might be of some of these type of approaches"
Expertise/ Stakeholder input	The successful implementation of living shorelines requires collaboration from a more diverse set of disciplines to achieve engineering, ecological and socio-economic outcomes.	"Everybody goes straight to engineers to deal with these things. [We need to get] buy-in from all the other professions - planners, economists, environmental…"

3.1.2. Survey of coastal practitioners

In total, 67 coastal practitioners completed the survey. Most respondents (64 %) were from local government authorities, while 9 % of respondents were from community organisations, 8 % from state government organisations, 6 % from Natural Resource Management (NRM), and < 2 % each from federal government, engineering consultancy and non-governmental and Traditional Owner organisations. We also had one respondent from a not-for-profit Aboriginal Charitable Trust, two private coastal landowners, and one respondent who worked at a university. The survey respondents were primarily from South Australia (36 %), Victoria (19 %) and Tasmania (17 %), followed by Queensland (13 %), New South Wales (13 %) and Western Australia (3 %), with no respondents from the Northern Territory.

A total of 44 respondents (69 %) stated that they or their organisation had used living shorelines, while 23 % stated that they hadn't used living shorelines and 8 % were unsure. Forty-one respondents (67 %) stated that living shorelines were a priority for them or their organisation for future projects to manage the risk of hazards for coastal assets, while 15 % stated they were not a priority, and 18 % said they were unsure. Respondents who had used living shorelines previously were more likely to consider them a priority for future risk management ($P < 0.001$; Fig. 1). There was no effect of prior use of living shorelines ($X^2 = 5.10$, d.f. = 13, $p > 0.05$) or State that the respondent worked in ($X^2 = 39.41$, d.f. = 65, $p > 0.05$) on the frequency that different barriers to implementation were selected (Fig. 2). The top five most selected barriers were: uncertainty in the level of risk reduction; lack of necessary expertise; planning or regulation barriers; lack of good examples being used; and a lack of clarity in the options available.

Forty respondents who had used living shorelines were willing to be contacted, 26 of whom provided information on the living shoreline

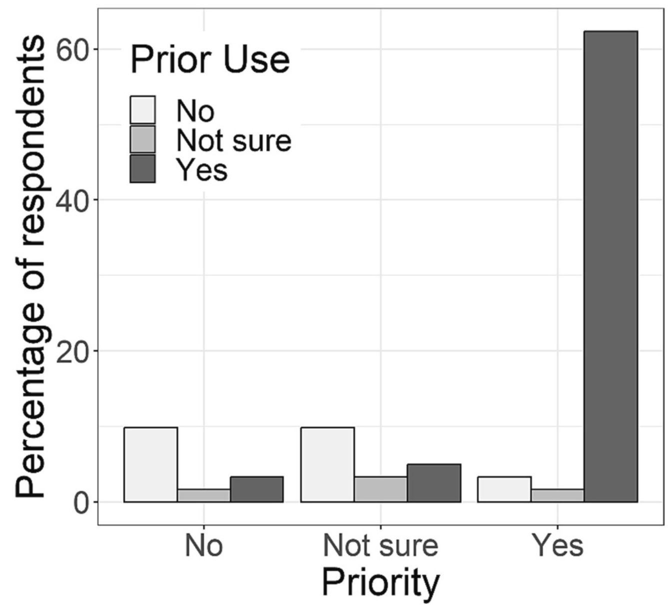


Fig. 1. Percentage of respondents that have previously used living shorelines and consider living shorelines a priority for future management of coastal hazard risk.

projects they had been involved in, representing a 65 % response rate. After removing projects that did not have a coastal protection objective, the stakeholder survey yielded 52 projects for inclusion in the living shoreline database.

3.2. Living shoreline database

Of the initial 1095 papers that were screened from the literature search, 11 were empirical papers describing relevant projects in Australia, and reference lists were screened in a further five review papers. The total number of living shoreline projects identified through the combined sources of information received during the study was 138, as of September 30, 2022 (Table S5). The database was made publicly available online as an interactive map with project details (Living Shorelines Australia; www.livingshorelines.com.au). The number of living shoreline projects significantly increased from the period 2006–2010 (Fig. 3a; Table S6). There were significantly more beach (32 %), dune (26 %), and mangrove (27 %) projects than saltmarsh (5 %), seagrass (7 %) or shellfish reef projects (3 %) (Fig. 3a; Table S6). No kelp forest or coral reef projects were identified. Four projects were classified as 'other', which included two artificial reefs, the revegetation of a cliff top, and one project that used tea-tree log and brushwood groynes. The number of living shoreline projects through time differed by State (Fig. 3b; Table S6). New South Wales had a higher number of projects implemented in 2001–2015 (Fig. 3b). Overall, New South Wales had the greatest percentage of projects (43 %), followed by Queensland (18 %), Victoria (17 %), South Australia (11 %), Tasmania (6 %) and Western Australia (5 %) (Fig. 4). No projects were recorded for the Northern Territory.

There was a significant difference in the geographic context ($X^2 = 112.13$, d.f. = 12, $p < 0.001$), primary objective ($X^2 = 113.58$, d.f. = 24, $p < 0.001$), hazard mitigated ($X^2 = 30.71$, d.f. = 18, $p < 0.05$) and asset protected ($X^2 = 89.42$, d.f. = 24, $p < 0.001$) among the living shoreline approaches. Mangrove, saltmarsh and shellfish reef living shorelines were used more frequently in estuaries, while seagrass was used most frequently in bays. Beach nourishment and dune management more commonly occurred on the open coast and in bays (Fig. 5a). Beach, dune and mangrove projects had a high percentage (> 70 %) of projects where the primary objective was coastal protection (Fig. 5b). For saltmarsh,

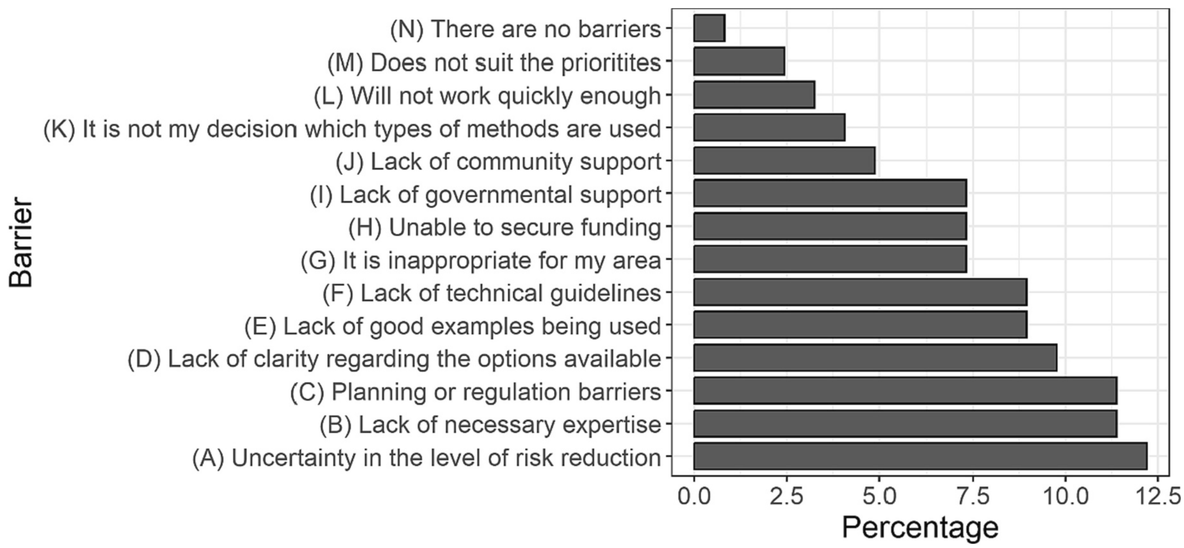


Fig. 2. The percentage of responses for different barriers to living shorelines.

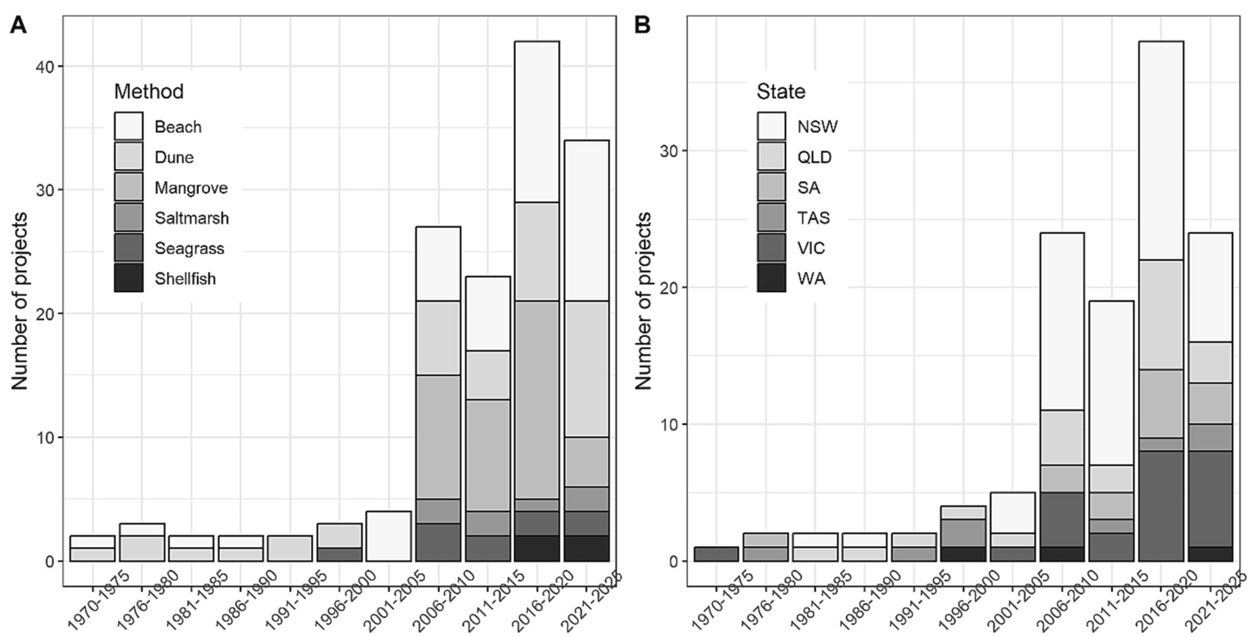


Fig. 3. The number of living shoreline projects through time based on the year of installation for (A) the approach used and (B) the state implemented.

seagrass and shellfish reefs there was a greater number of projects where the primary objective was habitat restoration, with a secondary objective of coastal protection (Fig. 5b), and 45 % of seagrass projects had the primary objective of testing methods for restoration.

Almost all projects (except one) were installed for erosion mitigation, 23 % of projects additionally aimed to mitigate storms, flooding or SLR as well as erosion. Beach, dunes and shellfish reefs were more commonly implemented to protect against storms (Fig. 5c). Protection against flooding and SLR were less frequently cited as the reason for living shoreline implementation (Fig. 5c). Mangroves, saltmarsh, seagrass and shellfish reefs were most frequently implemented to protect natural assets, while beaches and dunes were used to protect built and recreational assets (Fig. 5d). Only 2.5 % of responses stated that living shorelines were used to protect cultural assets, and all used either beach nourishment or dune management (Fig. 5d).

Overall, the living shorelines were considered successful by the authors and/or the responsible organisation with respect to their stated goals in 59 % and 57 % of the projects recorded for coastal protection or habitat restoration outcomes, respectively, and 54 % of projects stated success for both coastal protection and habitat restoration (Fig. S2). Thirteen and 6 % of projects were deemed somewhat or not successful at achieving coastal protection or habitat restoration outcomes respectively, while the remaining percentage were either unsure of success or the projects had been implemented too recently for results. Formal monitoring was undertaken for approximately half of the projects (54 % and 50 % for coastal protection and habitat restoration outcomes), and this was either quantitative (30 % and 32 % respectively) or qualitative (24 % and 18 % respectively). Informal monitoring had occurred at 16 % and 13 % of the projects for coastal protection and habitat restoration outcomes respectively, while 4 % of the projects were unmonitored for coastal protection outcomes. No projects were considered unmonitored for habitat restoration outcomes, although for 37 % there was no information about whether the projects had been monitored or not, compared to 26 % of the projects for coastal protection outcomes where

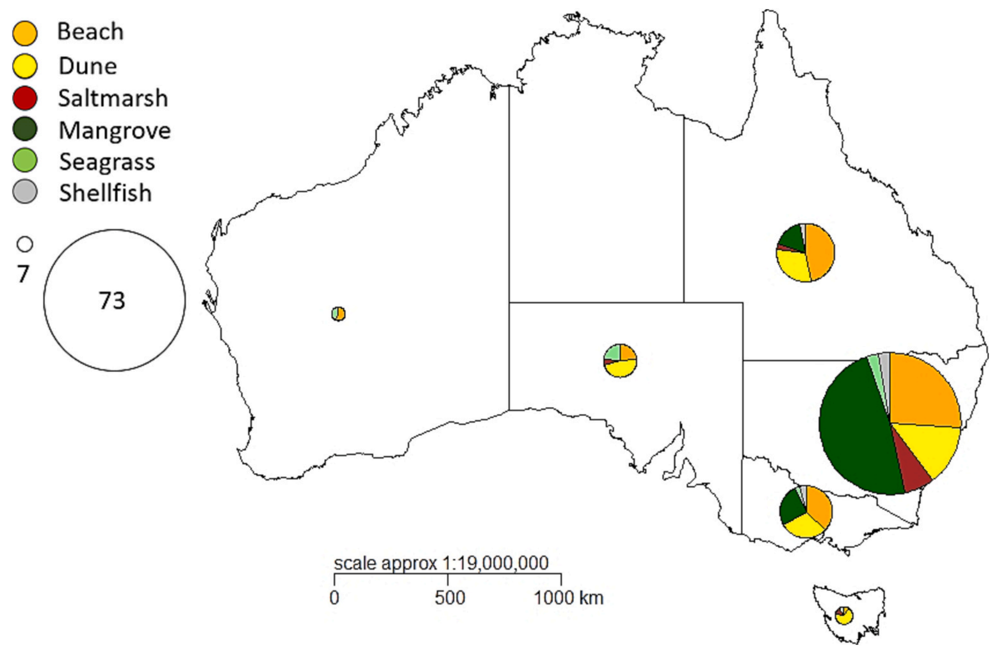


Fig. 4. Map of the location and number of living shoreline projects included in the database ($n = 138$). The size of the pie chart reflects the total number of projects in each state.

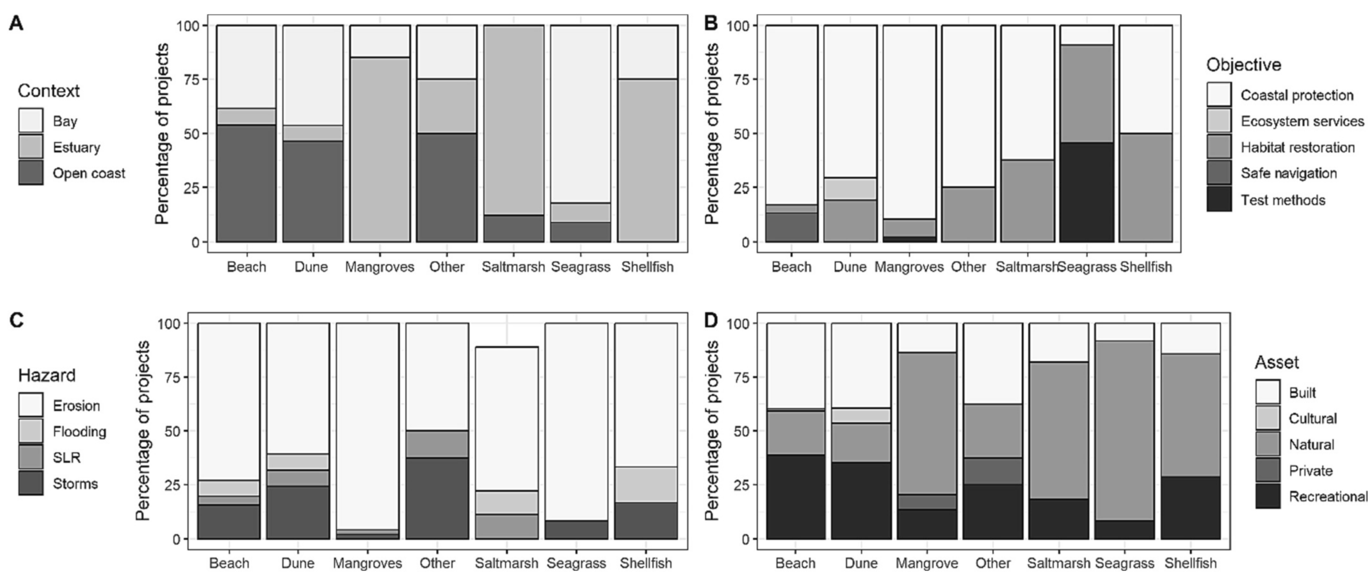


Fig. 5. The percentage of projects for the (A) geographic context; (B) primary objective; (C) hazard mitigated; and (D) asset protected for the different living shoreline approaches.

monitoring was unsure.

Whether projects were considered a success ($X^2 = 37.26$, d.f. = 24, $p < 0.05$, and $X^2 = 36.81$, d.f. = 24, $p < 0.05$ for coastal protection and habitat restoration outcomes respectively) and how they were monitored ($X^2 = 89.05$, d.f. = 24, $p < 0.001$, and $X^2 = 59.73$, d.f. = 18, $p < 0.001$ respectively) significantly differed among living shoreline approaches (Fig. 6). No saltmarsh or shellfish reef projects were considered unsuccessful at achieving coastal protection outcomes (Fig. 6a); however, a greater percentage of projects from these approaches were also unknown or considered too early to tell. No seagrass projects were classed as being successful and most of these projects (63 %) were listed as unsure of success from a coastal protection perspective, however, 54 % were considered successful at achieving habitat restoration outcomes (Fig. 6b). >60 % of beach, dune and mangrove living shorelines were considered successful at coastal protection (Fig. 6a), but 50 % and 30 % of beach and dune projects respectively were listed as being unsure of their success at habitat restoration (Fig. 6b). Beach, dune and shellfish reef living shorelines received the most formal quantitative monitoring for coastal protection (Fig. 6c) while saltmarsh, seagrass and shellfish reefs received the most for habitat restoration (Fig. 6d). A higher percentage of saltmarsh projects received formal qualitative monitoring, while no seagrass projects received formal quantitative monitoring, and a higher percentage of seagrass projects were either informally or not monitored for coastal protection (Fig. 6c). The monitoring status for a high percentage (50 %) of mangrove projects was unknown for both coastal protection and habitat restoration (Fig. 6b,c). Projects were more likely to be listed as successful or not when they had received either formal or informal monitoring (Fig. 6 e,f). Where the monitoring for a

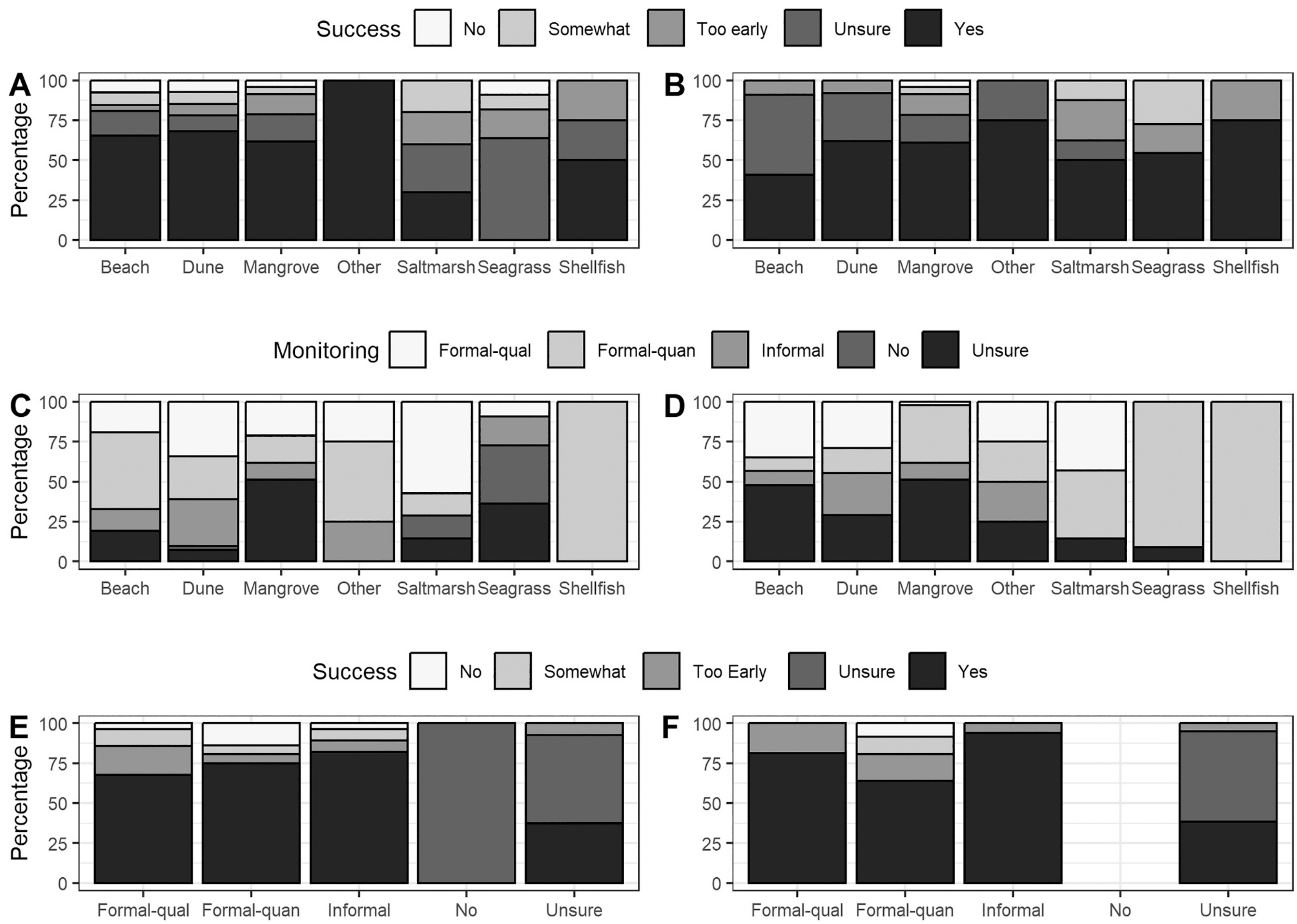


Fig. 6. The percentage of projects for the (A,B) success and (C,D) monitoring of (A,C) coastal protection and (B,D) habitat restoration of different living shoreline approaches. The percentage of projects listed for different categories of success based on the type of monitoring for (E) coastal protection and (F) habitat restoration.

project was unsure (or not present) logically, this resulted in greater uncertainty or less information about the success of this project (Fig. 6 e, f). There were, however, some projects that were listed as successful in the information sourced but the monitoring to substantiate this was unsure (Fig. 6 e,f).

3.2.1. *Techniques within the living shoreline approaches*

Dune and saltmarsh living shoreline projects used predominantly soft approaches, whereas beaches, mangroves and seagrass used a combination of soft and hybrid approaches, and shellfish reefs were all hybrid projects (Fig. 7). Shellfish reefs were considered hybrid if there had been substrate addition. Table 1 provides examples of the techniques used for soft and hybrid approaches within each ecosystem.

Our survey suggests that a total of at least 178 linear kilometres of Australia's coastline has had living shorelines applied. The average length of shoreline protected by a living shoreline project was 1.8 km and ranged from 80 to 36,000 m with a median of 690 m (Table 3). The average cost per linear metre of all living shoreline approaches was AU $4238, but ranged from AU$10 m^{-1} to AU$102,033 m^{-1}, with hybrid approaches more expensive than soft approaches (Table 3). The median cost was AU$207 m^{-1}. Projects were most often funded through State (65 %) or Local (36 %) governments. Other sources of funding were the federal government (13 %), community grants (8 %), research grants (5 %) and the private sector (3 %).

4. Discussion

Previous reviews of the scientific literature identified that, except for beach nourishment, there was little (Morris et al., 2018) or no (Smith et al., 2020) use of living shorelines applied for coastal hazard risk reduction in Australia. Predominantly through stakeholder surveys and grey literature obtained, we have shown that the use of living shorelines dates back as far as the 1970s for beach and dune management. Further, living shoreline use has been emerging over the last 25 years for saltmarsh, mangroves, and seagrass, and 5 years for shellfish reefs. Despite this progress, the number of projects for ecosystems other than beaches and dunes is still low in most States, except for mangroves in New South Wales, and the application of living shorelines is far from standard practice. Living shoreline projects are often run by local or state governments or community groups, so understandably results are not frequently published in the scientific literature. More than half of the project representatives stated that formal monitoring either quantitatively or qualitatively had, however, been done. If, these data have not been collected and written up in a robust and defensible manner, and are not publicly available, it can limit the extent to which projects can be used as precedent for future living shoreline applications. A lack of examples and clarity in the options available were top barriers for living shoreline implementation experienced by the coastal practitioners surveyed. The mechanism for reporting these project data needs to be accessible to those delivering living shorelines and other end users of this information. This means that peer-reviewed scientific literature may not be the right forum for this information or should not be the only method used to communicate outcomes of living shorelines projects. The project monitoring should, however, still be grounded in a strong scientific method to enable confidence in the evaluation.

The Living Shorelines Australia database aimed to fill the gap in the

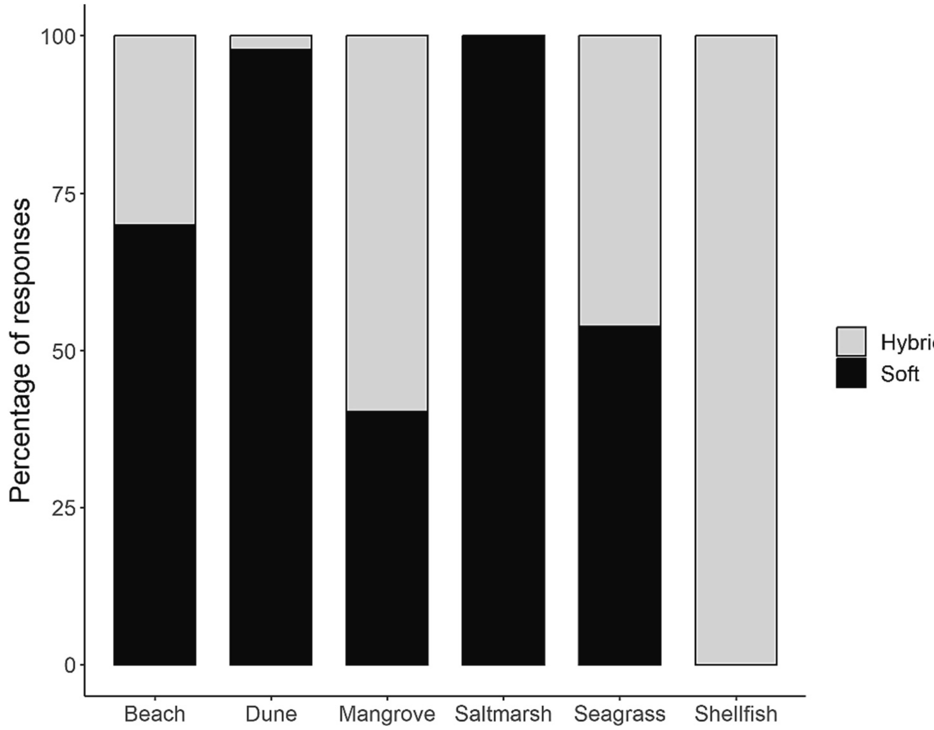


Fig. 7. The percentage of soft and hybrid approaches per ecosystem.

Table 3
Median length of coastline protected and median cost ($AUD) per linear metre of living shoreline approaches for "soft" and "hybrid" techniques. Costs were adjusted for inflation before calculation.

Approach	Technique	Example	Length (m)	Cost (m^{-1})
Beach	Soft	Artificial nourishment, replenishment or scraping	690	356
	Hybrid	Sand pumping, sand bypassing	1000	5235
Dune	Soft	Restricting access, revegetation, reshaping, sand fencing	800	46.5
	Hybrid	Dune with rock core	550	4000
Mangrove	Soft	Planting seeds or seedlings, hydrological restoration	2750	60
	Hybrid	Rock fillet/sill, wooden logs or pilings	407.5	158
Saltmarsh	Soft	Restricting access, hydrological restoration, revegetation	1000	10
	Hybrid	–	–	–
Seagrass	Soft	Planting seeds or fragments	5000	Unknown
	Hybrid	Metal pins, sediment stabilising matting	Unknown	Unknown
Shellfish	Soft	–	–	–
	Hybrid	Rock or shell consolidated or unconsolidated	1037.5	1396.5

transfer of knowledge among coastal practitioners implementing living shorelines by sharing information in a publicly available portal to develop best practice that can be used to inform technical guidelines for different approaches. We obtained information from a variety of sources including scientific and grey literature and coastal practitioner questionnaires/interviews to identify projects that had not been detected in previous systematic reviews. This multi-faceted approach in obtaining information about knowledge gaps and research priorities for living shorelines has been highlighted in a recent study in the United States (Mednikova et al., 2023). This method, however, does require the engagement of coastal practitioners nationally and while we showcased a wide range of projects there may be some gaps (e.g., due to lower response rates in some states) that need to be filled. The database should be considered a living database, where projects are added as they occur into the future to maintain its relevance for sharing information on living shoreline application.

4.1. Barriers and enablers of living shorelines

A previous assessment of barriers to implementation of living shorelines identified them as being function-based or related to public perception or acceptance (DeLorme et al., 2022). Function-related barriers include uncertainty in the level of risk reduction provided, potentially from a lack of evidence on performance. Public perception related limitations include a lack of community or government support, misalignment of public values to the processes and functions of living shorelines, and the potential financial cost (DeLorme et al., 2022). In our survey, the function-related problems were most frequently cited, with uncertainty in the level of risk reduction the primary barrier, followed by a lack of necessary expertise, clarity in the options available and documented examples being used. Planning or regulation barriers were also regarded as a significant limitation to the implementation of living shorelines. In Australia, coastal policy and strategies are set at the state level, and these pass on responsibilities to local government authorities for managing the coast and hazards (Morris et al., 2021a). This means that the process for permitting and implementing a living shoreline differs nationally, and for different types of living shorelines due to complex, often multi-institutional management of the land-sea interface. While the survey responses largely came from local government representatives who were the main stakeholder group represented, a lack of precedent of living shorelines was also highlighted in the interviews with the state and federal government representatives.

A lack of diverse stakeholder engagement and input was also considered an important barrier to living shorelines by the state and federal government representatives. Communication with the wider community to increase understanding is a prerequisite for greater support of living shorelines. Previous public surveys have shown that in general there is global support for more ecologically sustainable approaches to coastal protection (Strain et al., 2019a), however, community response to living shorelines (and coastal protection structures more generally) can be very local and site-specific (e.g., local opposition to mangrove planting; McManus, 2006) requiring carefully planned consultation in the early stages of living shoreline planning. There was also recognition that the design and implementation of living shorelines requires more diverse, multi-disciplinary expertise than typically used for construction of conventional protection structures. These have traditionally been viewed as an engineering exercise and contracted to local consultancies by government agencies to advise, design and deliver coastal protection projects. There is increasing realisation that collaboration between ecologists, geomorphologists and engineers is an appropriate strategy to develop technical design guidance for living shorelines (Morris et al., 2019b; Scheres and Schüttrumpf, 2020), and other experts such as landscape architects, land planners, economists, social scientists will be integral in project scaling and uptake (e.g., Scyphers et al., 2020). Despite being an important stakeholder group in the implementation of living shorelines, coastal engineering or environmental consultants were notably missing from the survey respondents. Given that consultancies are often contracted by local and state governments, it is likely that many of the projects delivered by consultants would have been captured in the database through the survey and reports provided. However, identifying the barriers to delivering living shorelines by engineering and environmental consultants (Scheres and Schüttrumpf, 2020) will be important to understand as they will be one of the primary pathways of expertise accessed by coastal managers. Engagement with this stakeholder group may also identify projects for other clients (e.g., private land holders) that may not have been captured here if this information is not confidential. Further, a more detailed assessment of each of the broader barriers identified (e.g., through focused workshops) will help to identify specific knowledge gaps for targeted solutions to enable wider use of living shorelines.

4.2. The application of living shorelines

Beaches and dunes were most well represented in Australian living shorelines. These have a long history of being used for coastal protection globally (Hanley et al., 2014; Morris et al., 2018). The use of mangroves for coastal protection within low energy estuaries in Australia has accelerated since 2000, particularly in NSW where hybrid mangroves using rock or timber fillets to produce a hydrodynamically sheltered area for fringing mangroves to re-establish have been widely used for erosion control (Jenkins and Russell, 2017; Morris et al., 2023). Shellfish reefs have been widely used for erosion control in the United States (La Peyre et al., 2014; Morris et al., 2021b), but have only been used in Australia in the last five years with most national shellfish reef restoration projects not targeted at coastal protection but habitat restoration or other services like water quality (McAfee et al., 2022a). Similarly, with only three projects using saltmarshes and four in combination with other habitats, this habitat was not well-represented as an ecosystem for living shorelines in Australia, despite saltmarshes being an endangered ecological community in temperate and sub-tropic southern Australia (Saintilan and Rogers, 2013), which are the focus of rehabilitation efforts for habitat recovery (Knight, 2018). Few projects used seagrass in living shorelines, and none reported use of coral reefs or kelp forests, despite strong evidence that coral reefs, at least, are effective at hazard risk reduction and adaptation (Ferrario et al., 2014). Geographical location that effects the occurrence/morphology of habitats as well as the coastal hazard risk (due to the spatial distribution of hazard drivers and coastal populations in Australia; Morris et al., 2021a), technical knowledge combined with the organisations involved in living shorelines are likely reasons for the distribution of projects using different habitats. Most projects were implemented by government or community groups. These groups are more likely to use scalable techniques in habitats that have established restoration methods, such as dunes and beaches (Saunders et al., 2022). Restoration methods in kelp, coral reefs and seagrasses are still relatively experimental and small-scale (Bayraktarov et al., 2016), and a survey of restoration practitioners in Australia showed that projects on these habitats were more likely to be led by scientists at research institutions (Saunders et al., 2022). Due to jurisdictional boundaries, coastal or intertidal habitats may also be favoured by local government authorities or community groups (Saunders et al., 2022), which was also highlighted in the stakeholder interviews (Table 2).

The distribution of habitats used for living shorelines in Australia had some differences with other countries globally. For example, despite coastal saltmarsh being one of the most highly cited habitats for restoration in Australia (Saunders et al., 2022), from the projects identified in this database it has been rarely applied in living shorelines. This contrasts with other areas globally such as the United States (Morris et al., 2018; Smith et al., 2020) and Europe (Kosmalla et al., 2022; Moraes et al., 2022) where saltmarsh is a predominant ecosystem used in living shorelines. Saltmarsh occurs higher in the intertidal zone than do mangroves, and therefore has the potential to provide significant protection from storm surge and waves (Duarte et al., 2013). The coastal protection value of saltmarsh communities in Australia needs specific research, however, as they often differ ecologically and morphologically from *Spartina* sp. that has been intensively studied in the USA and Europe (Friess et al., 2012; Boon et al., 2015). Oyster reef living shorelines are also one of the most common types in the United States (Smith et al., 2020; Morris et al., 2021b), and have been applied in other areas such as Bangladesh (Chowdhury et al., 2019) and the Netherlands (Walles et al., 2016; Marin-Diaz et al., 2021). In Australia, oyster reef restoration for coastal protection is emerging (Morris et al., 2019a; Saunders et al., 2022) and is an attractive hybrid method as the reef substrate can be similarly parameterised to submerged breakwaters in the engineering literature (Webb and Allen, 2015). However, this can lead to an excessive focus on engineering, whereas projects also need to focus on integrating the species' ecology with engineering principles to achieve success in establishing a shellfish living shoreline (Morris et al., 2019b). Although most living shoreline projects focused on one ecosystem, 21 % of projects used multiple ecosystems. Multi-ecosystem living shorelines are another emerging technique which may increase infrastructure resilience, maximise co-benefits and provide protection under a wider range of conditions (Bouma et al., 2014; McAfee et al., 2022b; Moody et al., 2022).

The context of living shoreline application differed among the habitats. Habitat suitability for beaches and dunes, saltmarshes, mangroves, seagrasses and shellfish reefs differ across the open coast, bay and estuarine environments, which was reflected in their use in these different areas. The distribution of these types of habitats across Australia also varies, driven by oceanic and climatic factors that favour expansive coastal wetlands in the macrotidal, lower wave energy tropical northern coastlines compared to more extensive dune systems in the microtidal wave-dominated southern temperate coastlines (Lymburner et al., 2020). The opportunities for different types of living shorelines therefore needs to incorporate the habitat suitability across the diverse Australian coastline (Morris et al., 2021a; Young et al., 2023). Built assets were more often protected using beaches and dunes, while mangroves, saltmarsh, seagrass and shellfish reefs were implemented to protect natural assets. This could reflect the greater confidence and history of using beaches and dunes in hazard risk mitigation, geographical location of most projects (in southern Australia) but could also be driven by public perception of living shorelines adjacent to residential areas. For example, although oyster reefs were once expansive in Australian estuaries, this is not in the living memory of most Australians and oyster reef restoration can result in a change to the sea view with a reef exposed at low tide. Similarly, mangrove restoration can be hampered by negative public views on restriction of views, water access or mosquitoes (McManus, 2006; Dahdouh-Guebas et al., 2020). This highlights the need for a more complete assessment of the public benefits and costs (including non-financial) of living shorelines so that the trade-offs between coastal protection and other outcomes of such projects – both positive (e.g., the co-benefits, like habitat restoration) and negative (e.g., aesthetics; increased risk of mosquito-borne disease) - can be properly understood.

Given that many living shorelines using coastal vegetation and shellfish reefs were considered successful, with greater use and technical guidance it would be expected that these techniques can also be used to protect built as well as natural assets. Indeed, in general natural assets across all habitats (40 %) were more frequently cited than other assets (27 % and 28 % for built and recreational respectively) for living shorelines, which could restrict their wider application as coastal protection projects are most frequently targeted at human assets. The technical guidance will need to be simultaneous with stakeholder engagement, education and co-design, which includes Indigenous peoples. The resilience of cultural assets was rarely addressed using living shorelines, despite many recorded Aboriginal sites on the Australian coast, most of which are shell middens but also burials and rock engravings, that are experiencing significant coastal erosion (Aboriginal Heritage Office, 2019). The extent to which living shorelines could be used as part of a coastal erosion strategy for Aboriginal heritage needs further work, which should be led or co-designed with Traditional Owners.

4.3. *The evaluation of living shorelines*

It was clear from the stakeholder interviews and survey that demonstrating and communicating the success of living shorelines in Australia was a primary factor to promote upscaling of their use. Encouragingly, more than half of the projects were considered successful, and up to 70 % of projects had been formally or informally monitored for coastal protection (70 %) and habitat restoration outcomes (63 %). Given, however, that coastal practitioners stated that few good examples of living shorelines are available, it appears there is a barrier in this information being shared among agencies. There were also large discrepancies in the evaluation and monitoring of the different types of living shorelines. The majority of beach, dune and mangrove projects were deployed for the primary purpose of coastal defence and were considered successful by the organisations responsible. The beach and dune projects often received either formal or informal monitoring that could be used to determine success. The monitoring status of many mangrove projects, however, was uncertain. Quantitative assessment of the success of mangrove rock fillets, which was a common method employed, are few (Vincent et al., 2018; Tachas et al., 2021) but necessary to inform the effective design and implementation of this technique (Morris et al., 2023). Seagrass was the least well monitored habitat for coastal protection used in living shorelines, which led to most projects being unsure of success. The seagrass projects were more often deployed for habitat restoration and to test restoration methods as a primary objective. These outcomes received formal quantitative monitoring for the majority of projects and were considered either successful or somewhat successful for those projects that it was not too early to tell, from a habitat restoration outcome. This, however, shows that despite coastal protection being identified as a secondary outcome in seagrass projects, whether it achieved this outcome was not being quantified. This is common globally, where the evidence base for the processes occurring within seagrass translating into erosion control have recently been identified as being weak (Twomey et al., 2022), and therefore more research is needed in this area. One gap in the evaluation of success in this project was that our assessment was not based on the quality of the monitoring programs. However, projects that were listed as successful or not were more likely to have received either formal or informal monitoring. The quality of monitoring programs is something that has plagued environmental monitoring (Lindenmayer et al., 2012), and while guidelines have been developed for monitoring living shorelines (e.g., Yepsen et al., 2016), an assessment of the programs in place warrants further research.

5. Conclusions

A lack of precedence for living shorelines is often cited as a fundamental barrier to upscaling their use in Australia by coastal practitioners, and this conclusion has been supported by scientific reviews of the published literature (Morris et al., 2018; Smith et al., 2020). The development of a National Living Shorelines database as an outcome of this study, however, highlighted a growing number of living shoreline projects and is a step towards sharing examples of these solutions in action (www.livingshorelines.com.au). The number of projects identified emphasises the importance of sharing knowledge among practitioners and different agencies in publicly available publications, reports and databases so that the outcomes of these projects can inform a business case for upscaling living shoreline application and develop best practice. A synthesis of the projects included in the database can help guide the context for the use of different living shoreline approaches. However, to increase expertise in this area, technical guidelines need to be developed for different methods to inform use at scale. The inventory of projects can be used to identify methods that may have enough on-ground demonstration to build an evidence-base that would support technical guidance through existing resources or additional data collection. The database can also be used to identify emerging technologies that can be supported by programs of research that include ecological, engineering and socio-economic evaluation (e.g., Gittman et al., 2014; Gijón Mancheño et al., 2021; Morris et al., 2021b; Strain et al., 2022). This study combined with a synthesis of living shoreline projects in other areas globally (e.g., Europe, Moraes et al., 2022; United States, NOAA, 2022) contributes to addressing some of the major barriers experienced by coastal practitioners on living shorelines implementation by providing examples and experience and can inform upscaling the use of living shorelines as standard practice for coastal hazard risk management.

CRediT authorship contribution statement

Rebecca L. Morris: Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Writing – original draft. **Erin Campbell-Hooper:** Investigation, Writing – review & editing. **Elissa Waters:** Conceptualization, Investigation, Writing – review & editing. **Melanie J. Bishop:** Conceptualization, Writing – review & editing. **Catherine E. Lovelock:** Conceptualization, Writing – review & editing. **Ryan J. Lowe:** Conceptualization, Writing – review & editing. **Elisabeth M.A. Strain:** Conceptualization, Writing – review & editing. **Paul Boon:** Conceptualization, Writing – review & editing. **Anthony Boxshall:** Conceptualization, Writing – review & editing. **Nicola K. Browne:** Conceptualization, Writing – review & editing. **James T. Carley:** Conceptualization, Writing – review & editing. **Benedikt J. Fest:** Conceptualization, Writing – review & editing. **Matthew W. Fraser:** Conceptualization, Writing – review & editing. **Marco Ghisalberti:** Conceptualization, Writing – review & editing. **Bronwyn M. Gillanders:** Conceptualization, Writing – review & editing. **Gary A. Kendrick:** Conceptualization, Writing – review & editing. **Teresa M. Konlechner:** Conceptualization, Writing – review & editing. **Mariana Mayer-Pinto:** Conceptualization, Writing – review & editing. **Andrew W.M. Pomeroy:** Conceptualization, Writing – review & editing. **Abbie A. Rogers:** Conceptualization, Writing – review & editing. **Viveka Simpson:** Investigation, Writing – review & editing. **Arnold A. Van Rooijen:** Conceptualization, Writing – review & editing. **Nathan J. Waltham:** Conceptualization, Funding acquisition, Writing – review & editing. **Stephen E. Swearer:** Conceptualization, Funding acquisition, Methodology, Project administration, Writing – review & editing.

Declaration of competing interest

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

Data availability

The database is available at www.livingshorelines.com.au

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.170363.

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