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EDITED BY

Shaoda Liu,
Beijing Normal University, China

REVIEWED BY

Laure André,
Institut de recherche pour le développement
(IRD), New Caledonia
Haile Yang,
Shanghai Aquatic Wildlife Conservation and
Research Center, China

*CORRESPONDENCE

Danelle Agnew,
✉ danelle.agnew@hdr.mq.edu.au

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Cost-benefit analysis of working with recovery in river management using Marxan

Danelle Agnew*, Kirstie Fryirs and Michelle R. Leishman

School of Natural Sciences, Macquarie University, Sydney, NSW, Australia

With the impact and cost of continued river degradation and climate change-induced extreme rainfall and floods, there is growing urgency to achieve and maintain good river health to meet global sustainable development goals. Up-scaling and working with nature-based solutions at regional, catchment and fluvial corridor scales is critical. One way to achieve this is to work within a recovery-enhanced approach to river rehabilitation, incorporating processes of geomorphic and vegetative recovery to build fluvial corridors in areas where they have become fragmented. Geomorphologically-informed cost-benefit analysis has not previously been applied in a riverine or riparian context, at the catchment or regional scale needed. We applied Marxan in a novel manner to undertake the first cost-benefit analysis for geomorphologically-informed rehabilitation of river systems. We estimated that to rehabilitate 75,500 km of streams in coastal catchments of NSW will cost \$8.2 billion, comparing favourably to recent single flood event insurance losses, and projected future losses. We developed Marxan scenarios based on three broad approaches to river management: *ad hoc and reactive*, *working with recovery* and *corridors*, across current and future time periods. We found there are considerable current and flow-on future financial and non-financial benefits, and lower initial total and per-hectare rehabilitation costs, by fully adopting *working with recovery* or *corridors* approaches and moving away from the *ad hoc and reactive* approaches which dominate current practice. Implementing targeted rehabilitation based on a rolling sequence over time of *corridors* scenarios provides optimal holistic solutions to improve geomorphic condition and enhance recovery potential at landscape-scale. Our study demonstrates the use of Marxan as an accessible tool to address prioritisation complexity, and to run and cost landscape-scale rehabilitation scenarios over time. Our study also demonstrates the positive offsite feedbacks that occur through multiplier effects, as recovery occurs, and corridors are built. Geomorphologically-informed decision making becomes more robust, transparent, cost-effective, consistent across catchments, and adaptive to local situations and evolving river management priorities.

KEYWORDS

fluvial corridor, working with recovery, cost-benefit analysis, Marxan, nature-based solutions, river management, recovery potential, prioritisation

Abbreviations: Con, Conservation; Strat, Strategic; HRP, High recovery potential; MRP, Moderate recovery potential; LRP, Low recovery potential; RRP, Rapid recovery potential; Corr, Corridors approach; WWR, Working with recovery approach; AHR, Ad hoc and reactive approach.

1 Introduction

Both the UN's Sustainable Development Goals and Decade on Ecosystem Restoration contain targets to restore freshwater ecosystem habitat and improve riverine and riparian biodiversity (Perry, 2023; UN DESA, 2023; United Nations, 2023). With weather-related disasters costing the global economy an estimated US\$258 billion (~A\$348 billion) in 2020 (AON, 2021; Naughtin et al., 2022), and continued biodiversity degradation, there is a sense of global urgency to meet these goals (European Commission, 2022b).

Globally there is recognition of the potential of nature-based solutions to mitigate impacts of climate change and land use change, secure ecosystem services and support biodiversity (Seddon et al., 2020; Tickner et al., 2020). Nature-based solutions use naturally occurring features and processes to sustainably rehabilitate and manage ecosystems for socio-biodiversity benefits (Cohen-Shacham et al., 2016). Nature-based solutions can be instrumental in planning for rehabilitation of fluvial corridors to meet diverse challenges such as biodiversity protection, flood mitigation and climate adaptation (Beyer et al., 2018; Albert et al., 2021). For freshwater ecosystems, valuing the benefits of river rehabilitation and working with nature-based solutions at regional, catchment and fluvial corridor scales is critical to achieve Sustainable Development Goals (Szalkiewicz et al., 2018; Cohen-Shacham et al., 2019; Basak et al., 2021). However, with large catchments and resource allocation constraints, one challenge river managers and decision-makers face is how to systematically and strategically prioritise river rehabilitation efforts to get the best environmental return on investment (Perry, 2023). As elsewhere in nature, river conservation and rehabilitation efforts need to be focussed where sustainable, cost-effective environmental solutions can be implemented (Bergstrom and Loomis, 2017; Vörösmarty et al., 2018; Kroeger et al., 2019; Hartig et al., 2020).

Healthy fluvial corridors, at catchment and landscape scales, including riparian zones, act as critical natural infrastructure (Tickner et al., 2020; Skidmore and Wheaton, 2022), and allow for natural ecosystem functioning and connectivity (Pittock et al., 2018; Hermoso and Filipe, 2021). Anthropogenic disturbances that reduce geomorphic diversity and complexity, or “structural starvation”, have been identified as key drivers of biodiversity loss (Tickner et al., 2020; Skidmore and Wheaton, 2022). As a result, fluvial corridors have become fragmented, resulting in “poor quality” sections of river in between “good quality” sections. Identifying where this fragmentation has occurred and whether it can be repaired is critical to river management (Agnew and Fryirs, 2022; Agnew et al., 2022).

In a global context there are essentially three approaches to river management in operation.

First, the *ad hoc and reactive* (AHR) approach tends to focus on rehabilitation of individual river reaches at the local scale. It is a reactive, opportunistic approach that addresses “problems” in isolation (Hermoso et al., 2012; Robins, 2023; Friberg et al., 2016). It often occurs despite recognition that reach-scale rehabilitation projects should be placed within a catchment-scale context and reach selection should be based on an evidence-based prioritisation framework (Koehn et al., 2001; Beechie et al., 2010; Speed et al., 2016; Robins, 2023). In many cases, societal and

financial values override environmental values in project and reach selection (Anderson et al., 2019), sometimes the result of necessity, with rehabilitation occurring where possible rather than where most needed. The *ad hoc and reactive* approach results in projects being implemented in poorer condition reaches, at great cost, and with a much lower chance of success (Guimarães et al., 2021). Increasingly, this approach to river management is unable to respond to catchment-scale challenges (Speed et al., 2016).

Second, a *working with recovery* (WWR) approach, as a nature-based solution, adopts a working with the river ethos (Fryirs and Brierley, 2021; Burgess-Gamble et al., 2017). River recovery reflects the ability of a river system to repair, either via assisted and strategic intervention or by “leaving the river alone” (Fryirs and Brierley, 2016). River recovery in this context is defined as *geomorphic*, where there is noticeable improvement in a river's physical structure and function (Fryirs and Brierley, 2016; Mabbott and Fryirs, 2022) *vegetative*, where there is noticeable improvement in instream and riparian vegetation cover and quality (O'Donnell et al., 2016; Fryirs et al., 2018; Mabbott and Fryirs, 2022), and *hydrologic*, where increased vegetative roughness results in longer flood peak travel times and reduced flood wave celerity (Fryirs et al., 2023). *Working with recovery* as an approach means identifying where in a catchment recovery can be triggered and/or enhanced to improve the condition (or health) of river systems using process-based, nature-based approaches to improve valuable ecosystem services provision (Beechie et al., 2010; Hawley, 2018; Wheaton et al., 2019; Fryirs and Brierley, 2021). The *working with recovery* approach requires less physical intervention and maintenance, and is considered to be more cost-effective and sustainable than the *ad hoc and reactive* approach (Fryirs and Brierley, 2016; Moore and Rutherford, 2017). When implemented at the catchment rather than reach-scale, *working with recovery* can have other positive off-site and downstream effects such as reduced flood risk and improved longitudinal connectivity for fish migration (Langhans et al., 2016; Hermoso et al., 2021). The *working with recovery* approach typically requires that practitioners understand the recovery potential (high, moderate, or low) of the river systems they are working on (Fryirs et al., 2021). This necessitates that each reach is placed within a catchment context and that the impact of external pressures and internal limiting factors on current and future reach condition are understood (see Brierley and Fryirs (2005); Fryirs and Brierley (2016) for details). In this study, the recovery potential of reaches is used as a prioritisation tool (Agnew and Fryirs, 2022). *Working with recovery* is then applied by prioritising the protection of *conservation* reaches, which are reaches already in good condition with the highest geoeological values. This is followed by intervention to treat *strategic* reaches that contain threatening processes which may impact the integrity of adjacent conservation or other good condition reaches. Then, rehabilitation is further prioritised according to a scale of declining recovery potential in reaches with *high recovery potential* (HRP), followed by *moderate recovery potential* (MRP) and finally *low recovery potential* (LRP) (Brierley and Fryirs, 2005). The recovery potential of a reach will determine the level of intervention that is required. As recovery potential declines, more and costlier intervention is needed. However, strategic reaches may require a range of costly interventions depending on the type of threatening processes being treated.

TABLE 1 Examples of river rehabilitation costs and cost-benefit ratios drawn from the literature.

Rehabilitation project	Costs, benefit-cost ratios, inclusions	Source
<i>Global cost estimates</i>		
European Commission proposed Nature Restoration Law impacts assessment – all EU member states	€1.05 (~A\$1.65) trillion Present Value to 2070. Present value of total rehabilitation cost plus annual maintenance of rivers, lakes, and alluvial habitats	European Commission (2022a)
ESVD Global ecosystem services valuation database	International\$108,000 (~A\$145,000)/ha/year (~50% from waste treatment) Mean value of ecosystem services provided by rivers and lakes	De Groot et al. (2020)
Systematic review of United Kingdom and EU river restoration projects 1989–2016	Costs: €310,000 (~A\$490,000)/ha Restoration (ecosystem services) value €7,757 (~A\$12,300)/ha/year Instream, riparian zone, floodplain costs, and associated ecosystems services value	Szałkiewicz et al. (2018)
New Forest Life III project, United Kingdom: Example case study from RiverWiki database	£2.9 (~A\$5.1) million. 10 km of stream length, 600 ha of riparian zones and wetlands Remeandering and flood risk management, riparian habitat and biodiversity rehabilitation, forestry land use management, monitoring	ECRR (2018)
Case study for standardised reporting of costs of management intervention in Israel	Israeli New Shekel 17,600 (2005 value) = (~A\$5,000) ~600 ha Invasive species eradication	Iacona et al. (2018)
<i>Australian cost estimates</i>		
Hunter Valley – 1st order prioritisation	A\$16,700/ha Riparian revegetation cost	Brooks et al. (2017)
Australian-wide hydrology management	A\$42,235/structure Removal and/or installation of in-stream structures. Includes both management and on-ground costs	Yong et al. (2023)
Australia-wide habitat restoration	A\$440,080/km ² (median) and \$AUD 176,164/km ² (most common) Weed control, and bush regeneration across all major terrestrial vegetation groups. Riparian zones not explicitly costed. Includes both management and on ground costs	Yong et al. (2023)
Upper Hunter River Rehabilitation Initiative (UHRRI)	A\$418,000 expenditure (2004), ~10 km stream length Installation of large wood/bed control structures	DIPNR (2004)
<i>Global and Australian cost-benefit ratios</i>		
EU waterways and alluvial habitats	Strong benefit-cost ratio (BCR) of 24–26 (despite high costs) Rehabilitation of inland waterways and alluvial habitats	De Groot et al. (2020); European Commission (2022a)
EU Flood risk management models (multiple studies)	Benefit-cost ratio >1 in all cases Assessment of the cost-benefit of flood protection under various climate scenarios	Kull et al. (2013); Ward et al. (2017); Corderi-Novoa et al. (2021)
Riparian restoration (New Zealand)	Net benefits up to NZ\$5.2 (~A\$4.9) billion/year, with a benefit-cost ratio between 1.4 and 22.4. Cost-benefit of riparian restoration at national scale	Daigneault et al. (2017)
Mary River catchment (Queensland, Australia)	Positive benefit-cost ratio up to 6.5 times Riparian restoration	Sillar Associates and Kingston Rural Management (1998)
Off-stream watering in farms (Victoria, Australia)	Positive benefit-cost ratio of 1.5 times. Installation of off-stream watering	Dobes et al. (2021)

Third, the *corridors* (Corr) approach prioritises the (re) building of longitudinally continuous river reaches that are in good condition. This catchment and landscape scale approach considers connections with adjacent and surrounding reaches, and works with reach and loci connections to build corridors of

river recovery (Agnew and Fryirs, 2022). Reach connections are defined as an upstream to downstream section of river, linked end-to-end. Loci connections are defined as isolated river sections from which recovery can be established and extended into surrounding reaches and tributaries. In this approach, river managers regard the

fluvial corridor as the management unit, and prioritise the treatment of reaches to connect corridors and undertake rehabilitation where it will enhance the recovery potential of the system as a whole (Beechie et al., 2010; Harvey and Gooseff, 2015; Fryirs and Brierley, 2016; Fryirs et al., 2018; Piégay et al., 2020). Combined with knowledge of local conditions, the *corridors* approach forms a significant input to decision making when prioritising and developing river management strategies, and should provide superior rehabilitation benefits to the *ad hoc and reactive* and *working with recovery* approaches.

In the river management sector no studies have been undertaken on the cost-benefit of the *ad hoc and reactive*, *working with recovery* or *corridors* approaches to quantify their environmental return on investment. For this to take place requires that data are available on the costs of rehabilitation and that a monetary value can be placed on the benefits that ensue (see Table 1 for examples of river rehabilitation costs) (DIPNR, 2004; Brooks et al., 2017; ECRR, 2018; Iacona et al., 2018; Szalkiewicz et al., 2018; European Commission, 2022a; Yong et al., 2023). In some places there are formalised and widespread data available on the scope, outcomes, and costs of river restoration/rehabilitation projects, and some attempts have been made to value the ecosystem service benefits of rehabilitation. For example, an EU and United Kingdom maintained publicly available river restoration database (ECRR, 2023) provides data on broad restoration costs of 119 EU and United Kingdom river restoration projects from 1989 to 2016 (Szalkiewicz et al., 2018). (Table 1). Other sources of costings include a global ecosystem services valuation database (De Groot et al., 2020) and a comprehensive and detailed Impact Assessment Working Paper for the EU-proposed Nature Restoration Law (European Commission, 2022a).

In Australia, however, a systematically organised, publicly available, and transferable approach to river rehabilitation costing, and conservation cost reporting more generally, is lacking (Iacona et al., 2018). Costing data has generally been gleaned from academic and conference papers (Pietsch et al., 2021; Yong et al., 2023), individual project reports (Hunter-Central Rivers CMA, 2008; Brooks et al., 2017), analysis of government programs (Yong et al., 2023) (e.g. Victoria's Strategic Management Prospects program (Thomson et al., 2020) and NSW's Saving Our Species program (DPIE, 2021b)), or direct expert advice obtained from private and government organisations operating in the river management field (Table 1).

Environmental cost-benefit analysis compares the monetary costs and benefits derived from a project to systematically identify and express in monetary terms, the widest possible range of economic, social and environmental costs and benefits of taking (or not) a management action, whereas cost-effectiveness is the quantitative benefit, e.g. rate of species survival or improved ecosystem functioning, compared to its cost (Atkinson et al., 2018; Logar et al., 2019). Managing landscapes to optimise both ecosystem and human benefits, and cost effectiveness (Albert et al., 2021) is complex and dynamic, and often driven by multiple, sometimes conflicting objectives (Renwick et al., 2020). If done well, environmental cost-benefit analysis is a transparent method for project prioritisation *ex ante*, and evaluation *ex post* (Dobes et al., 2016; Atkinson et al., 2018). In most cost-benefit analyses, economic costs and benefits are straightforward to measure in financial terms.

However, non-financial environmental and social costs and benefits require various assumptions to be identified and quantified in financial terms and incorporated into cost-benefit analysis (Dobes et al., 2016; Atkinson et al., 2018; Boardman et al., 2018). Financial proxies, or shadow pricing, including ecosystem service valuation, e.g. willingness to pay, clean water targets, or opportunity cost of pollution abatement, can be assigned to non-financial environmental costs and benefits (Howarth and Farber, 2002; Obst, 2018; Bonner, 2022).

Globally, there is wide variation in the extent of environmental costs and benefits being considered in cost-benefit analysis (Atkinson et al., 2018). In river management, the challenges lie in linking a direct cost to a measure of success (the benefit). Attempts have been made to determine the cost-benefit of riparian revegetation (Kimball et al., 2015), determine public preferences and willingness to pay for rehabilitation and to translate ecological and ecosystem services into economic values (Logar et al., 2019). In the EU, cost-benefit analysis has been used to assess the ecological impact of proposed riverine restoration actions to 2050 under the proposed Nature Restoration Law, finding strong benefit-cost ratios despite high costs (De Groot et al., 2020; European Commission, 2022a) (Table 1). Elsewhere, flood risk management models yield positive benefit-cost ratios (Kull et al., 2013; Ward et al., 2017; Corderi-Novoa et al., 2021), and in New Zealand, riparian restoration at national scale would yield a positive benefit-cost ratio (Daigneault et al., 2017) (Table 1).

In Australia, cost-benefit analysis for freshwater systems have largely been focussed on biodiversity conservation, e.g., in south-east Queensland streams (Mantyka-Pringle et al., 2016). Other cost-benefit analyses have analysed the provision of environmental flows at flood stage in the Murray Darling Basin (Kahan et al., 2021), and riparian restoration of Queensland's Mary River catchment, the latter yielding a positive benefit-cost ratio up to 6.5 times (Sillar Associates and Kingston Rural Management, 1998). Cost-benefit analysis has also been used to demonstrate the economic benefits from off-stream watering in farms (Dobes et al., 2021) and the mutual environmental and economic benefits from improving (e.g. fencing off) riparian zones (Cary et al., 2002; NRMSouth, 2015; NSW Government, 2021), resulting in positive benefit-cost ratios (Table 1).

Dobes et al. (2016) addresses some of the issues with environmental cost-benefit analysis in Australia and recommends that cost-benefit analysis frameworks be comprehensively harmonised and systemised across government organisations to provide transparency and rigour to project analysis. Systematic integration of geomorphological, ecological, and economic objectives into strategic planning is essential to identify the trade-offs between biodiversity conservation and ecosystem service delivery and optimise rehabilitation solutions both financially and environmentally (Hermoso et al., 2015; Fastré et al., 2020). Therefore, there is a need to identify, adapt and use a cost-benefit analysis tool and framework that can meet these requirements.

In conservation planning the maxim has been to emphasise the protection of intact habitat compared to restoration of degraded areas to achieve conservation goals, firstly addressing areas in good condition and working outwards into poorer areas (Dodds et al., 2008; Possingham et al., 2015; Garcia et al., 2021). In river

management, rehabilitation can deliver improved ecosystem services (Bernhardt et al., 2005; Logar et al., 2019; Kaiser et al., 2020; Lin et al., 2020). For example, restoration of natural sediment regimes can support improved ecosystem functioning (Wohl et al., 2015). Nature-based solutions can be used to rehabilitate floodplain wetlands and riparian buffers to arrest biodiversity loss by improving channel and floodplain form and habitat heterogeneity (Hamilton et al., 2007; Sheldon et al., 2012; Langhans et al., 2014; Tickner et al., 2020). Tulloch et al. (2017) demonstrate the benefits of classification of remotely sensed geomorphic mapping as a surrogate for biodiversity representation.

Marxan is a spatial prioritisation tool, extensively used globally for systematic conservation planning (Lewis et al., 2003; Ball et al., 2009), most often in marine (Lewis et al., 2003) and terrestrial systems. Where it has been applied to freshwater and riparian systems, the focus has been on biodiversity, not geomorphology (Linke et al., 2019; Szabolcs et al., 2022). In Reis et al. (2019), Marxan was used to assess ecosystem protection using floodplain-wetland longitudinal and lateral connectivity. Marxan has been used to systematically prioritise cost-effective rehabilitation strategies in Swiss cantons by optimising the spatial allocation of costed repair, based on riparian condition assessment, to meet ecological benefits (Langhans et al., 2014). Where Marxan has incorporated geomorphology, this has been in marine reserves (Heyman and Wright, 2011; Tulloch et al., 2017) and at broad scales in terrestrial systems (Nel et al., 2009; Anderson et al., 2015), rather than in fluvial systems. However, Heyman and Wright (2011) advocate the use of geomorphology in marine reserve planning, and Álvarez-Romero et al. (2016) undertook marine planning based on river sediment plumes. Marxan can be used to prioritise the allocation of barrier removal projects to improve river geomorphology, allowing for augmented fish populations (Hermoso et al., 2021). Within Australian river systems, Marxan was instrumental in determining floodplain water allocation plans in the Murray-Darling Basin (DPIE, 2020), and in the New South Wales Hawkesbury/South Creek catchment to create a comprehensive map integrating strategic planning priorities for protection and enhancement of streamlines, riparian vegetation, and other water-dependent ecosystems (Dela-Cruz et al., 2021).

In this study we undertake the first cost-benefit analysis for river management in coastal catchments of NSW, Australia. The cost-benefit analysis focus in this study is restricted to using quantifiable costs and implied benefits from improved recovery potential over time to demonstrate the value in undertaking geomorphically-informed rehabilitation. We first calculate the potential costs of river rehabilitation based on the current recovery potential of these rivers. Using percentages of each recovery potential rehabilitated as determined by the river management approach, we then quantify the cost of the *ad hoc and reactive, working with recovery and corridor* approaches for these rivers. We then employ Marxan in a novel manner, setting targets for different river classifications, rather than species or habitats, to identify optimal locations for rehabilitation under present day and future scenarios. We then use Marxan as a cost-benefit analysis tool to systematically prioritise rehabilitation of fluvial corridors, working at the landscape scale, for current and future timescales, demonstrating benefits from improvements in recovery potential over time.

2 Methods

2.1 Study area

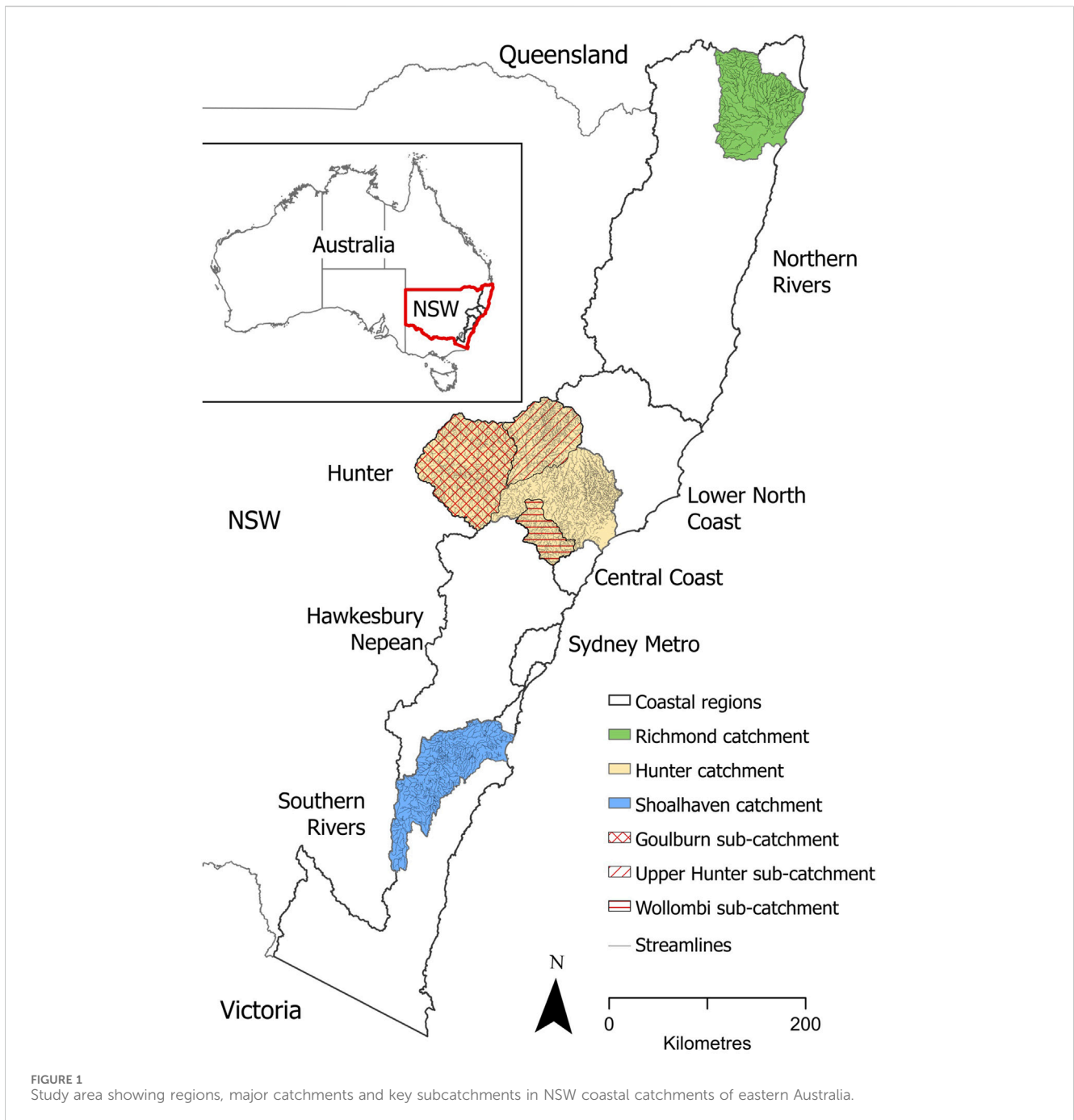
The study area covers the 20 major coastal catchments of NSW (140,025 km²), 75,461 km of freshwater stream length and seven regions (Figure 1, Supplementary Table S1 in Supplementary Material). In each region, the recovery potential of each streamline has already been assessed using the River Styles Framework (Brierley and Fryirs, 2005; DPIE, 2021a; Fryirs et al., 2021). Fluvial corridors containing reach and loci connections of various combinations have also already been identified for rehabilitation prioritisation (Fryirs et al., 2021; Agnew and Fryirs, 2022). Both these datasets are available Open Access at the NSW Government SEED portal, River Styles at NSW Government and DCCEEW (2023) and corridors datasets at Commonwealth of Australia and Macquarie University (2023).

For regional costings we analysed the whole study area using the corridors dataset of Agnew and Fryirs (2022). Additionally, three major catchments and three key sub-catchments were selected for more detailed costing analysis and cost-benefit analysis using Marxan (Figure 1). Selection criteria were the overall length and diversity of suitable reach and loci connections. Three representative major catchments with diverse valley settings and assemblage of recovery potentials, Richmond (3,324 km stream length, 7,033 km² catchment area), Hunter (15,269 km, 21,447 km²) and Shoalhaven (3,962 km, 7,208 km²) were selected for analysis. In addition, the Hunter catchment has a diverse range of recovery potentials, and reach and loci connections, and long stream length. Therefore, three key sub-catchments with these characteristics were selected from the Hunter catchment to test the level of variability in cost-benefit analysis results produced; the Upper Hunter (upstream of Denman township) (3,563 km, 4,490 km²), Goulburn (4,715 km, 7,782 km²) and Wollombi (1,408 km, 1,909 km²).

Some reaches have multiple reach and/or loci connections, e.g., a strategic reach may be both upstream of high recovery potential and downstream of conservation reaches. To avoid double counting, overlapping reaches within reach and loci connections have been removed from the analysis. However, there is still overlap where a reach forms part of both a reach connection and a loci connection. This resulted in 4,926 km and 5,888 km of reach and loci connections, respectively, to be used in the analysis, detailed by River Styles regions, and selected catchments and sub-catchments (Supplementary Table S1 in Supplementary Material).

2.2 Quantifying instream and riparian rehabilitation costs

A 40 m wide riparian zone (20 m perpendicular to each channel bank) was identified as a suitable and consistently applied average riparian zone width for rehabilitation, based on recommended riparian zone widths for Australian agricultural lands of between 20 and 38 m reported in Hansen et al. (2015), and optimum ideal width modelled by Malcher et al. (2023). Costs were applied assuming a 40 m riparian zone was being rehabilitated for all streams.



Typical rehabilitation activities and techniques were identified from a range of options identified in the literature (Brierley and Fryirs, 2005; Szalkiewicz et al., 2018) and from government and industry sources (Wheaton et al., 2019; The River Restoration Centre, 2020). To determine costings for the rehabilitation activities, we consulted expert industry professionals within Hunter Local Land Services, Landcare Australia, and MidCoast Council; three organisations actively involved in river rehabilitation in NSW coastal catchments. We obtained detailed estimates and actual costings for a variety of rehabilitation techniques, activities and from completed projects. Costs obtained were current from 2020 to 2023, and not inflation

adjusted. Costs were restricted to on-ground rehabilitation and maintenance costs to enable direct comparison between the different rehabilitation approaches. Costs excluded design, management and other logistics costs, such as those included in Yong et al. (2023). Rehabilitation costs include instream structural works (e.g., bed control), riparian zone structural works (e.g., bank attached structures, fencing, off stream watering) and vegetative works (site preparation, weed removal, seeding and planting, ongoing maintenance). Rehabilitation costs can vary significantly across regions. Differences occur due to project size and site-specific rehabilitation requirements, methods, and limitations such as access. Costly components of rehabilitation include labour, and

TABLE 2 Rehabilitation cost assumptions and inputs for cost-benefit analysis.

Rehabilitation activity	Cost (AUD) (average unless otherwise specified)	Cost assumptions (discount rate used 2.5% pa (ABS, 2023))
Riparian fencing	\$40,000/km	Based on bare paddock, installed by contractor including materials
Off stream watering	\$5,000/km	1 trough/bank/km
Weeding	\$2,250/ha	
Revegetation	\$15,000/ha	Planting in a bare paddock/riparian zone with no native vegetation 300 plants/100 m of stream length @\$10 each seedling. Tube-stock with tree guard, planted by contractor
Ongoing vegetation maintenance	\$450/ha	Annually for 4 years
Instream rock bed controls for headcuts	\$105,000/bed control, range \$60,000 - \$150,000	1 bed control/km
Engineered log jams	\$30,000/log jam, range \$10,000 - \$50,000	5 log jams/km
Timber deflectors	\$5,000/deflector	10 deflectors/km
Riparian % wood coverage	n/a	Riparian woody vegetation coverage by recovery potential, derived from NSW OEH Woody Vegetation data based on SPOT 5 imagery (Brooks et al., 2017)

the installation of in-stream structures. Some costs decrease on a per-hectare basis as project size increases, i.e. those where transport and equipment deployment form an integral fixed cost component e.g. fencing, direct seeding, herbicide boom spraying (Schirmer and Field, 2000). Other costs relate directly to project size, particularly consumable costs, e. g. seedlings, seeds, and stakes; and the per-hectare cost stays relatively stable irrespective of project size (Schirmer and Field, 2000). The rehabilitation activities selected for this study are indicative rather than exhaustive and reflect using nature-based solutions where possible to work with a river's recovery trajectory. Based on the activities required for each level of recovery potential, and using a discount rate of 2.5% pa (ABS, 2023), a per hectare average cost for rehabilitation was calculated. This average cost, based on a representative selection of rehabilitation activities, varied depending on the level of recovery potential, rather than on a bespoke cost developed for each reach, thus enabling comparison between the different recovery potentials across the study area.

Rehabilitation costs were applied to conservation and strategic reaches, to each category of recovery potential (high, moderate and low), and to selected reach and loci connections identified as reaches that can be used to build corridors of recovery (sourced from Agnew and Fryirs (2022)). In that study, reach and loci connections ranged from <1 to >155 km in length, averaging 2.6 km. The primary aim is to compare rehabilitation costs between different recovery potentials and reach and loci connections. For each recovery potential, the estimated and/or actual costs of each activity were collated to determine an average rehabilitation cost. Riparian coverage by recovery potential was calculated and used as an input (Brooks et al., 2017) and cost assumptions based on the literature e.g. Yong et al. (2023). Costings were converted to a per hectare basis to enable comparison with the literature (Table 2).

2.3 Marxan parameter and scenario selection

In this study, Marxan is used in a novel manner to identify optimal locations for rehabilitation and to systematically prioritise

rehabilitation of fluvial corridors. Marxan enables users to satisfy user-defined conservation management targets for the minimum cost. Whilst Marxan does not explicitly use cost-benefit or cost-effective analysis in solving target-based problems, Marxan invariably delivers cost-effective options. Marxan's algorithm provides a "near optimal" solution based on the costs of conservation targets of selected "features" (Morrell et al., 2015). This "near optimal" solution should however be considered within a continuum of good options, one of Marxan's strengths as a prioritisation tool (Ardron et al., 2010). Marxan is generally used for ecological optimisation, but can also include economic and social characteristics, e.g., the cost-effectiveness of ecosystem services provision (Adame et al., 2015). Numerous prioritisation criteria can be included, e.g. percentage level of species protection and cost of protection (Kark et al., 2009). Costs can be financial or non-financial, e.g., land or cultural values (Adams et al., 2016; Dela-Cruz et al., 2021). By varying the selection criteria, multiple scenarios can be run.

In Marxan, features are usually based on species distribution datasets within a reserve area (Morrell et al., 2015). In this study, we have considered the varying recovery potentials of reaches within a catchment as features. Firstly, we determined the average per hectare rehabilitation cost of each category of recovery potential feature. This rehabilitation cost was then used as the cost parameter to prioritise reaches for rehabilitation within Marxan. Following Marxan best practice guidelines (Ardron et al., 2010), we elected to use the default settings where possible, thus removing an additional layer of decision making for river managers. This potentially makes the analysis more accessible to river managers for uptake and use. Using the default settings did not affect comparison between scenarios, however, river managers can elect to adjust Marxan settings to accommodate their strategic preferences.

Using Marxan, the study area is divided into small geographic parcels of regular or irregular shapes such as hexagons or squares, and/or from hydrological drainage areas (catchments), to create planning units (Reis et al., 2019). In this study, we used hexagons,

TABLE 3 Marxan scenarios for reaches by recovery potential, and reach and loci connections, with target percentages of each recovery potential (in ha) protected, based on expert advice of several practicing agency river managers which was reasonably aligned with the literature. Depending on local conditions and their own strategic requirements, river managers can select their own protection percentages, and run different scenarios in Marxan. All scenarios, except *working with recovery #2 with budget*, are without budgetary constraints. The River Styles database (DPIE, 2021a) also contains a rapid recovery potential classification. For this analysis rapid recovery potential was combined with high recovery potential.

Scenario	Scenario rationale	Target percentages protected
Time slice 1 = current recovery potential classifications		
AHR1	<i>Ad hoc and reactive #1</i> Worst case #1 with a higher percentage of moderate recovery potential reaches protected than low recovery potential reaches. Percentages selected to demonstrate the effect of focussing rehabilitation efforts in lesser quality recovery potentials	Conservation 0%, strategic 100%, high recovery potential 10%, moderate recovery potential 80%, low recovery potential 50%
AHR2	<i>Ad hoc and reactive #2</i> Worst case #2 with equal target percentage of moderate and low recovery potential reaches protected. Most reach-based rehabilitation projects are done in moderate and low recovery potential reaches. As in <i>ad hoc and reactive #1</i> , percentages selected to demonstrate the effect of focussing rehabilitation in the lesser quality recovery potential reaches to an even greater degree	Conservation 0%, strategic 100%, high recovery potential 10%, moderate recovery potential 70%, low recovery potential 70%
WWR1	<i>Working with recovery #1</i> Protection, based on protecting 100% of conservation reaches, the most conservative <i>working with recovery</i> option	Conservation 100%, strategic 90%, high recovery potential 100%, moderate recovery potential 50%, low recovery potential 0%
WWR2	<i>Working with recovery #2</i> Assume conservation reaches do not need protection because already in good condition and should not require any rehabilitation funds allocated, so are excluded in this scenario. The target percentage protected reduces as recovery potential reduces	Conservation 0%, strategic 90%, high recovery potential 100%, moderate recovery potential 50%, low recovery potential 0%
WWR3	<i>Working with recovery #3</i> Assume conservation reaches do not need protection, and high recovery potential at 100% protection and moderate and low recovery potential at 0% - this is truly working with recovery	Conservation 0%, strategic 90%, high recovery potential 100%, moderate recovery potential 0%, low recovery potential 0%
WWR2B	<i>Working with recovery #2 with budget.</i> Same assumptions as <i>working with recovery #2</i> , with a fixed budget	Same as <i>working with recovery #2</i>
Corr1	<i>Corridors approach #1</i> Selecting reach connections from corridors analysis (Agnew and Fryirs, 2022), and working with recovery	Conservation 0%, strategic 90%, high recovery potential 100%, moderate recovery potential 0%, low recovery potential 0%
Corr2	<i>Corridors approach #2</i> Differentiate between reach and loci connections as determined by corridors analysis (Agnew and Fryirs, 2022)	Conservation (all connections) 0%, strategic (all) 90% high recovery potential (reach 100%, loci 80%) moderate recovery potential (all) 0%, low recovery potential (all) 0%
Time slice 2 = future scenarios (15 years) using Hunter as a demonstration catchment		
WWR4	<i>Working with recovery #4</i> Improved recovery potentials with diminishing cost effect and based on <i>working with recovery #3</i> scenario percentages. Low recovery potential reaches stay the same because not focussing efforts on them. Effort is focussed on strategic to improve them, and prevent deterioration of conservation and high recovery potential reaches. Assume the following reclassification in recovery potential: strategic to moderate recovery potential, high recovery potential to conservation. Other recovery potentials, i.e. conservation, moderate recovery potential, and low recovery potential stay the same	Conservation 0%, strategic 90%, high recovery potential 100%, moderate recovery potential 50%, low recovery potential 0%
AHR3	<i>Ad hoc and reactive #3</i> Deteriorating recovery potentials with increasing cost effect, and based on <i>ad hoc and reactive #2</i> percentages. Assume the following reclassification due to strategic threatening processes negatively impacting the adjoining conservation and high recovery potential reaches: high to low recovery potential, conservation to moderate recovery potential. Other recovery potentials, i.e. strategic, moderate and low recovery potentials stay the same	Conservation 0%, strategic 100%, high recovery potential 10%, moderate recovery potential 70%, low recovery potential 70%

rather than catchments, as hexagons provide a compact efficient interlocking shape, suitable for incorporating the fixed-width riparian zones for rehabilitation and following streamlines of various configurations. Hexagons were also the preferred planning unit as their scale enables scenario selection at the smaller recovery potential-classified reach scale as well as at

corridor scale, compared to catchment or subcatchment scale planning units which are too large and encompass both corridor and non-corridor sections. The planning units were defined from catchments and sub catchments derived using the River Styles recovery potential database (DPIE, 2021a) and an open access digital elevation model (Wilson et al., 2011). This provided

planning units covering both streamlines and adjacent riparian zones. Planning units were defined as 10 ha hexagons, equating to an ~400 m longitudinal section of stream, which is considered an appropriate unit size for river rehabilitation project planning, given an ~2 km mean reach length across NSW coastal catchments. To reduce processing time, the number of planning units was reduced by removing terrestrial-only components more than 200 m from streamlines. Only planning units within 200 m of streamlines were retained for analysis, fully encompassing the 40 m riparian zone, and allowing longitudinal analysis along entire streamlines. The number of planning units in each catchment depended on each catchment's stream length, and ranged from 113,853 planning units in the Hunter catchment to 10,860 planning units in the Wollombi sub catchment.

We calibrated the Boundary Length Modifier to locate the optimal efficiency of cost increase versus boundary length reduction (Ardron et al., 2010), based on the 100% conservation protection scenario in Wollombi sub-catchment. Average reserve cost plotted against the average value of total boundary length of all solutions resulted in an optimal boundary length modifier of 0.6, which we then used for all Marxan analysis. Equation of best fit: $y = -15.213x + 7E+07$; $R^2 = 0.8885$.

Marxan output determines how many, and which specific, planning units should be optimally selected for each scenario. In this study we ran Marxan 100 times for each scenario to provide sufficient repetition, as the solutions generated were a representative sample of the solutions available (Ardron et al., 2010). For each solution, a score is derived for each planning unit, with lower scores preferred to higher scores, where protection targets, e.g. percentage of a recovery potential classification protected, are met with minimum cost. From these 100 possible solutions, Marxan outputs the "best" solution, which has the lowest overall score. Marxan also derives a summed solution, based on selection frequency, to show how often a planning unit is selected for inclusion. Planning units that are more frequently selected under varying scenarios are more likely to meet all management targets and form higher priority for protection (Ardron et al., 2010).

We started by running the *ad hoc and reactive*, *working with recovery* and *corridors* scenarios across the study area (Table 3). For each, we tested scenarios based on current recovery potentials (time slice 1), and future (in 15 years) estimated recovery potentials (time slice 2). For each scenario, we based the percentages of each recovery potential to be protected on expert advice from several practicing agency river managers and the literature, without any budgetary constraints. Input of percentages protected obtained from agency river managers was reasonably aligned with the literature. The selection was focussed on creating an approach to the comparison of scenarios. However, river managers can select their own protection percentages to tailor scenarios to their strategic planning. For time slice 1, we developed seven scenarios based on the current recovery potential classifications to analyse what would be considered best practice i.e. working with recovery in the highest recovery potential reaches and reach and loci connections (scenarios *working with recovery* #1, #2, and #3, and *corridors* #1 and #2), versus worst case *ad hoc* practices working in lower recovery potential reaches (*ad hoc and reactive* #1 and #2). For time slice 2, we developed two future scenarios based on improved recovery potentials (*working with recovery* #4) and deteriorating

recovery potentials (*ad hoc and reactive* #3), applying an inflation rate of 2.5% pa (ABS, 2023). We did not develop time slice 2 scenarios based on the corridors approach as that would involve reassessment of all reach and loci connections, a potential future study. We used the Hunter regional catchment to demonstrate the effect of these future scenarios, as this catchment has considerable diversity, and long stream length. For demonstration purposes, as input to the future scenarios, we reclassified current recovery potentials to proposed future recovery potentials following the likely rehabilitation impact of two current scenarios, *working with recovery* #3 and *ad hoc and reactive* #2. In addition, we developed a rehabilitation scenario based on *working with recovery* #2 with a fixed dollar budget (*working with recovery* #2 with budget) and the Cost Threshold Penalty variable to demonstrate the use of Marxan for optimal rehabilitation project selection. The Cost Threshold Penalty enables the user to assess scenarios in reverse, i.e. find a solution which is the best representation for all features constrained by a maximum cost (Ball and Possingham, 2000).

3 Results

3.1 Rehabilitation costs by recovery potential and reach and loci connections

Rehabilitation costs were applied to buffered recovery potentials to obtain total rehabilitation costs for the combined 20 coastal catchments, three representative major catchments and three key subcatchments. Total rehabilitation costs were based on 20 m buffered streamlines and ranged from \$11,115/km (\$2,779/ha) of stream length for conservation reaches to \$326,715/km (\$81,679/ha) of stream length for low recovery potential reaches (Supplementary Table S2 in Supplementary Material). Total estimated rehabilitation cost for the 20 coastal catchments is \$8.165 billion (Figure 2, Supplementary Table S2 in Supplementary Material). This ranges from the Northern Rivers region with both the longest stream length (25,540 km) and the largest total rehabilitation cost of \$2,650 million, to the smallest stream length (702 km) and cost of \$62 million in the Sydney Metro catchment. Combined strategic and low recovery potential rehabilitation cost and stream length as a proportion of total rehabilitation cost and stream length across all regions, catchments and sub-catchments ranges from 13%–55% and 3%–29%, respectively (Supplementary Table S2 in Supplementary Material). The Goulburn sub-catchment has the largest proportion (55%) of combined strategic and low recovery potential reach rehabilitation costs, and the highest proportion (29%) of combined strategic and low recovery potential reach length. Within the Hunter region, the Goulburn, Upper Hunter, and Wollombi sub-catchments have similar proportions of combined strategic and low recovery potential rehabilitation costs compared to total rehabilitation costs, 55%, 45% and 52% respectively.

Rehabilitation costs by buffered recovery potential were applied to selected reach and loci connections to obtain corridor rehabilitation costs for the combined 20 coastal catchments, three representative major catchments, and three key sub catchments in the Hunter region. Total estimated rehabilitation cost for the selected reach and loci connections of the 20 coastal catchments was \$940 million and

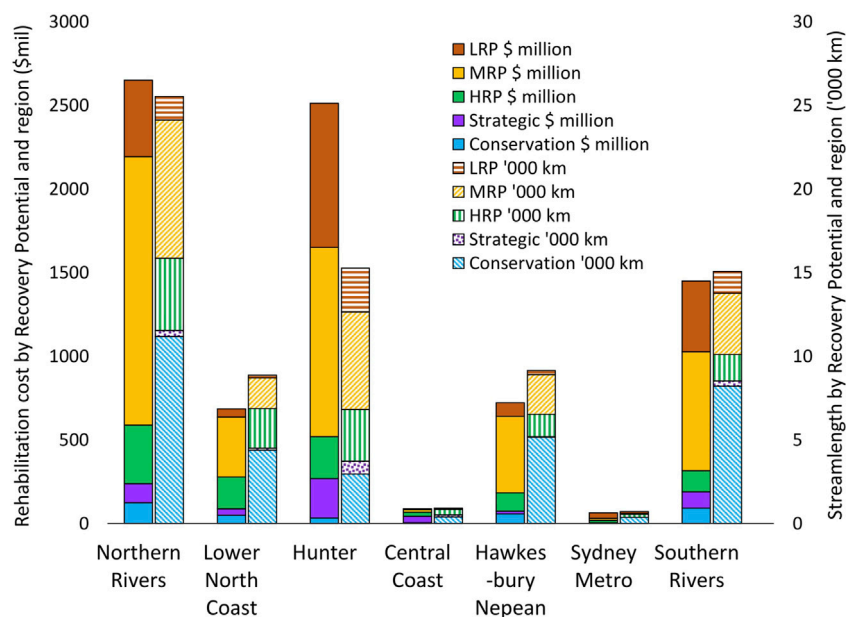


FIGURE 2 Stream length and total rehabilitation costs (\$ million) and stream length ('000 km) for each recovery potential, by region. HRP = High recovery potential; MRP = Moderate recovery potential; LRP = Low recovery potential.

\$592 million, respectively (Figure 3, Supplementary Table S3 in Supplementary Material). There was minor overlap between the totals for reach and loci connections, as a reach may form part of both a reach connection and a loci connection. Total reach connection rehabilitation costs represented less than 12% of the \$8.165 billion total recovery potential rehabilitation cost across the study area, despite a ‘skewing’ to strategic reach connections. Correspondingly, total loci connection rehabilitation costs represented 7% of total recovery potential rehabilitation costs. Generally, reach connection rehabilitation cost as a percentage of total regional recovery potential cost was less than 13%, except for Sydney Metro and Central Coast, 26% and 92% respectively. Generally, loci connection rehabilitation cost as a percentage of total regional recovery potential cost was less than 10%, except for Central Coast at 35%.

3.2 Marxan results

3.2.1 Time slice 1 – current situation

The seven Marxan scenario best solution (lowest objective function) results were based on protecting varying percentages of the different buffered recovery potentials and reach and loci connections within a system. Total rehabilitation costs for all scenarios ranged from \$12 million (*corridors #1* in Upper Hunter) to \$1,633 million (*ad hoc and reactive #2* in Hunter) (Figures 4A, 5, and Supplementary Table S4 in Supplementary Material). Generally, total costs were lowest for *working with recovery #3*, *corridors #1* and *corridors #2*, and highest for *ad hoc and reactive #1* and *ad hoc and reactive #2*. Total costs for Hunter catchment scenarios were higher than all other catchments, due to its longer total stream length. The total hectares of buffered recovery potentials and reach and/or loci connections available for selection impacted each scenario outcome. Total rehabilitation cost and total area

protected for *corridors #1* and *corridors #2* was lower compared to *working with recovery* and *ad hoc and reactive* scenarios, as *corridors #1* and *corridors #2* drew from only the corridor connections, and not total stream length, in each catchment (Figures 4A, 5, and Supplementary Table S4 in Supplementary Material).

Rehabilitation cost per hectare followed a similar trend, ranging from \$12,552/ha (*working with recovery #1* in Shoalhaven) to \$61,506/ha (*ad hoc and reactive #2* in Goulburn) (Figures 4B, Figure 5, and Supplementary Table S4 in Supplementary Material). Generally, *working with recovery #1* scenario generated the lowest per hectare cost followed by *working with recovery #3*, *corridors #1* and *corridors #2* scenarios. For all catchments, *ad hoc and reactive #2* scenario generated the highest per hectare cost. For all catchments, per hectare costs of *working with recovery #2* and *working with recovery #3* scenarios were similar to *corridors #1* and *corridors #2* scenarios, but with a lower total area protected. If *working with recovery* or *corridors* scenarios are implemented, the cost per hectare will be lower than if *ad hoc and reactive* scenarios are implemented, providing a financial benefit (Figures 4B, 5, and Supplementary Table S4 in Supplementary Material).

Protection targets (percentage protected) of all recovery potentials and reach and loci connections met a threshold of approximately 90% of each scenario’s parameters. The number of planning units selected was similar between the best solutions for each recovery potential scenario in each catchment. The spatial distribution of selected planning units among the seven scenarios was similar, and only varied according to the scenario parameters. Generally, planning units selected under the optimal solution for each scenario were scattered throughout the study area with clear spatial pattern and clumping. The Marxan results can be visualised as follows, using the *corridors*

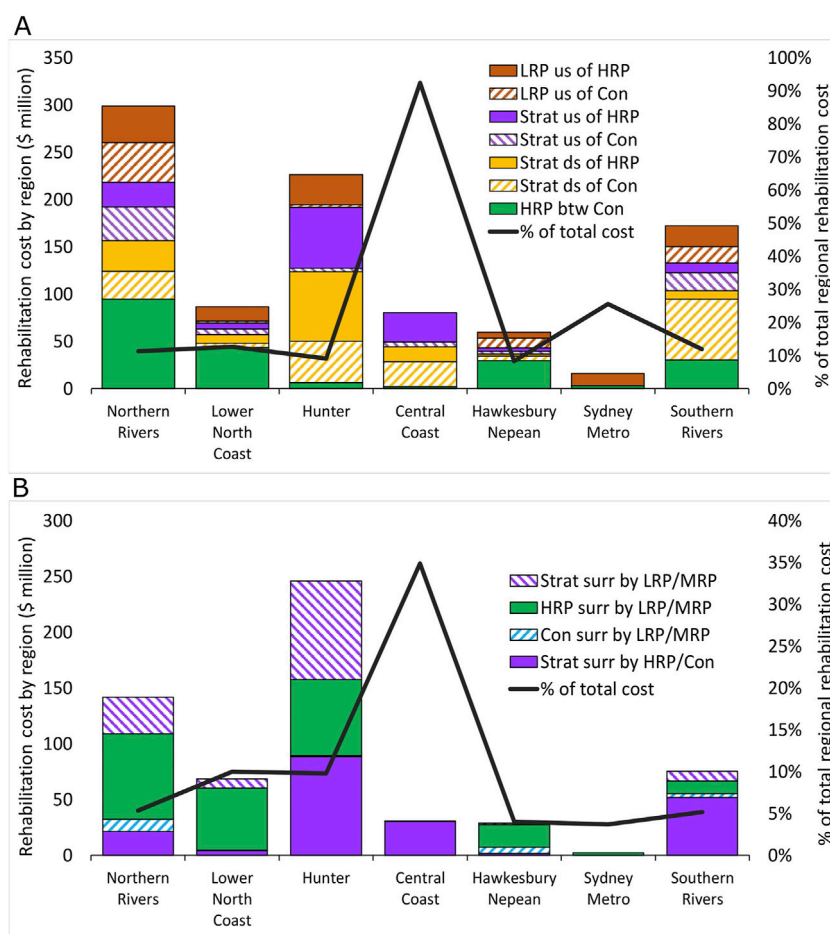


FIGURE 3 Rehabilitation costs (\$ million) and as % of total regional recovery potential rehabilitation cost, for selected (A) reach and (B) loci connections, by region. Con = Conservation; Strat = Strategic; HRP = High recovery potential; MRP = Moderate recovery potential; LRP = Low recovery potential; ds of = downstream of; us of = upstream of; surr by = surrounded by.

#2 scenario for Upper Hunter catchment as an example, and Pages River in detail (Figure 6).

The best solution for each scenario for a catchment or sub-catchment yielded a range of optimal planning unit combinations. This can clearly be seen in the example in Figure 7, a detailed portion of Goulburn River sub-catchment, showing Kerrabee Creek and Widden Brook. Yellow hexagons represent the planning units included in the optimal solutions under each scenario, whilst blue hexagons represent planning units omitted from the optimal solution. There is good clumping of included planning units in all scenarios. Across scenarios, there is spatial variability in included planning units, however this will be influenced by the different scenarios, which completely excluded specific recovery potentials and reach and/or loci connections. However, in *ad hoc and reactive #1* and *ad hoc and reactive #2* scenarios, where the percentage proportion of moderate and low recovery potential reaches included in the solution only varied from 50% to 80%, spatial variability between the two scenarios was similar. For *corridors #1* and *corridors #2*, the scenarios using reach and/or loci connections, there are fewer planning units for potential inclusion, reflected in the more sparsely distributed optimal solutions.

3.2.2 Time slice 1 - fixed budget demonstration

Using Marxan, we applied a fixed budget scenario (*working with recovery #2 with budget*) of \$300,000 to two subcatchment scale projects to demonstrate the difference in rehabilitation outcomes. The two project areas each comprised approximately 15 km of stream length, one optimal with 85% high recovery potential reaches, and one sub-optimal with 67% moderate and 18% high recovery potential reaches. The optimal project had 46% more riparian zone area selected for rehabilitation (Figure 8).

3.2.3 Time slice 2 – future situation

In time slice 2, over a 15 year period, based on the Hunter catchment for demonstration purposes, total rehabilitation cost for *working with recovery #4* (time slice 2) was \$543 million, approximately 50% of *working with recovery #1* and #2 time slice 1 scenarios, and approximately 25% higher than *working with recovery #3* (Figure 9 and Table 4). Alternatively, following the *ad hoc and reactive* approach, total rehabilitation cost for *ad hoc and reactive #3* (time slice 2) was \$3.433 billion, higher than all other *working with recovery, ad hoc and reactive* and *corridors* time slice 1 scenarios. The per hectare cost for *working with recovery #4* was \$50,394, higher than time slice 1 *working with recovery* scenarios, due to the lack of lower cost high recovery

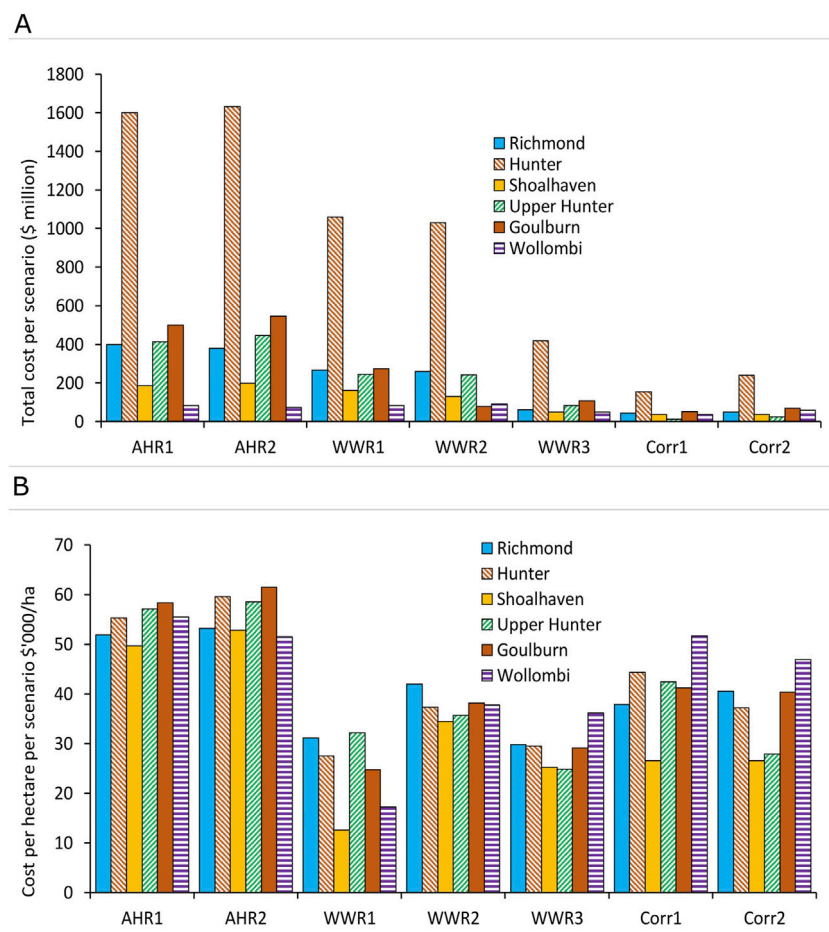


FIGURE 4 Comparison of (A) total (\$ million) and (B) per hectare (\$'000/ha) rehabilitation cost for major catchments and key subcatchments for each of the seven current scenarios (time slice 1). AHR = *ad hoc and reactive*; WWR = *working with recovery*; Corr = *corridors*.

potential reaches in the time slice 2 scenario, which drove the per hectare cost down. Overall, 18% of reaches were identified for rehabilitation in *working with recovery* #4, lower than time slice 1 *working with recovery* scenarios, again due to a lack of high recovery potential reaches requiring rehabilitation. Conversely, the percentage of reaches identified for rehabilitation in *ad hoc and reactive* #3 was 72%, higher than *ad hoc and reactive* time slice 1 reaches, as more strategic and moderate recovery potential reaches required rehabilitation. Figure 9 and Table 4 show the impact of changing rehabilitation approach, and evolution over time.

4 Discussion

4.1 Rehabilitation costs in context

In this study, the financial cost to rehabilitate 75,461 km of stream length across NSW coastal catchments is \$8.165 billion. This represents <0.5% of Australia’s GDP of \$1.688 trillion (ABS, 2023). The rehabilitation cost compares favourably to the estimated insurance losses of ~\$6.41 billion from eastern Australia’s 2021–2022 floods (Insurance Council of Australia, 2022; O’Kane and Fuller, 2022) that

were amongst the costliest natural disasters in Australia’s recorded history. With targeted rehabilitation restricted to selected fluvial reach and loci corridor connections, the estimated rehabilitation cost reduces to \$940 million and \$592 million, respectively. Whilst at the state level the estimated \$8.165 billion is a considerable total cost, this cost can be distributed, over decades, by region, major catchment or subcatchments and associated river management authorities (Figure 10).

The contrast between disaster relief expenditure and disaster resilience expenditure in Australia is stark. Federal Government expenditure on disaster resilience (\$0.51 billion) over the period 2005 to 2022 represented only 2.12% of expenditure on disaster relief (\$23.99 billion) (Insurance Council of Australia, 2022; Lefebvre and Reinhard, 2022). There are calls for government to focus more on resilience and future-proofing against natural disasters (Fryirs et al., 2023). The CSIRO has forecast the annual economic cost of natural disasters in Australia will reach \$35.2 billion by 2050, or three times 2017 costs, if there is no substantial investment in mitigation (Naughtin et al., 2022). The Federal Government committed \$1.1 billion across 6 years (2019–2023) for environmental protection and a further \$1.1 billion commitment for 2023–2028 through the Natural Heritage Trust (DCCEE, 2024). This contrasts with the estimated \$2 billion annual expenditure (0.1% of GDP) required to support

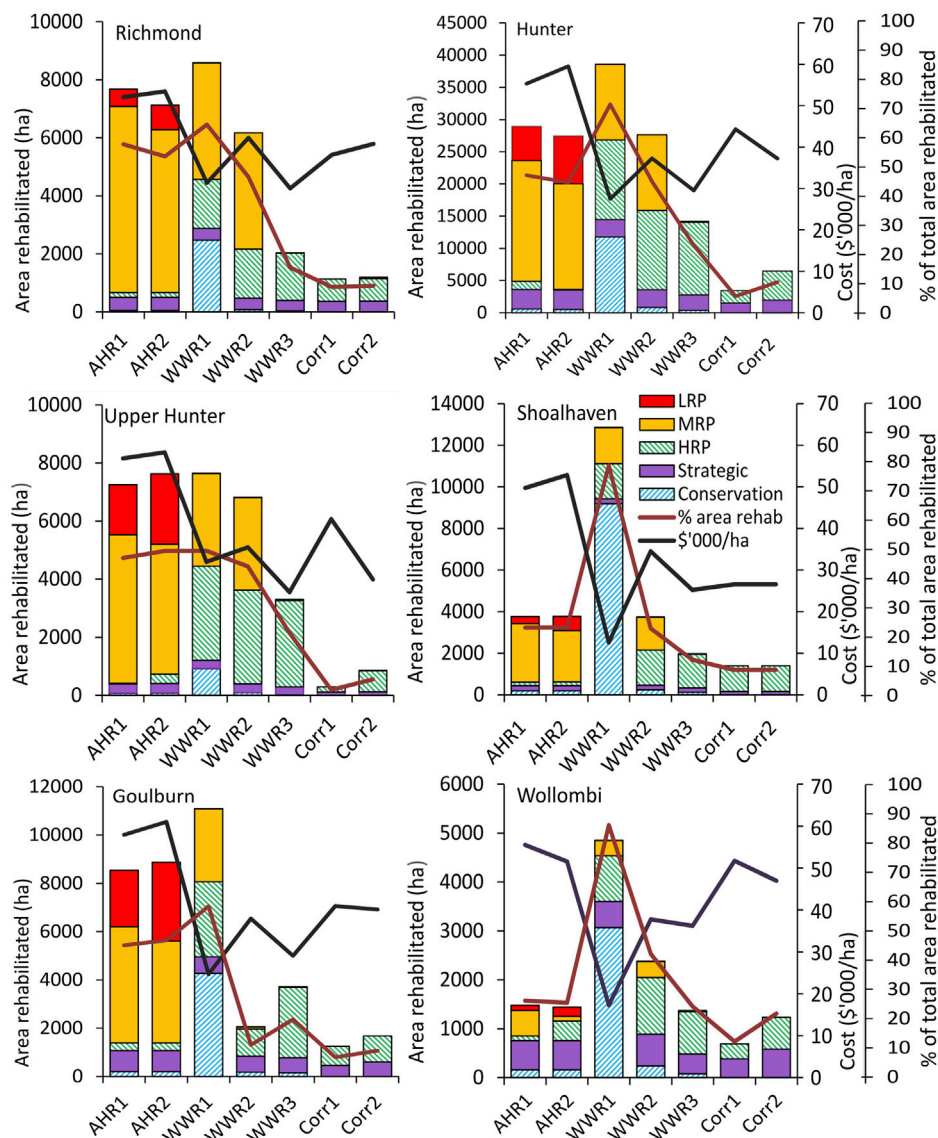


FIGURE 5 Major catchments and key subcatchments showing total area rehabilitated (ha), % of total area rehabilitated (%), and cost per hectare (\$'000/ha) for each of the seven current scenarios (time slice 1). AHR = *ad hoc and reactive*, WWR = *working with recovery*, Corr = *corridors*. HRP = High recovery potential, MRP = Moderate recovery potential, LRP = Low recovery potential.

restoration of just *terrestrial* ecosystems Mappin et al. (2021). Furthermore, Federal Government commitments for all environmental protection (water, soil, flora and fauna) is a small percentage of estimated annual disaster relief spending to 2050 (Deloitte Access Economics, 2021; Lefebvre and Reinhard, 2022). In this context, river rehabilitation is an investment in the future recovery of rivers to improve resilience and mitigate the costs of future natural disasters and anthropogenic impacts on the environment and society (O’Kane and Fuller, 2022).

4.2 Costs versus benefits

For stakeholders, a successful rehabilitation project can have multiple combined benefits both economic and environmental,

including carbon sequestration and enhanced biodiversity (Smith et al., 2016; Worley et al., 2023), and financial and non-financial. Both financial and non-financial costs and benefits can be applied to river rehabilitation cost-benefit analysis. Our analysis is based on readily quantifiable financial costs, and based on the comparison between the different scenarios, in both time slices 1 and 2. From this analysis, it is evident that there is considerably greater financial incentive from reduced costs in adopting *working with recovery* or *corridors* scenarios compared to *ad hoc and reactive* scenarios. Alternatively, if rehabilitating using the *ad hoc and reactive* model, then rehabilitation costs will outweigh the financial and non-financial benefits over time. Reaches with a higher recovery potential generally are in better condition and provide better ecosystem services. Using *working with recovery* and *corridors* approaches will substantially improve recovery

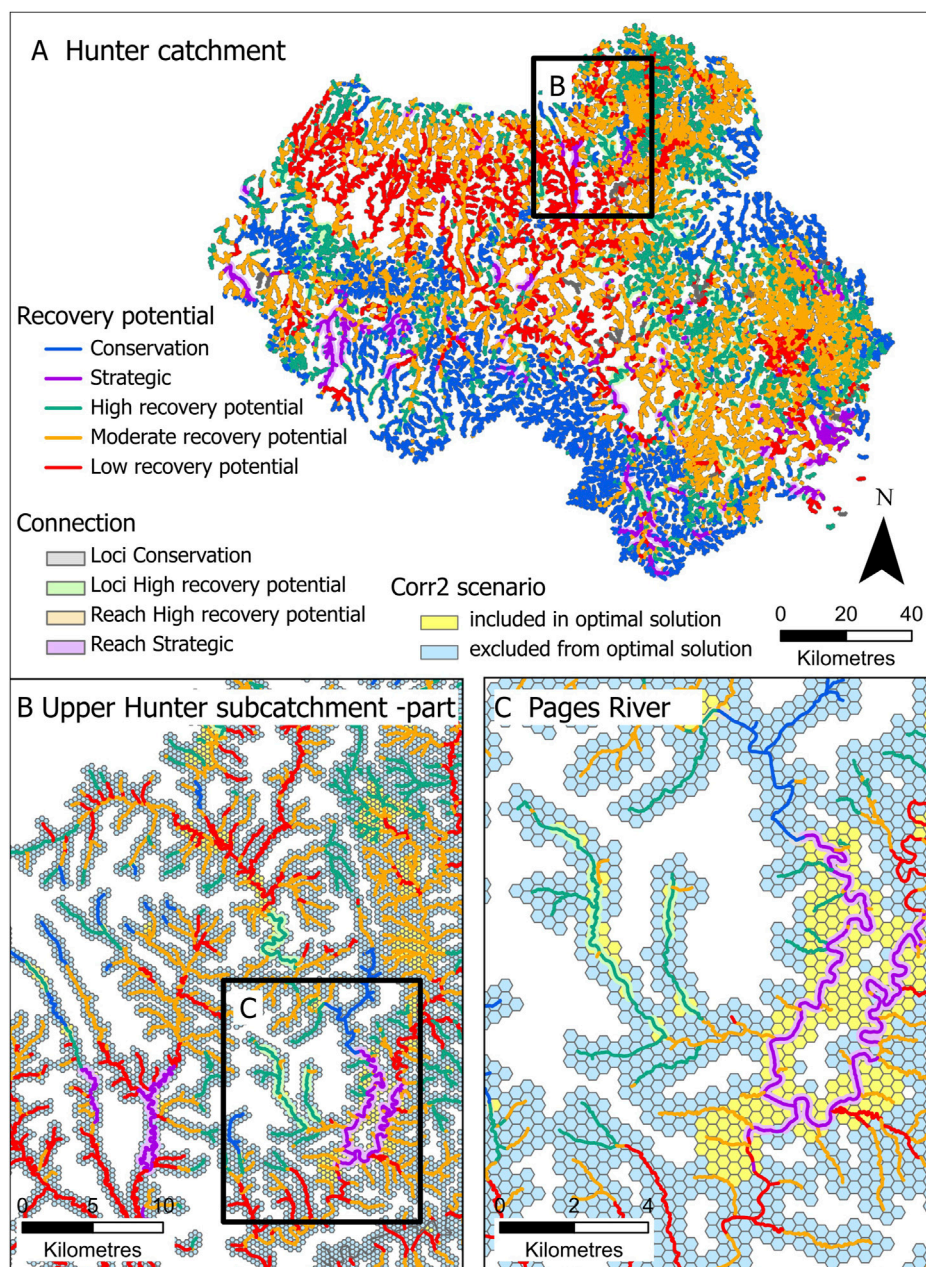


FIGURE 6 Marxan corridors #2 scenario for the Hunter regional catchment, showing (A) whole catchment (B) portion of Upper Hunter subcatchment including Pages River, and (C) Pages River detail. The optimal solution is shown by coloured hexagons (yellow = planning units included in the optimal solution, blue = planning units excluded from the optimal solution). Reach and loci connections selected in the optimal solution (yellow hexagon planning units) are considerably clumped, providing a corridor suitable for rehabilitation. Streamlines are classified by recovery potential. Yellow hexagon planning units wholly outside of the 40 m riparian zone are an artefact of the spatial resolution, have no value, and do not affect the scenario result. Corr = corridors.

potential across systems and provide enhanced ecosystem services and thus higher environmental benefits (Chessman et al., 2006; Wohl et al., 2015; Brierley and Fryirs, 2022). Therefore, working with recovery can be considered a surrogate for the improved ‘environmental benefits’ in cost-benefit analysis. If using a *working with recovery* approach to improve riparian zones, there are mutual economic and environmental benefits for property owners (Cary et al., 2002; NRMSouth, 2015; NSW Government, 2021).

In our analysis, quantification of the reduction in financial costs is twofold:

- 1) Current lower rehabilitation costs involved in implementing *working with recovery/corridors* versus *ad hoc and reactive* scenarios, based on time slice 1 that represents the present day situation (DPIE, 2021a).
- 2) Future reduction in financial costs accrued from the diminishing effect of *working with recovery* and *corridors*

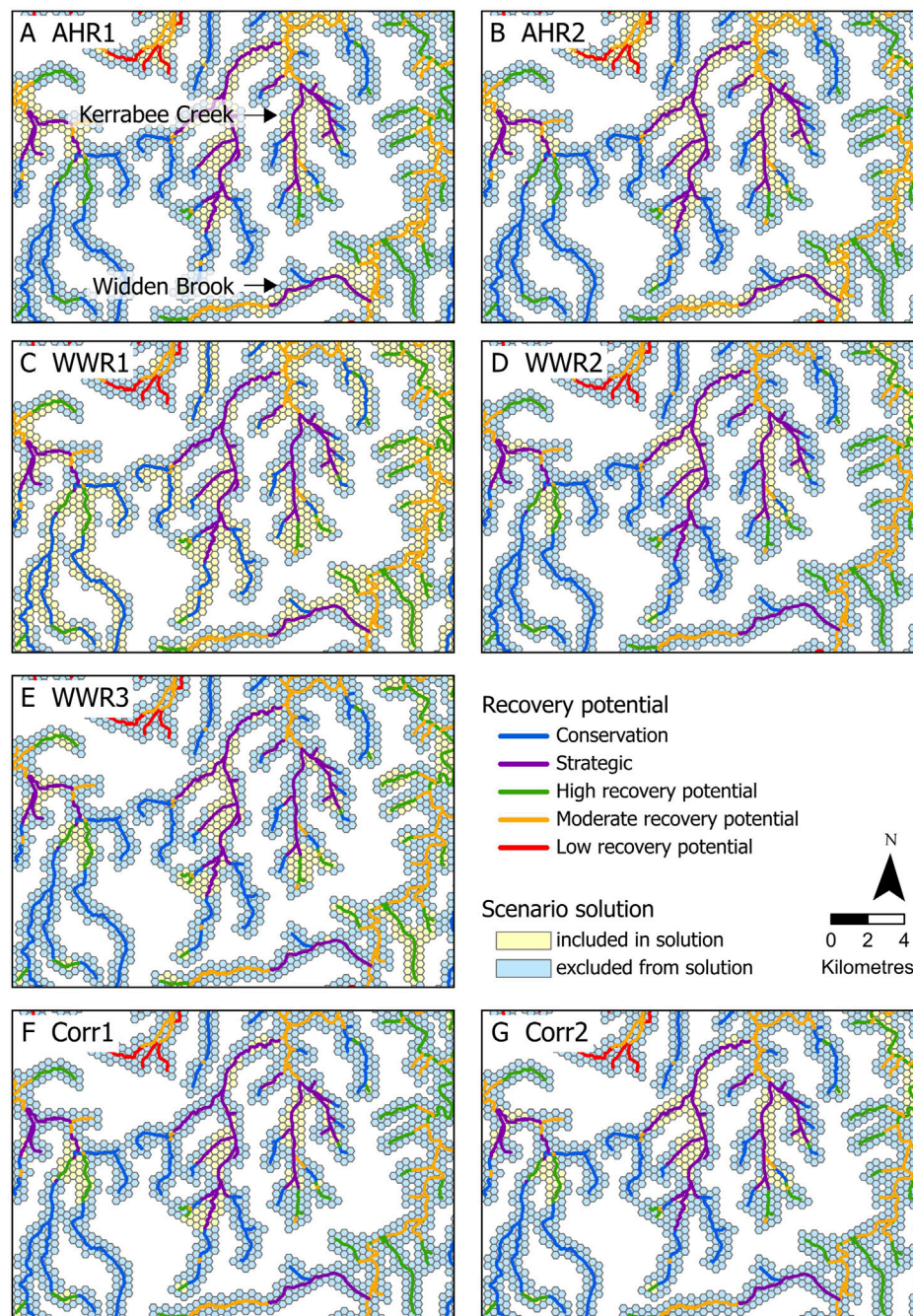


FIGURE 7
 The best solution output for Goulburn subcatchment scenarios (A–G), detailing Kerrabee Creek and Widden Brook to demonstrate comparison between the seven scenarios. AHR = *ad hoc and reactive*; WWR = *working with recovery*; Corr = *corridors*.

scenarios in the present day which then leads to improved recovery potential in the future. Future rehabilitation (time slice 2) would be carried out on reaches that have improved their condition and therefore recovery potential, with a corresponding lower cost for the reaches that have been reclassified with improved recovery potential. The reduced future total project rehabilitation cost can be implied as a quantifiable future increased financial benefit. This diminisher effect is a flow-on effect that is built into time slice 2.

The cost of rehabilitating streams can be considered an investment with both accompanying long-term flow-on financial and non-financial benefits. This is the additional multiplier effect which can be applied in the cost-benefit analysis. For example, for agricultural landowners, treating the riparian zone as an asset where non-financial ecological improvements occur can lead to flow-on financial benefits including carbon credit scheme income (DCCEEW, 2023), reduced pesticide use due to increased natural pest control

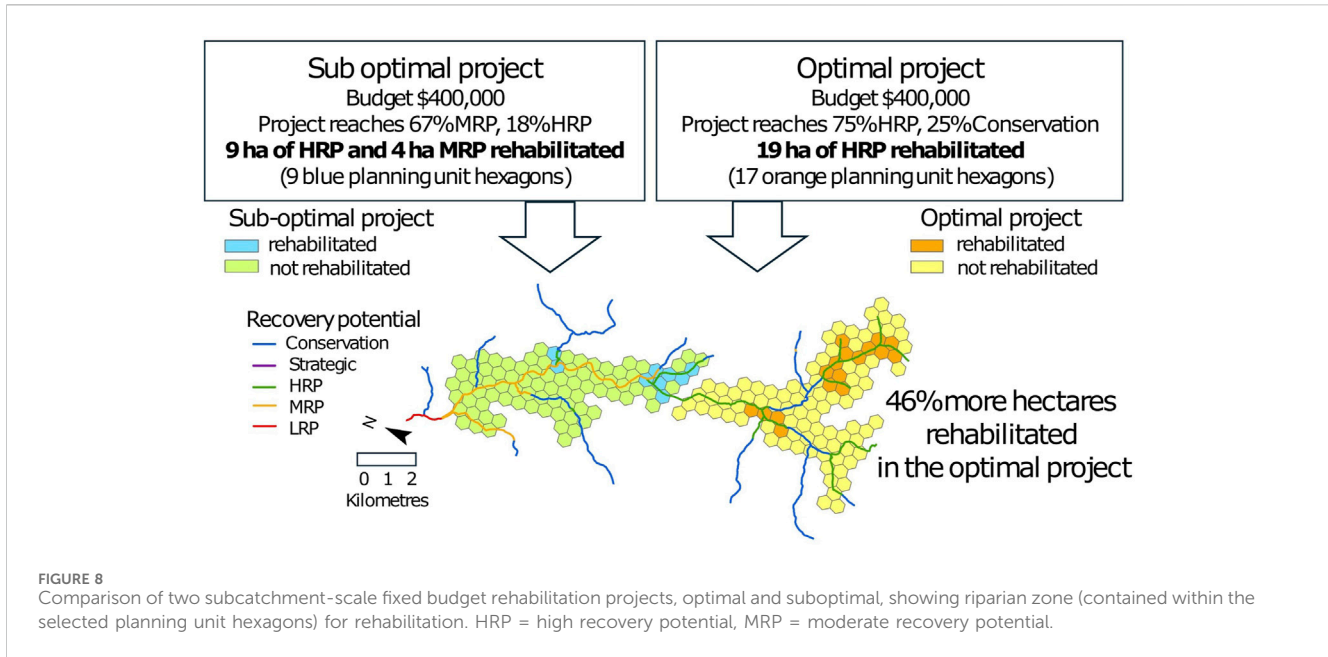


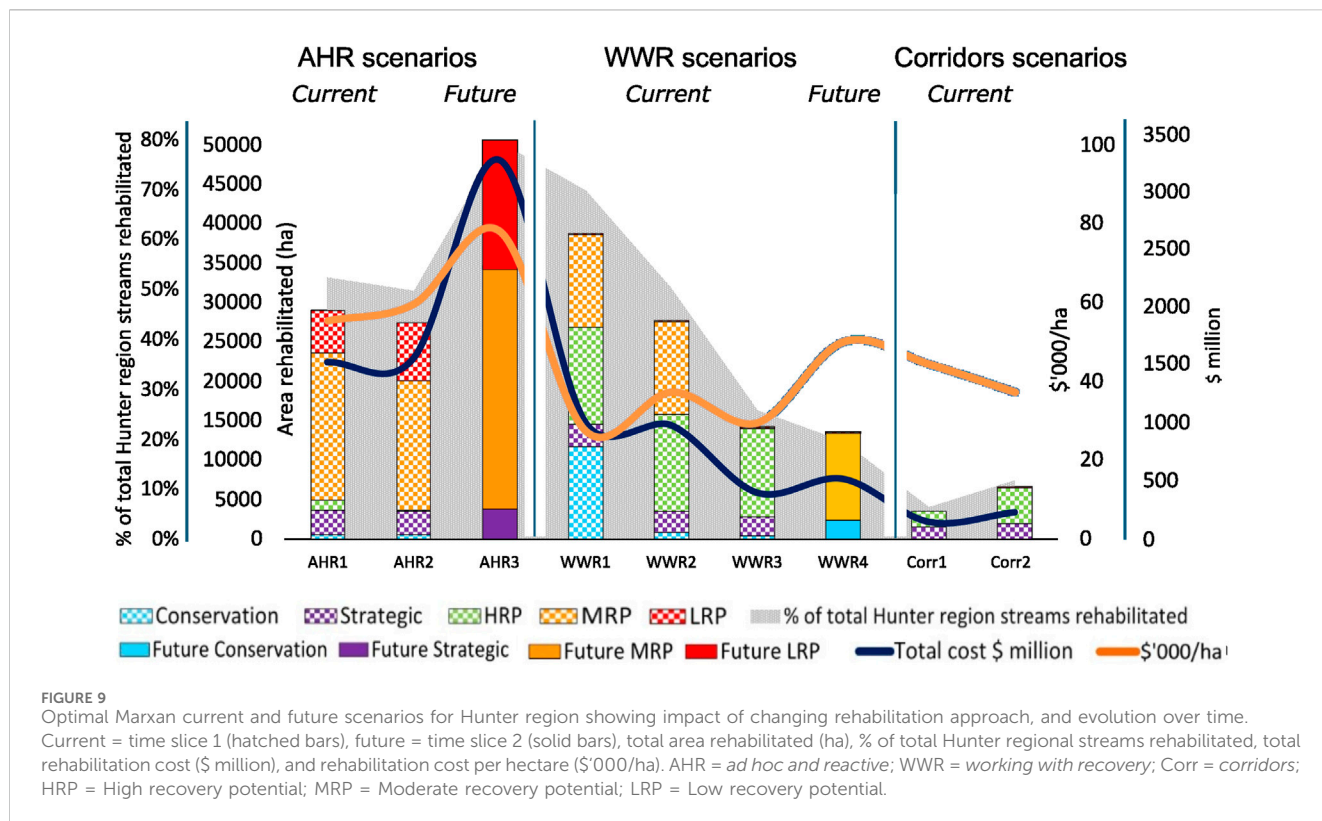
TABLE 4 Optimal Marxan current (time slice 1) and future (time slice 2) scenario results for Hunter region. Time slice 2 adjusted for inflation of 2.5% pa over average 15 years (ABS, 2023).

Hunter region scenario percentages	Strat 100% HRP 10% MRP 80% LRP 50%	Strat 100% HRP 10% MRP 70% LRP 70%	Strat 100% MRP 70% LRP 70%	Con 100% Strat 90% HRP 100% MRP 50%	Strat 90% HRP 100% MRP 50%	Strat 90% HRP 100%	MRP 50%	Strat 90% HRP 100%	Strat (R&L) 90% HRP(R) 100% HRP(L) 80%
Scenario	AHR1	AHR2	AHR3	WWR1	WWR2	WWR3	WWR4	Corr1	Corr2
Time slice	1	1	2	1	1	1	2	1	1
Area rehabilitated (hectares), by recovery potential									
Conservation (ha)	598	517	—	11,780	837	373	1,913	—	7
Strategic (ha)	3,018	2,978	3,025	2,711	2,720	2,382	—	1,480	1,950
HRP (ha)	1,248	108	—	12,341	12,330	11,283	—	1,978	4,494
MRP (ha)	18,771	16,424	24,701	11,732	11,732	130	8,861	—	—
LRP (ha)	5,288	7,404	16,150	9	8	6	1	—	1
Total rehabilitation cost (\$million)	1,601	1,633	3,433	1,060	1,030	418	543	153	240
Total area rehabilitated (ha)	28,923	27,431	43,877	38,573	27,627	14,173	10,775	3,459	6,452
\$/ha	55,340	59,540	78,241	27,475	37,274	29,517	50,394	44,343	37,246
% of total Hunter region streams rehabilitated	47%	45%	72%	63%	45%	23%	18%	6%	11%

AHR = *ad hoc and reactive*; WWR = *working with recovery*; Corr = *corridors*; Con = Conservation; Strat = Strategic; HRP = High recovery potential; MRP = Moderate recovery potential; LRP = Low recovery potential; For *corridor* scenarios; R = reach connection; L = loci connection.

from biodiverse-rich riparian zones adjacent to agricultural land (Cole et al., 2012; Cole et al., 2020; Giraldo et al., 2022), and increased livestock valuations (Dobes et al., 2021). Working with recovery can also have flow-on non-financial benefits such as the improvement in ecosystem services provision from vegetated riparian zones (Maes et al., 2020; Riis et al., 2020; Garcia

et al., 2021; European Commission, 2022a). Quantification of these benefits could be included in future research. In this study, reach and loci connections which overlapped were excluded from the analysis. There may be multiplicative effect on benefits from the rehabilitation of these connections, which could form part of a future study.



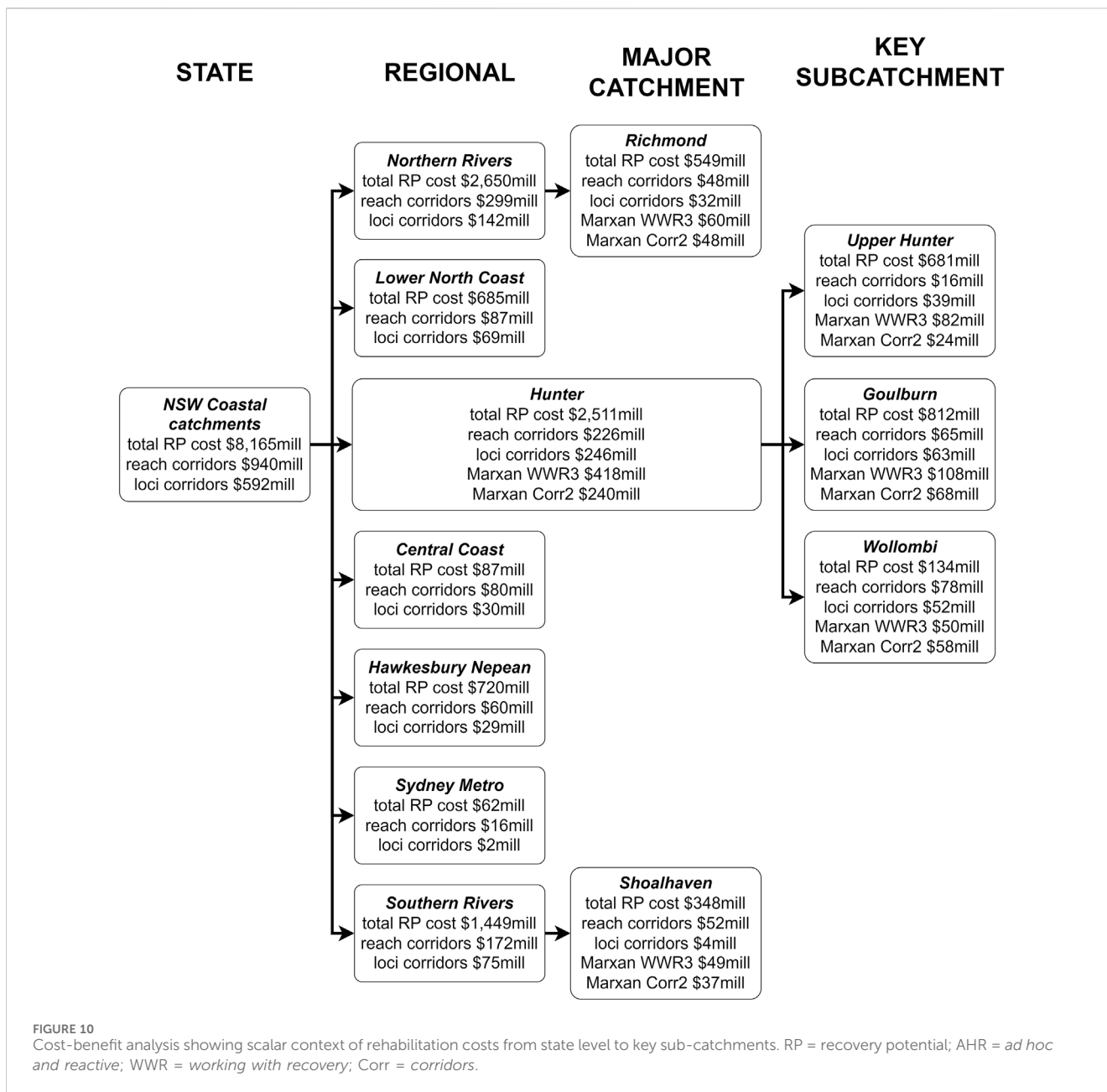
For the river management sector, cost-benefit analysis can be used to inform or improve decision support tools in river management and quantify both financial and non-financial benefits. For example, cost-benefit analysis results can be used in decision support tools to prioritise the projects that will have best environmental return on investment (Schultze et al., 2019). Multi-objective planning can also be undertaken to identify complementary benefits and trade-offs in economic and environmental values (Álvarez-Romero et al., 2021).

4.3 Using Marxan as a cost-benefit analysis tool for working with recovery

The use of Marxan and the tailoring of it so it is fit-for-purpose for cost-benefit analysis of fluvial and riparian systems means that river managers anywhere can run Marxan as a cost-benefit analysis tool in their catchments (Ball et al., 2009; Langhans et al., 2014; Adams et al., 2016; DPIE, 2020; Dela-Cruz et al., 2021). Whilst the focus in this study is on the reduction of costs, additional ecological information, e.g. habitat protection or riparian biodiversity measures, can also be incorporated into the Marxan analysis to identify environmental benefits, and further refine river rehabilitation strategies, depending on river management priorities. For coastal catchments of NSW, Marxan is now ready to be used to prioritise future rehabilitation projects. No programming skills are required, making this decision-making approach accessible to a wide variety of stakeholders. We have now demonstrated the cost-benefit of transitioning management practice fully towards *working with recovery* and *corridors*

approaches and moving away from *ad hoc and reactive* approaches (Beechie et al., 2010; Hawley, 2018; Wheaton et al., 2019; Fryirs and Brierley, 2021). We demonstrate that the protection of better-quality (high recovery potential) reaches, along with treating strategic reaches, results in lower initial total and per hectare rehabilitation costs (Fryirs and Brierley, 2016). Importantly, a dual benefit is achieved, i.e. more sustainable rehabilitation coupled with lower investment cost (Hermoso et al., 2015). This approach is not a drive to actively select the lowest cost approach, but rather a benefit that derives from selecting the most sustainable approach to river management (Fryirs and Brierley, 2021). The intent of the Marxan analysis is to demonstrate the conceptual use of Marxan and the relative solutions produced. This approach can be modified by others, whereby scenarios with different recovery potential protection percentages or inclusion of ecological datasets are developed. Rather than determining actual costs of rehabilitation using different scenarios, the take away message is that *working with recovery* is more cost effective than the *ad hoc and reactive* approach. We have demonstrated that flow on multiplier benefits, both financial and non-financial, occur over time slices 1 and 2 with the adoption of *working with recovery* rather than *ad hoc and reactive* approaches to river management (Figure 11).

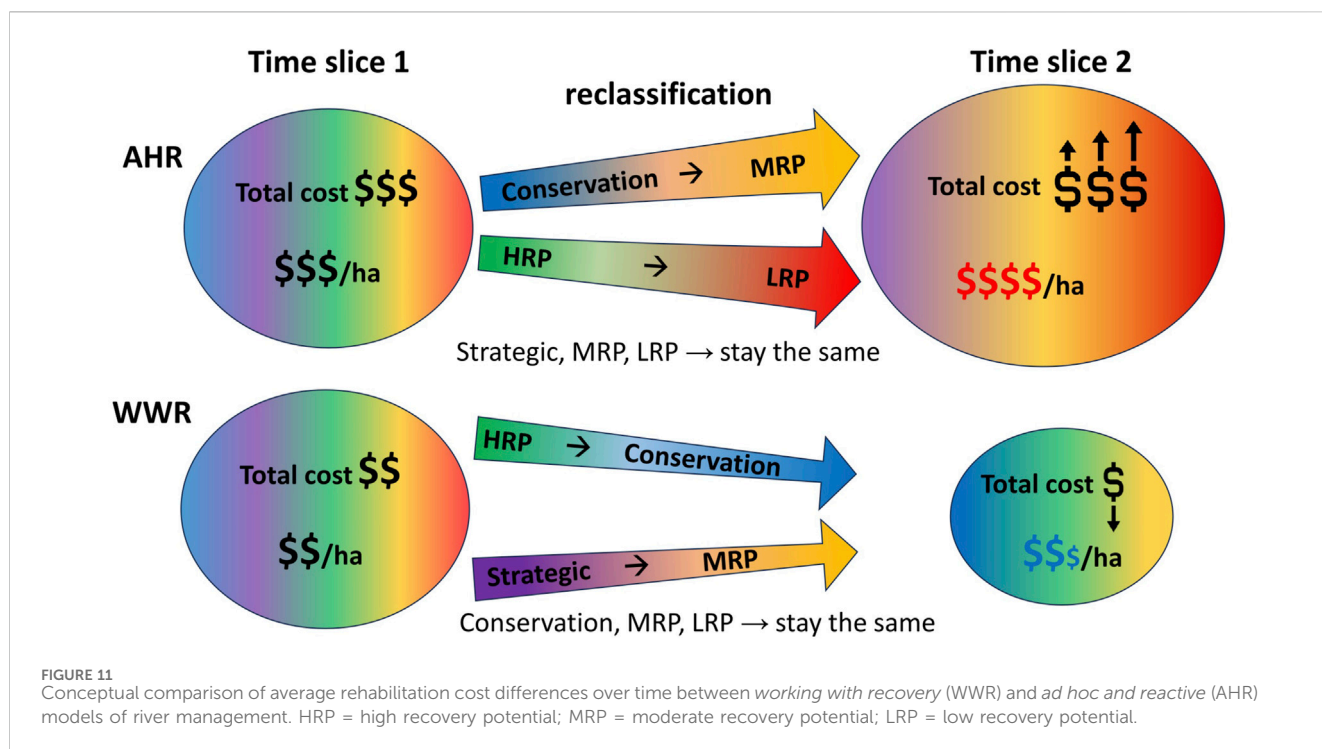
The timeframe over which river recovery will occur will be specific to the conditions in each system, i.e. the extent and severity of pressures and limiting factors that need to be addressed (Fryirs and Brierley, 2016; Fryirs et al., 2018). Improvements can occur quickly (years) (Schulz-Zunkel et al., 2022), or take much longer (decades) (Higginson et al., 2019; Cohen et al., 2022; Kauffman et al., 2022), depending on whether biotic (ecosystem respiration, species



diversity) and/or abiotic (geomorphic units, flow velocity) conditions require treatment. In some places, actively working with recovery can accelerate further improvement and creation of positive feedbacks in the system. Therefore, the sooner that *working with recovery* and *corridors* approaches to river management are adopted, the sooner that benefits will begin to accrue.

The benefits that accrue from transitioning to *working with recovery* now (time slice 1) will become apparent over time as rehabilitation outcomes become more sustainable and potentially trigger improvements in recovery potential elsewhere in the system, creating positive feedback for improvement. This is demonstrated in [Figure 11](#) whereby if river managers focus rehabilitation efforts on high recovery potential and strategic reaches, and the rehabilitation is successful, the trajectory of improvement may be sufficient to reclassify strategic reaches as moderate recovery potentials, and high

recovery potentials as conservation. In this analysis, time slice 2 total rehabilitation costs are lower as they are based on reclassified reaches. There is only a small increase in per hectare costs due to the higher portion of moderate recovery potential versus high recovery potential reaches included in the time slice 2 Marxan scenario. Alternatively, if river managers continue to use an *ad hoc and reactive* approach, the reverse is likely ([Figure 11](#)). In this case, most rehabilitation work is done in poorer quality moderate and low recovery potential reaches, that have a higher failure risk. Current total and per hectare rehabilitation costs are high, and overall rehabilitation outcomes are unlikely to be sustainable. If moderate and low recovery potential reaches impact any adjoining high recovery potential and conservation reaches it is likely that these reaches will deteriorate in condition and be reclassified as poorer recovery potential reaches. Future rehabilitation costs will increase.



In addition to the types of analyses undertaken in this study, other cost-benefit analyses that can now be undertaken include; back-running scenarios to prioritise rehabilitation based on a fixed budget, running other sorts of corridor scenarios (e.g. working in poorer quality reaches (moderate and low recovery potential) that may occur between/upstream/downstream of high recovery potential and conservation reaches), or building in other variables and weighting them (e.g. weighting reaches where community groups are already in place and there is a willingness to participate) (Ball et al., 2009; Linke et al., 2019). Other environmental (e.g. ecological, water quality) datasets can also be incorporated as additional non-financial features into Marxan analysis for further prioritisation (Ball et al., 2009; Dela-Cruz et al., 2021; Hermoso et al., 2021). For example, Marxan can be run using a fixed budget (*working with recovery #2 with budget*) to assess and select optimal project sites (Figure 8). Under this scenario, the optimal project would be able to rehabilitate 19 ha of riparian zone, 46% more than at the adjoining suboptimal project site. Working with recovery will be a collaborative exercise with multiple landowners, especially where adjoining landowners are situated on reaches with different recovery potentials. At smaller scales, under 10 km stream length, Marxan is less effective in identifying optimal sites, as not all recovery potentials will be sufficiently represented, if at all. However, at larger scales, Marxan identifies sites where most cost-effective rehabilitation can be undertaken. This provides a method to assess cross-scalar rehabilitation opportunities, upscaling with a higher budget to subcatchment and catchment scale (Figure 10).

In this study, the future time slice was not run using the *corridors* model. However similar benefits to the *working with recovery* approach would accrue and a positive reclassification of recovery potentials should result. Importantly, the *corridors* approach extends connections to adjacent and surrounding good quality reaches, thus

creating longer fluvial corridors, and moving towards landscape scale rehabilitation (Sholtes and Doyle, 2011). Working at fluvial corridor scale, rather than at reach scale, is critical. For example, the influence of increased floodplain roughness on flood wave attenuation has been determined as a significant factor over stream lengths of 20–50 km (Anderson et al., 2006; Ghavasieh et al., 2006) and increased biodiversity and ecosystem connectivity benefits are also needed at much larger scales (Kool et al., 2013; Linke et al., 2019; Renwick et al., 2020). Marxan can be used to run and cost corridor-scale rehabilitation scenarios over time, and as recovery occurs and corridors are built. As a multiplier effect, this builds on the important effects of off-site positive feedback in river systems.

Naturally, when working with recovery, local on-ground expert decisions by river managers are required to assess, prioritise, and cost for rehabilitation, individual reaches and connections, according to the specific characteristics. In this study Marxan's default settings were used enabling straightforward comparison between scenarios. Planning units were restricted to those within 200 m of streamlines. River managers may elect to tailor Marxan settings to their own strategic goals and consider expanding the spatial extent of planning units where rehabilitation strategies consider land cover and land use changes. Indeed, systemic planning using a conservation planning tool such as Marxan, combined with on-ground expert judgement, can provide the best possible outcomes and enhance the overall efficacy of rehabilitation strategies (Langhans et al., 2016).

5 Conclusion

The total cost of fluvial rehabilitation of NSW coastal catchments is insignificant compared to the annual and

increasing costs of insurance losses. Nature-based solutions such as river rehabilitation which enhance river recovery are a remedy for mitigating the effects of climate change-related floods and extreme weather. It is a cost-effective approach to proactive river management. If river managers work with recovery and at corridor scale, we have demonstrated that the benefits of undertaking rehabilitation go well beyond financial. Ecosystem benefits accrue from this approach, and lower costs are incurred both now and into the future through the multiplier effect. Here we have successfully demonstrated the application of cost-benefit analysis for coastal NSW catchments using a robust approach with Marxan, an accessible optimisation/prioritisation tool. No programming skills are required, making this decision-making approach accessible to a wide variety of stakeholders. This enables river managers and other stakeholders to address the complexities of strategic river rehabilitation planning prioritisation using a transparent, geomorphologically-informed approach at the landscape scale rather than opportunistically at the reach scale.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

DA: Writing–original draft, Writing–review and editing, Formal Analysis, Investigation, Methodology, Visualization. KF: Conceptualization, Funding acquisition, Supervision, Writing–review and editing, Methodology. ML: Writing–review and editing, Supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2024.1425668/full#supplementary-material>

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