T5: FUTURE DEPLOYMENT SCENARIOS AND COSTING

A report provided to the Australian Government by the Reef Restoration and Adaptation Program

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1. PREAMBLE

The Great Barrier Reef

Visible from outer space, the Great Barrier Reef is the world's largest living structure and one of the seven natural wonders of the world, with more than 600 coral species and 1600 types of fish. The Reef is of deep cultural value and an important part of Australia's national identity. It underpins industries such as tourism and fishing, contributing more than $6B a year to the economy and supporting an estimated 64,000 jobs.

Why does the Reef need help?

Despite being one of the best-managed coral reef ecosystems in the world, there is broad scientific consensus that the long-term survival of the Great Barrier Reef is under threat from climate change. This includes increasing sea temperatures leading to coral bleaching, ocean acidification and increasingly frequent and severe weather events. In addition to strong global action to reduce carbon emissions and continued management of local pressures, bold action is needed. Important decisions need to be made about priorities and acceptable risk. Resulting actions must be understood and co-designed by Traditional Owners, Reef stakeholders and the broader community.

What is the Reef Restoration and Adaptation Program?

The Reef Restoration and Adaptation Program (RRAP) is a collaboration of Australia's leading experts aiming to create a suite of innovative and targeted measures to help preserve and restore the Great Barrier Reef. These interventions must have strong potential for positive impact, be socially and culturally acceptable, ecologically sound, ethical and financially responsible. They would be implemented if, when and where it is decided action is needed and only after rigorous assessment and testing.

RRAP is the largest, most comprehensive program of its type in the world; a collaboration of leading experts in reef ecology, water and land management, engineering, innovation and social sciences, drawing on the full breadth of Australian expertise and that from around the world. It aims to strike a balance between minimising risk and maximising opportunity to save Reef species and values.

RRAP is working with Traditional Owners and groups with a stake in the Reef as well as the general public to discuss why these actions are needed and to better understand how these groups see the risks and benefits of proposed interventions. This will help inform planning and prioritisation to ensure the proposed actions meet community expectations.

Coral bleaching is a global issue. The resulting reef restoration technology could be shared for use in other coral reefs worldwide, helping to build Australia's international reputation for innovation.

The $6M RRAP Concept Feasibility Study identified and prioritised research and development to begin from 2019. The Australian Government allocated a further $100M for reef restoration and adaptation science as part of the $443.3M Reef Trust Partnership, through the Great Barrier Reef Foundation, announced in the 2018 Budget. This funding, over five years, will build on the work of the concept feasibility study. RRAP is being progressed by a partnership that includes the Australian Institute of Marine Science, CSIRO, the Great Barrier Reef Foundation, James Cook University, The University of Queensland, Queensland University of Technology, the Great Barrier Reef Marine Park Authority as well as researchers and experts from other organisations.

2. SUMMARY AND KEY FINDINGS

The Reef Restoration and Adaptation Program (RRAP) seeks to develop and validate prototype implementation solutions to help protect and restore the Great Barrier Reef. This will play a key role in maintaining the Reef's outstanding universal values in the face of the increasing threats it faces from climate change.

The first phase of the program, termed concept feasibility, included evaluation of a range of potential interventions, the associated implementation methodology and development pathways. Due to the vast size of the Great Barrier Reef, the operational costs of intervention delivery are likely to be substantial. Gaining an understanding of these likely costs early in the program's next phase—delivering the R&D program—is necessary to evaluate the effectiveness of potential interventions and to identify the synergies and cost-savings. This work will then guide the development of the interventions. This report provides a first assessment of the possible and probable delivery costs. During the initial scoping of this planning phase, the intention was to only cost the delivery of one intervention method as a base case (the aquaculture intervention). This scope was subsequently expanded to consider the other proposed interventions strategies, to identify optimal methods to achieve scale, synergy between complementary interventions and to minimise delivery costs.

The cost-estimating assessment of options is based on a specific concept design for each method assessed. In some instances, it was feasible to undertake detailed bottom-up estimates of engineering solutions, in others, a high-level 'rates-based' approach was needed. Many delivery methods under consideration are in very early development, with limited quantitative concept design details available.

A list and short description of the delivery methods considered in this report is presented in Table 1 below. More information about the proposed interventions can be found in T3—Intervention Technical Summary.

Table 1: Delivery methods considered for proposed RRAP interventions, organised by development pathway.

DEVELOPMENT PATHWAY	DELEIVERY METHOD	DESCRIPTION	LOGISTICS
Moving corals (reproduction and recruitment)	Translocation	Collect larval slicks, transport to recipient reef, and deploy	Collector and transport vessels
	Larval slick-device based settlement	Collect larval slicks, transport to recipient reef, settle on settlement devices, deploy as larval cloud	Collector and transport vessels
	Assisted larval movement	Collect larval slicks into enclosure, tow to recipient reef and deploy	Enclosures, towing vessels, small slick-collecting vessels, deployment vessels
	Fragmentation - asexual reproduction	Collect fragments, micro-frag, deploy	Autonomous systems to collect and deploy, surface vessels
Cooling and shading (primarily solar radiation management)	Cloud brightening	Spray or release dry particles into lower atmosphere	Spraying and support vessels, fixed stations, airborne platforms
	Misting	Spray fine mist into lower atmosphere	Spraying and support vessels, fixed stations
	Ultra-thin surface films	Spray material over sea surface	Deployment vessels
	Mixing and pumping	Pumps and pipes to transfer and mix water surrounding reefs	Pumps and pipes, support vessels
Reef structures and stabilisation	Grouting	Vessel-based and applied subsurface	Surface vessels, subsurface application
	Chemical bonding	Vessel-based and applied subsurface	Surface vessels, subsurface application
	Mesh fixing	Fabricated onshore or on-deck then deployed	Surface vessels, subsurface application
	Mars spiders	Fabricated onshore or on-deck then deployed	Onshore or on-deck fabrication, vessels for deployment
	Gabion baskets	Fabricated on-deck or onshore, deployed from surface vessel	Onshore on on-deck fabrication, vessels for deployment
	Bioballs	Fabricated onshore or on-deck then deployed	Onshore on on-deck fabrication, vessels for deployment
	Reef hubs	Fabricated onshore or on-deck then deployed	Onshore or on-deck fabrication, vessels for deployment
	Artificial massive corals (coral-skinned shapes)	Fabricated onshore or on-deck then deployed	Onshore or on-deck fabrication, vessels for deployment
	Rubble removal	Vacuum up rubble and consolidate	Surface and subsurface infrastructure
	3D-printed complex structures	Vessel-based and then deployed	Onshore or on-deck fabrication, vessels for deployment
Aquaculture	Optimised existing nursery methods	Corals produced in shore-based facility and deployed from vessels	Shore-based facilities and vessels for transport and deployment
	Medium-scale shore-based aquaculture		
	Large-scale shore-based aquaculture		
	Very large-scale breakthrough larval/polyp-based aquaculture		
	Treatments	Not costed	Vessels to support underwater operations

A summary of findings as they relate to cost estimates for these initial delivery methods is provided in Tables 2 and 3 below. A detailed explanation of the methods used to develop these is provided in the body of this report. Table 2 reflects the build-up of estimates based on established rates for development pathways which are rate-based, for example the reef structures and stabilisation methods. Table 3 presents several deployments based on largescale implementation scenarios with associated costs for other intervention strategies.

Table 2: Cost-estimating assessments – unit rates for proposed RRAP intervention delivery method.

DEVELOPMENT PATHWAY	DELEIVERY METHOD	UNITS	UNIT RATES ($) Low	Medium	High
Moving corals (reproduction and recruitment)	Translocation of larval slicks	Cost per one-year-old coral	$0.30	$18.00	$213.00
	Larval slick-device based settlement		$1.18	$4.71	$12.71
	Assisted larval movement		$0.68	$12.1	$50.08
	Fragging - asexual reproduction		Not assessed		
Cooling and shading (primarily solar radiation management)	Cloud brightening		Only assessed as scenarios		
	Misting				
	Ultra-thin surface films				
	Mixing and pumping	Deemed an unviable intervention			
Reef structures and stabilisation	Rubble removal	Cost per metre of a 5m-wide strip	not assessed		
	Biological bonding		not assessed		
	Grouting			$422	
	Chemical bonding			$422	
	Mesh-fixing			$290	
	Mars Spiders			$528	
	Gabion baskets	(Per m^2 seabed coverage)		$481	
	Bioballs				
	Reef hubs			$2316	
	Artificial massive corals (coral-skinned shapes)			$1439	
	3D-printed complex structures		not assessed		
Aquaculture	Optimised existing nursery methods				
	Medium-scale shore-based aquaculture				
	Large-scale shore-based aquaculture	Cost per one-year-old coral	$1.5	$3.0	$4.5
	Very large-scale breakthrough larval/polyp-based aquaculture				
	Treatments	Incorporated into above cost/coral			

In Table 3, the bracketed numbers represent the estimated number of vessels/vehicles required for each scenario.

Note that because the delivery methods are quite different, and have different scale limitations, a range of scenarios were analysed. Additionally, in each instance, a low, medium and high case was provided. The low and high cases were driven by an assessment of the degree of uncertainty for each option based on the current level of knowledge for that method, which as reflected in the estimates, and as expected, differs for each method.

Table 3: Cost-estimating assessments – scenarios for proposed RRAP intervention delivery method.

DEVELOPMENT PATHWAY	DELIVERY METHOD	SCENARIO DESCRIPTION (primary uncertainty in italics)	ANNUAL DEPLOYMENT COST ($) (numbers in brackets are deployment vessels)		
			low	**medium - base case**	**high**
Moving corals (reproduction and recruitment)	Translocation of larval slicks	Based on deploying two million one-year-old corals. This scale represents the likely limit using charter vessels and seasonal workers. Beyond this scale, costs would increase significantly. *Uncertainty driven by post-deployment survival rates.*	$0.6M (1)	$36M (21)	$427M (242)
	Larval slick-device based settlement		$2.36M (2)	$9.4M (6)	$25.4M (15)
	Assisted larval movement		$1.37M (4)	$23.7M (79)	$101M (336)
	Asexual reproduction	Difficult to cost as it requires extensive automation research and development			
Cooling and shading (primarily solar radiation management)	Cloud brightening	To protect entire Reef (300 000 km^2). *Uncertainty driven by different levels of required particle concentrations*	$107M (34)	$158M (50)	$338M (109)
	Misting	Based on protecting from 10 000 km^2. *Uncertainty driven by different levels of required particle concentrations*	$1.97M (1)	$4.93M (2)	$7.89M (3)
	Ultra-thin surface films	Based on protecting from 10 km^2. *Uncertainty driven by different levels of required formula concentration*	$29.26 M (5)	$58.52M (11)	$117.0 4M (21)
	Mixing and pumping	Deemed unfeasible			
Reef structures and stabilisation	Biological bonding	To stabilise 10km^2 of rubble, assuming a 3:1 benefit ratio (every m^2 installed stabilises 3m^2), and an average rate of $400 per 5m strip. *Uncertainty driven by the extent to which economies of scale can be achieved*	Not costed		
	Rubble removal		Not costed		
	Grouting		$120M	$260M	$520M
	Chemical bonding				
	Mesh-fixing				
	Mars Spiders				
	Gabion baskets	To install 10km^2 of 3D structure, assuming a 1/10 density ratio (devices are deployed in clusters with gaps between). Rate based on $1300/m^2 for 3D structure. *uncertainty driven by the extent to which economies of scale can be achieved*	$600M	$1200M	$2400 M
	Bioballs				
	Reef hubs				
	Artificial massive corals (coral-skinned shapes)				
	3D-printed complex structures		Not costed, however it would be considerably more expensive		
Aquaculture	Optimised existing nursery methods		Not costed		
	Medium-scale shore-based aquaculture		Not costed		
	Large-scale shore-based aquaculture	To deploy 36.5 million one-year-old corals	$54M	$110M	$158M
	Very large-scale breakthrough larval/polyp-based aquaculture		Not costed		

The key findings from this concept-level costing in terms of scalability, cost-drivers and key challenges can be found in Table 4 below. The scales that are referenced in Table 4 can be found in Table 5.

Table 4: Key findings: scalability, cost-drivers and challenges for delivery methods of proposed RRAP interventions.

DEVELOPMENT PATHWAY	DELIVERY METHOD	SCALABILITY	KEY COST DRIVERS	KEY CHALLENGES
Moving corals (reproduction and recruitment)	Translocation of larval slicks	Small	• Deployment vessel and infrastructure, compounded by episodic timing of slicks and limited availability of suitable vessels • Mortality/survivorship • Volume of water being transported	• How to achieve, and what can be achieved, in reducing volume of water transported and lowest possible cumulative mortality
	Larval slick-device based settlement	Medium		
	Assisted larval movement	Small		
	Asexual reproduction	Small unless highly automated, then medium	• Underwater labour using existing methods • Lack of available automation and adhesive technology	• How to automate process • Composition of required adhesive
Cooling and shading (primarily solar radiation management)	Cloud brightening	Large	• Deployment vessel and infrastructure • Deployment equipment energy costs • Permitting	• Required particle concentration • Optimal source material • Efficacy of method • Design, efficiency and energy requirements of sprayers
	Misting	Medium	• Deployment vessel and infrastructure • Misting source material • Deployment equipment energy • Permitting	
	Ultra-thin surface films	Small	• Cost of formula • Deployment vessels • Permitting	• Required formula concentration and recipe • Efficacy of method
Reef structures and stabilisation aquaculture	Rubble removal	Medium	• Underwater labour • Deployment vessels • Manufacturing and fabrication	• Efficacy of methods • When to apply which method • How to optimise methods
	Biological bonding			
	Grouting			
	Chemical bonding			
	Mesh fixing			
	Mars Spiders			
	Gabion baskets			
	Bioballs			
	Reef hubs			
	Artificial massive corals (coral-skinned shapes)			
	3D-printed structures			
Aquaculture	Optimised existing nursery methods	Micro	• Shore-based facility capital and operating (including husbandry) costs • On-after deployment, including vessel capex and operating costs • Mortality at each stage of the production process • Brood stock management requirements	• Methods to optimise husbandry, brood stock management • Ways to automate specific tasks in shore facility • Optimal vessel design and fleet configuration • Optimal deployment methods, including design of deployment device
	Medium-scale shore-based aquaculture	Small		
	Large-scale shore-based aquaculture	Medium		
	Very large-scale breakthrough larval/polyp-based aquaculture	Large		

Table 5: RRAP proposed intervention delivery method scale definitions.

SCALE COMMENTS			ASSUMED QUANTITIES REQUIRED FOR METHOD TO HAVE IMPACT AT THIS SCALE
Micro	Represents current restoration method levels	Small areas in limited sites	0.1 million corals plus 0.01 km^2 rubble stabilised per annum
Small	A scale that could retain/protect tourism and other key sites if required.	50 tourism-scale sites	50 x 0.02km^2 sites shaded 1-10 million corals per year plus 1 km^2 rubble stabilised per annum
Medium	A scale that could support several clusters of key reefs to support ecosystem functioning in key areas.	50 reefs	Five small multi-reef areas shaded 10-100 million corals per year 10km^2 rubble stabilised per annum
Large	A scale that would target retaining broader GBR ecosystem function and core economic and social Reef values.	200+ reefs	Entire Great Barrier Reef shaded 100 million corals per year plus 100km^2 rubble stabilised per annum

A more comprehensive assessment of these findings applied to each intervention is presented in Section 8.2.

In summary, the concept-costing exercise revealed the following:

- Deployment costs are substantial. This is not unexpected given the vast area of the Reef, and general costs for operating marine infrastructure.
- The extent to which a method can be deployed at scale is driven by cost per unit (or area) and the available funding for deployment. Within this context, two distinct unit-cost versus scale profiles were observed:
    a. Several delivery methods have seasonal or episodic deployment requirements, suggesting it would be more cost-efficient if existing infrastructure was leased and temporary personnel used. Once these available resources were exhausted, further operational scaling up would require the acquisition of infrastructure, amortising the cost over the short utilisation period (Figure 1). Similarly, there is a cost to holding the required capability and equipment spread unless there are other potential revenue streams to offset these costs which do not conflict with this timing. If scale is increased into this range, the costs per unit increases by up to an order of magnitude. This places a logistics constraint on these methods unless there is a market to fund the infrastructure when it is not being used for restoration purposes.

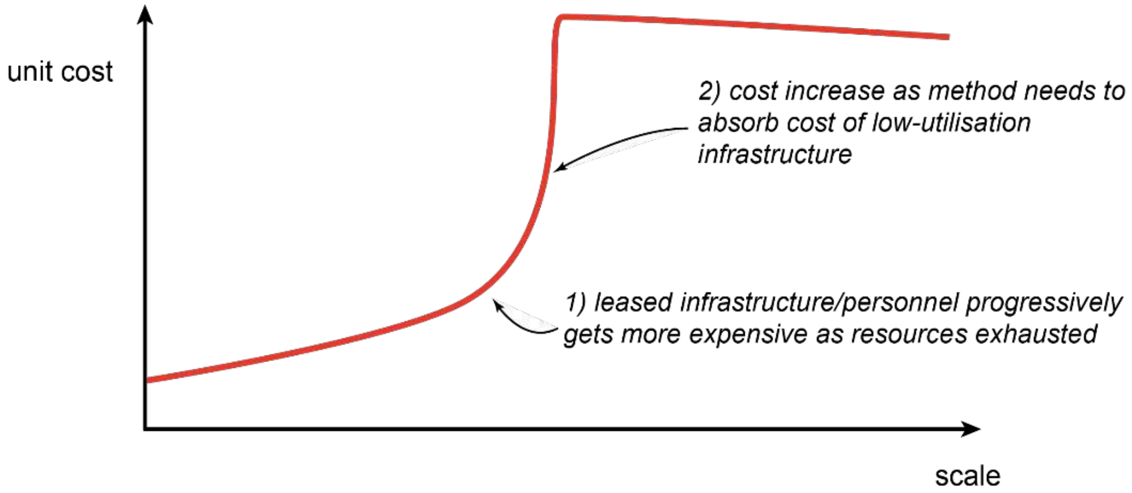

Figure 1: Conceptual figure of unit cost of deployment of intervention delivery methods.

b. Delivery methods that can be deployed year-round have reducing unit costs as scale increases (Figure 2). However, they all have points where the economy of scale flattens out and a commodity price rate is achieved. Further reductions in unit costs after this point, would require a different delivery method. Often these methods have a higher unit cost at a smaller scale, only performing better at a large scale. As such, intervention methods with this cost profile have an optimal scale that needs to be targeted if unit costs are to be minimised.

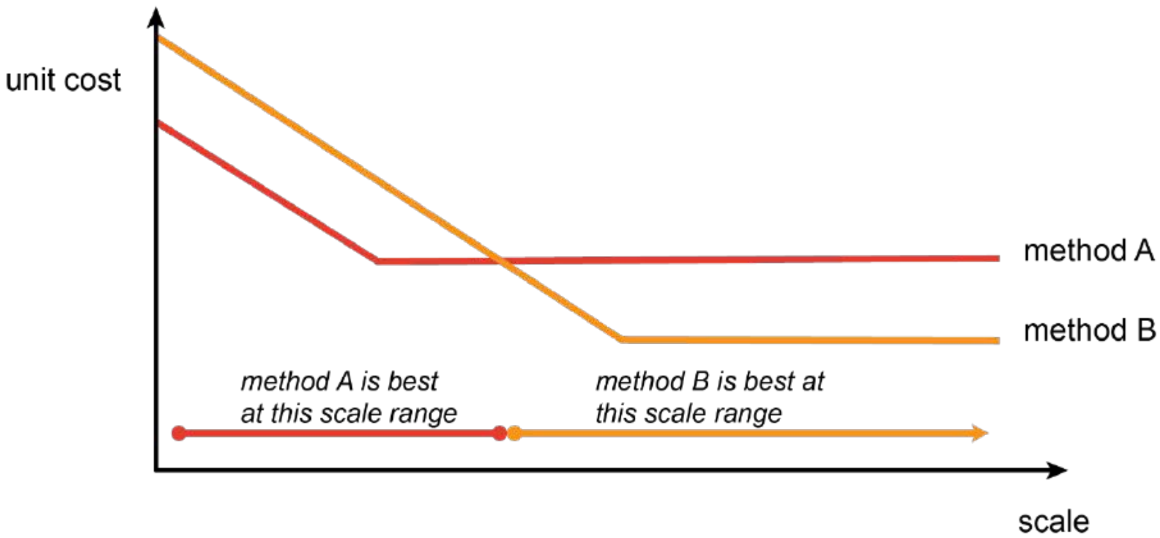

Figure 2: Conceptual figure of unit costs over a range of scales.

- The range between the low and high cost estimates identified in the sensitivity analysis reflect the conceptual and preliminary nature of the scheme development and the associated degree of uncertainty remaining in the cost estimates. This is a result of the compounding uncertainty in key parameters such as survival rates and efficacy of different methods. For example, with the larval slick capture and movement methods, the cost per coral ranges from less than $1 to more than $100, depending on assumptions around the cumulative survival rates. Reliable estimates of these survival rates either do not exist or have been ascertained from very small-scale and selective studies. This uncertainty will need to be reduced as a matter of priority and requires validation of the key assumptions making up these cost estimates.
- As well as validating key assumptions, the study also recognises there are significant opportunities to reduce deployment costs through optimising the methods: both within each method, and through shared infrastructure. For example, the same vessel can potentially be used for multiple intervention approaches at different times of the year; increasing the utilisation of expensive marine infrastructure. This also requires further investigation to optimise the preferred options for deployment.

3. BACKGROUND, SCOPE AND OBJECTIVES

The proposed RRAP Research and Development (R&D) Program is structured to develop the knowledge and tools to define active restoration options for the Great Barrier Reef at a scale that will have a significant impact.

The program's first phase, concept feasibility, concluded in early 2019 and identified possible intervention strategies and deployment methods, and undertook initial assessments of their efficacy.

The cost of deployment for these technologies will strongly influence their utility. While there are several active reef restoration initiatives underway in Australia and around the world (see T4—Current Practices), almost all are at very small scales, and in most cases, these techniques do not allow themselves to be effectively scaled up to address the needs of the Great Barrier Reef. RRAP's objective to develop at-scale interventions is arguably the largest challenge for the program.

To this end, initial—or concept-level—deployment calculations were performed to gain insight into the possible deployment and operating costs of the proposed delivery methods. These calculations are intended to guide research planning and investment and cost-benefit assessment, and to provide insight into opportunities where research and development can lead to method development improvements. This report aims to use existing knowledge of key parameter values in concept-level costing models, to gain insight into the scale and range of possible and probable deployment costs.

It is critical to highlight the limitations of this assessment: that the models and calculations presented here provide a 'first-cut', and are concept estimates only. In addition, the concept deployment strategies may not reflect the final concepts developed for each intervention. These estimates are high-level, and mostly developed from concept designs, applying industry-verified rates of the deployment requirements, rather than the result of detailed bottom-up infrastructure costings and use-case assessments.

The concepts presented here encapsulate a range of costing detail and reflect the additional deployment approaches and parallel studies that were commissioned (e.g. the T11—Automated Aquaculture Production and Deployment). This report integrates all deployment costing assessments undertaken during the RRAP Concept Feasibility Study. It represents the first in a set of studies planned for the next, research and development, phase of the program. The next study will be the preliminary costing report, which will further develop the cost estimates introduced here—especially the engineering cost estimates—to a greater level of detail and robustness.

This report considers delivery methods for most of the proposed interventions investigated during the RRAP Concept Feasibility Study (Table 6). Delivery methods associated with biocontrols and field treatments were not costed as there are no sufficiently developed concepts.

The assessed delivery methods cluster into four development pathways:

1. **Moving corals:** primarily involves collecting spawn and larval slicks and re-deploying them as a larval cloud from a vessel or enclosure, or by deploying settlement devices with settled corals attached. Approaches involved in the moving corals development pathway aim to increase natural recruitment and can alter the Reef coral community structure by transferring corals from warmer northern waters to cooler southern Reef waters.

2. **Cooling and shading:** altering the local water temperature, or temporarily reducing incoming solar radiation immediately prior to, and during, coral bleaching events. These approaches aim to protect reefs during coral bleaching or extreme heat events.

3. **Reef structures and stabilisation**: adding and enhancing reef habitat through engineering rubble substrates can result in additional reef settlement areas and facilitate increased recruitment of corals onto existing reefs.

4. **Aquaculture:** shore-based aquaculture facilities can effectively produce large quantities of more thermally tolerant corals that can be transported and settled onto identified recipient reefs. Shore-based aquaculture facilities allow controlled and managed husbandry that can lead to vastly reduced mortality rates of young corals compared with *in situ* conditions.

Table 6: Delivery methods considered for proposed RRAP interventions.

DEVELOPMENT PATHWAY	DELIVERY METHOD	DESCRIPTION	LOGISTICS
Moving corals (reproduction and recruitment)	Translocation of larval slicks	Collect larval slicks, transport to recipient reef and deploy as larval cloud	Collector and transport vessels
	Larval slick-device based settlement	Collect larval slicks, transport to recipient reef, settle on devices, deploy as larval cloud	Collector and transport vessels
	Assisted larval movement	Collect larval slicks into enclosure, tow to recipient reef and deploy	Enclosures, towing vessels, small slick collecting vessels, deployment vessels
	Fragging - asexual reproduction	Collect fragments, micro-frag, deploy	Autonomous systems to collect and deploy, surface vessels
Cooling and shading (primarily solar radiation management)	Cloud brightening	Spray or release dry particles into lower atmosphere	Spraying and support vessels, fixed stations, airborne platforms
	Misting	Spray fine mist into lower atmosphere	Spraying and support vessels, fixed stations
	Ultra-thin surface films	Spray material over sea surface	Deployment vessels
	Mixing and pumping	Pumps and pipes to transfer and mix water surrounding reefs	Pumps and pipes, and support vessels
Reef structures and stabilisation	Grouting	Vessel-based and applied subsurface	Surface vessels, subsurface application
	Chemical bonding	Vessel-based and applied subsurface	Surface vessels, subsurface application
	Mesh fixing	Fabricated onshore or on-deck then deployed	Surface vessels, subsurface application
	Mars Spiders	Fabricated onshore or on-deck then deployed	Onshore or on-deck fabrication, vessels for deployment
	Gabion baskets	Fabricated on deck or onshore and deployed from surface vessel	Onshore or on-deck fabrication, vessels for deployment
	Bioballs	Fabricated on onshore or on-deck then deployed	Onshore or on-deck fabrication, vessels for deployment
	Reef hubs	Fabricated onshore or on-deck then deployed	Onshore or on-deck fabrication, vessels for deployment
	Artificial massive corals (coral-skinned shapes)	Fabricated onshore or on-deck then deployed	Onshore or on-deck fabrication, vessels for deployment
	Rubble removal	Vacuum up rubble and consolidate	Surface and subsurface infrastructure
	3D-printed complex structures	Vessel-based and deployed	Onshore or on-deck fabrication, vessels for deployment
Aquaculture	Optimised existing nursery methods	Corals produced in shore-based facility and deployed from vessels	Shore-based facilities and vessels for deployment and transport
	Medium-scale shore-based aquaculture		

	Large-scale shore-based aquaculture		
	Very large-scale breakthrough larval/polyp-based aquaculture		
	Treatments	Not costed	Vessels to support underwater operations

Table 6 reveals the significant functional and deployment infrastructure synergies across the portfolio of methods under consideration. The focus of this report is on the cost of deploying individual interventions. Subsequent analyses, such as S9—Systems Engineering and Integrated Logistics explicitly consider how an integrated interventions delivery strategy can be operationalised.

4. COSTING ASSESSMENT METHODOLOGY

4.1 General basis of costs

The assessment of the cost estimates for the different options were performed using two different levels of detail.

The cost estimates for the aquaculture development pathway were defined from a bottom-up design that mapped out, quantified and costed the onshore and offshore infrastructure to at least a preliminary design level. Hence the aquaculture intervention and deployment strategies contain more detail than the other deployment pathway cost estimates contained in this report (see RRAP report T11—Automated Aquaculture Production and Deployment for details).

The cost estimates to deploy rubble stabilisation methods were also directly sourced from industry by commissioning contracting company Subcon. However, these costs were not provided as detailed bottom-up costings, rather as commodity out-turn costs for delivering existing technology on a per-unit basis and on scales commensurate to their operations (small scale).

By contrast, the other deployment costings were formed at high- or concept-level and can be thought of as concept stage costings. In some cases, the accuracy of these cost estimates were affected by a number of assumptions resulting from both individual parameter uncertainty and fundamental uncertainty over deployment methods; some of which may involve technology that does not yet exist (Table 7).

Table 7: Summary of basis of costs for delivery methods of proposed RRAP interventions.

DELIVERY METHOD	COSTING APPROACH
Translocation of larval slicks (capturing larval slicks and redeploying as a larval cloud)	Calculation assumes mortality at each step in the process and estimates the number of alternate vessel types required to collect slicks and deploy embryos
Larval slick-device based settlement (capturing larval slicks, settling onto devices and deploying)	Calculation assumes mortality at each step in the process and estimates the number of alternate vessel types required to collect slicks, the settlement of larvae onto devices, and deployment
Assisted larval movement (collecting slicks into floating enclosures and towing enclosures to recipient reefs)	Calculation assumes mortality at each step in the process and estimates the number of alternate enclosure/vessel types required to collect slicks and deploy larvae
Fragmentation - asexual reproduction (collecting fragments, splitting and redeploying micro-fragments)	Not costed in this report
Cloud brightening (injecting nano particles of salt into the lower atmosphere to temporarily increase cloud albedo)	Model estimates the infrastructure requirements and costs to deliver the specified particle concentration. Costed on a Great Barrier Reef-wide scale.
Misting (injecting a fine mist into the atmosphere at the sea surface to create a mist to temporarily reduce incoming radiation)	Model estimates the infrastructure requirements and costs to deliver the specified particle concentration. Costed for regional-scale deployment.
Ultra-thin surface films	Model estimates the infrastructure requirements and costs to deliver the specified formula concentration. Costed for small-scale deployment.
Mixing and pumping	Numerical modelling used to estimate demand-sizing requirements, then high-level infrastructure and energy costs estimated. Only Lizard Island considered
Grouting	Externally supplied out-turn costs for small-scale deployments
Chemical bonding	
Mesh fixing	
Mars Spiders	
Gabion baskets	
Bioballs	
Reef hubs	
Artificial massive corals (coral-skinned shapes)	
3D-printed complex structures	
Rubble removal	Not costed in this report
Optimised existing nursery methods	Not costed in this report
Medium-scale shore-based aquaculture	Not costed in this report
Large-scale shore-based aquaculture	Externally supplied
Very large-scale breakthrough larval/polyp-based aquaculture	Not costed in this report
Treatments	Not costed in this report

4.2 Scale and validation

The assessment intervention options require consideration of the scale of delivery proposed as this affects the cost estimate of each option significantly. Some delivery methods have the potential to be quickly scaled to Reef-wide delivery, while others act on smaller, regional scales, but over time may lead to Reef-wide interventions. The assumed deployment scales were dictated by the findings of the individual intervention investigations performed during phase one (Table 8, 9). This does not mean that these will be the ultimate deployable scales for each intervention; rather they are indicative of planning decisions that were made during the concept feasibility study.

Table 8: Scale definitions.

SCALE		COMMENTS	ASSUMED QUANTITIES REQUIRED FOR METHOD TO HAVE IMPACT AT THIS SCALE (TBC IN R&D PROGRAM)
Micro	Represents current restoration method levels	Small areas in limited sites	0.1 million corals per year plus 0.01 km^2/per annum rubble stabilised
Small	Minimum amount to keep industry going	50 tourism-scale sites	50 x 0.02km^2 sites shaded 1-10 million corals per year plus 1 km^2/per annum rubble stabilised
Medium	Minimum amount to retain limited Reef ecosystem function in five areas	50 reefs	Five small multi reef areas shaded 10-100 million corals per year 10km^2/per annum rubble stabilised
Large	Minimum amount to achieve core RRAP objectives of retaining core ecosystem, economic and social values of GBR	200+ reefs	Full Great Barrier Reef shaded 100+ million corals per year 100km^2/per annum rubble stabilised

Table 9: RRAP intervention development pathway scale and validation summary

DEVELOPMENT PATHWAY	DELIVERY METHOD	SCALE	VALIDATION
Moving corals (reproduction and recruitment)	Translocation of larval slicks	2M corals deployed (small-scale)	Independent validation: vessel costs validated by industry operator from market rates
	Larval slick-device based settlement	2M corals deployed (small-scale)	
	Assisted larval movement	2M corals deployed (small-scale)	
	Asexual reproduction	Not costed	
Cooling and shading (primarily solar radiation management)	Cloud brightening	300 000km^2 (large-scale)	Independent validation: vessel costs validated by industry operator from market rates
	Misting	Up to 100 000km^2 (medium-large scale)	
	Ultra-thin surface films	Up to 10km^2 (small-medium scale)	
	Mixing and pumping	5 km^2 (small-medium)	Requires market rates validation
Reef structures and stabilisation	Grouting	Annual costs derived from scaling-up individual m^2 surface area modified or created (small – medium scale)	Independent validation: costing supplied by industry contractor based on out-turn costs
	Chemical bonding		
	Mesh fixing		
	Mars Spiders		
	Gabion baskets	Annual costs derived from scaling-up individual m^2 surface area modified or created (small – medium scale)	
	Bioballs		
	Reef hubs		
	Artificial massive corals (coral-skinned shapes)		Requires market rates validation
	3D printed structures	Not costed	

	Rubble removal	Not costed	
Aquaculture	Optimised existing nursery methods	Not costed	
	Medium-scale shore-based aquaculture	Not costed	
	Large-scale shore-based aquaculture	36.5M corals deployed (medium scale)	Independent validation: out-turn costing undertaken, bottom-up costed by consulting engineers
	Very large-scale breakthrough larval/polyp-based aquaculture	Not costed	

Table 9 also shows the level of independent external validation that was able to be undertaken in this concept-level assessment. It shows that most of the cost estimates in this report have, to a large extent, been independently validated.

4.3 Addressing uncertainty through sensitivity analysis

Understanding the sources and levels of uncertainty are critical to interpreting and applying the concept-level costs developed in this study. This uncertainty derives from:

- Uncertainty in key parameters describing method efficacy and performance
- Engineering uncertainty.

Efficacy uncertainty arises from a lack of knowledge about the performance, throughput or biological attributes of the intervention strategies. By contrast to the uncertainty in engineering parameters, uncertainty around key efficacy parameters can be several orders of magnitude. Therefore, in general, the engineering uncertainty is less than the fundamental efficacy uncertainty.

Engineering uncertainty arises from a variability and lack of clarity of the optimal designs, general arrangements, and number of units of key infrastructure required for each deployment method, and the costs of this deployment infrastructure. Engineering assessments are generally of the range ±50 percent in the analyses presented here and these are affected by uncertainty in key parameters from method efficacy.

The following sections contain details of the delivery methods and key parameter values used in the costing assessments of the delivery methods considered. For many methods, three costing estimates were provided, based on sensitivity assessments: a low-cost, medium-cost (base case) and high-cost. The low and high costs are derived from low and high values of the key sensitive efficacy parameters and uncertainty around these parameters. The sensitivity assessment focused on uncertainty in efficacy parameters, as this is where most of the uncertainty lies.

4.3.1 Engineering and infrastructure uncertainty

As highlighted above, variability around key costing parameters primarily comes from the efficacy uncertainty, although there is also uncertainty around the operational costs of required infrastructure, which in some cases does not yet exist.

Intervention deployment will require infrastructure—shore-based production facilities, and marine-based deployment facilities—which includes vessels of various classes and dimensions, and other marine equipment and infrastructure.

In particular, vessels may be obtained using commercial mechanisms such as vessel ownership or short- or long-term leasing arrangements. Differences between annualised ownership and leasing costs depend on the nature of the vessels, annual demand for the vessel for reef restoration activities, and vessel availability and opportunity costs. This is illustrated schematically by considering possible deployment trajectories (per unit deployed—whether it be a structure or coral—or per day of solar radiation management) as scale increases over time (Figure 3 a,b).

For the moving corals development pathway, cost reductions are achieved through method development, but costs per unit of coral can increase as scale increases. This is a direct consequence of the episodic vessel requirements of this method; that is, significant infrastructure would be required for relatively short periods of the year (spawning periods). This has a cost penalty, after which cost per unit deployed increases as vessel availability reduces (Figure 3a-1).

By contrast, aquaculture has cost peaks as new capital is required, but economies of scale and technology/method development reduce the long-term at-scale cost. Vessels could be used almost year-round, meaning long-term contracts could be established and vessel daily rates would be close—if not the same—as commodity rates.

Cooling and shading costs over time are also somewhat less certain, as the infrastructure would only be required during summer months. However, over time, as a result of increased ocean warming, the annual demand would increase, which would drive down per unit operational costs and vessel costs, although overall annual costs would increase. It is likely that vessels of opportunity (such as the tourism fleet) could be used for at least some solar radiation management activities. However, these opportunities may be quickly exhausted, requiring a large fleet of other vessels to achieve the required scale (Figure 3a-1).

Reef structures and stabilisation activities could be performed year-round, avoiding vessel constraints and associated cost penalties. Research and development into method and technology development would somewhat lower the per-unit cost over time, and if activities were undertaken rear-round, vessel costs would be much closer to commodity costs; particularly if specialist vessels were not required. Hence, the gradual reduction is costs reflected by increasing efficiency with time.

For some methods, such as aquaculture and rubble stabilisation, the deployment scale is close to a linear function of expenditure; the more one invests, the greater the scale of restoration achieved (Figure 3b). By contrast, the cost-scale relationship for development pathways such as solar radiation management and moving corals is less linear, and achieving scale is more problematic (Figure 3a).

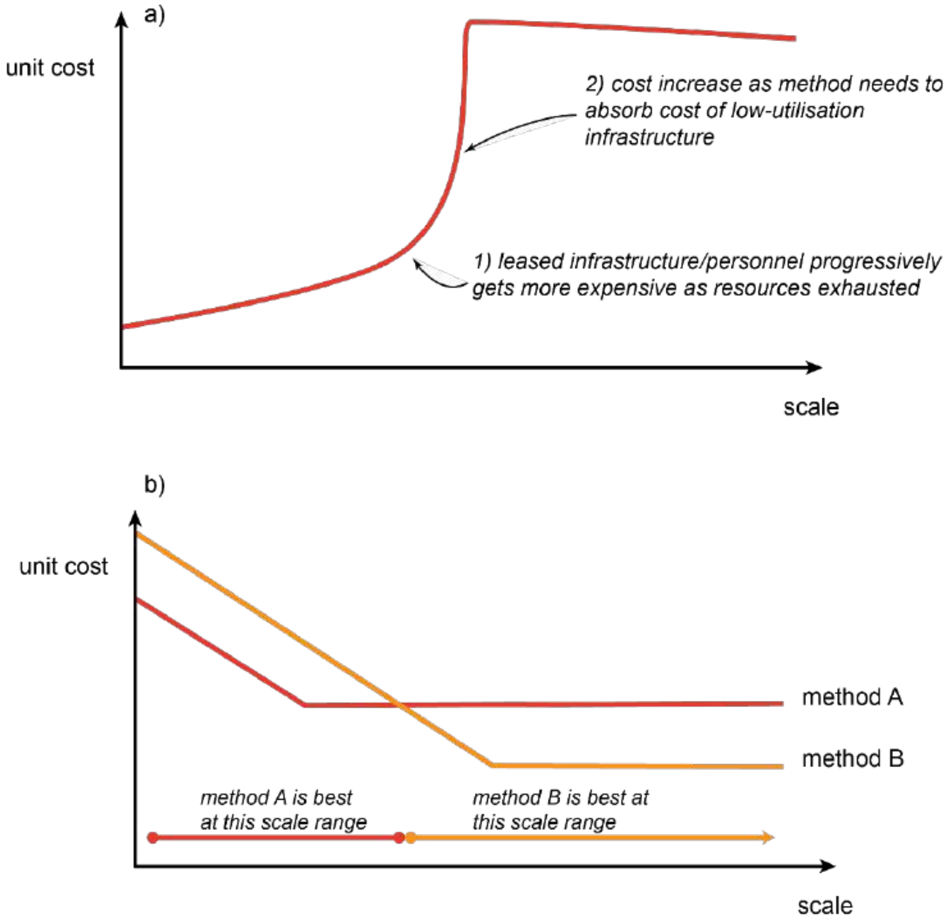

Figure 3: Schematic diagram showing possible intervention cost trajectories. Upper plot shows the impact of seasonal interventions, such as solar radiation management, that require seasonal infrastructure as opposed to steady, year-round infrastructure utilisation (lower plot) such as in reef stabilisation and aquaculture interventions.

The validation of the assumptions in cost estimating and our ability to confidently reduce marine infrastructure cost uncertainty, lead the study team to engage with and review methodology, day rates and assumptions with independent marine vessel operators. Table 10 provides a summary of these costs. The values used in the concept costing models were based on charter rates rather than the cost of ownership as it was not clear how many, if any, vessels would be owned by the range of organisations in the RRAP consortium. Subsequent reports will consider the benefits of ownership versus chartering.

Table 10: Verified vessel costs.

Descriptor	Overall length (m)	Cruising speed (knots)	Working deck area (m^2)	Tank/ hopper volume (m^3)	Min. crew	Comments	Example vessel	Daily rate ($)
Large accommodation barge	120	n/a	n/a	n/a	34	Repurposed ship		20 000
Large working vessel	60	13	450	40	8	Rig supply vessel		15 000
Large barge	54	n/a	1000	2000	4	Dumb barge		7 250
Medium utility vessel	40	15	250	10	5	Fast utility vessel		10 500
Medium Barge	36	n/a	250	30	2	Dumb barge		5 500
Medium transport	45	11	300	300	6	Landing craft		8 000
Small utility vessel	10	15	12	10	2	Small work vessel		2 200

The development of the preliminary cost estimates also revealed that in some scenarios, a considerable number of larger vessels may be required. However, there is presently a paucity of suitable larger vessels operating in Queensland that could be used in restoration activities.

For example, larger vessels (excluding commercial trading/bulk cargo vessels) operating in the Great Barrier Reef are working in the marine tourism sector. Table 11 provides a summary of these (extracted from the Great Barrier Reef Marine Park Authority list of high standard tourism operators – excludes sailing yachts and power vessels under 12m):

Table 11: Great Barrier Reef marine tourism fleet.

REGION	OPERATOR	FLEET
Far North	Mike Ball Expeditions	MV Spoilsport (30m power catamaran)
	Ocean Safari	Fleet of 12m RIBs
	Spirit of Freedom	37m monohull
	Eye to Eye Marine Encounters	Aroona (121ft motor yacht), Flying Fish (32m motor yacht), Elizabeth E II (33m motor yacht), The Boss (25m charter vessel), Eclipse D (16m power catamaran), Freedom IV (14m power catamaran), Phoenix (18m motor yacht), Enterprise (21m motor yacht)
	Deep Sea Divers Den	OceanQuest, ReefQuest, AquaQuest, SeaQuest (all ~25m charter catamarans)
Port Douglas	Poseidon Outer Reef Cruises	Poseidon (24m high speed catamaran)
	Wavelength	Wavelength 4 (20m power catamaran) Wavelength 6 (20m power catamaran)
	Calypso Reef Charters	Blue (21m power catamaran) Bubbles (21m power catamaran) Ten (24m power catamaran)
Cairns	Big Cat Green Island Reef Cruises	Big Cat (35m power catamaran), Reef Rocket (24m power cameraman)
	Cairns Dive Centre	Sun-Kist (16.8m charter monohull), Reef-Kist (18m power catamaran)
	Great Adventures	~30m power catamaran
	Passions of Paradise	25m sailing catamaran
	Pro-Dive Cairns	ScubaPro, I, II and II. 3 monohull 24m charter vessels
	Reef Magic Cruises	2, ~ 25m power catamarans
	Sunlover Cruises	Fleet of around 3, 30m power catamarans
	Tusa Dive	Tusa 6 (24m power catamaran), Spirit of Freedom (37m power yacht)
	Cairns Premier	Ocean Free (16.5m schooner), Ocean Freedom (20m power catamaran)
	Seastar Cruises	Seastar, Skedaddle (~25m powercats)
	Tim North Marine	26m tug, 14m workboat
	Down Under Cruise and Dive	Evolution (~24m power catamaran)
The Whitsundays	Cruise Whitsundays	Seaflight (37.17m) Freedom (33.3m) Sea Quest (30.49m) Sea Odyssey (31m) Seahorse (25.16m) Kingfish (25.98m) Cobia (23.88m) Orca (24.43m) Cruise Whitsundays managed fleet for Hayman Island: Sun Serenity (19.35m) Sun Symphony (19.35m) Sun Harmony (21m) Sun Experience (18.22m)
Capricorn Coast	Capricorn Star	~20m power charter vessel
Reef-wide	Coral Expeditions	4 small (>50m cruise ships)

The data shown in the table above suggest there is a fleet of around 33 charter vessels (primarily power catamarans) between 20m and 35m operating along the Great Barrier Reef. Additional vessels are employed for crown-of-thorns starfish management and fisheries compliance by state and federal agencies.

Table 12 shows the estimated maximum number of non-tourism commercial (in survey) vessels of each type currently available.

Table 12: Vessel availability penalties.

DESCRIPTOR	LENGTH (M)	VESSELS AVAILABLE AT ANY TIME	DAILY CHARTER RATE ($)	PENALTY RATE MULTIPLIER
Large working vessel	60	2	15 000	3
Large barge	54	4	7 250	3
Medium utility vessel	30	6	10 500	3
Medium barge	36	6	5 500	3
Medium transport	45	6	8 000	3
Small utility vessel	10	15	2 200	2
Medium and small airplane		3	27 500	2

Once again, the fleet size in the context of the overall scale of the Great Barrier Reef is small, restricting availability of vessels that could be redeployed for restoration activities.

In the development of the preliminary cost estimates, this lack of vessel availability is addressed through the application of a penalty rate multiplier applied to daily vessel charter rates. For example, a penalty in the form of a multiplier to the established rates of two means that in cases where vessels are scarce and generally not readily available, securing the use of additional vessels over and above the existing fleet for short duration deployments, would be subject to this penalty rate for the purpose of estimating. This increased rate for these vessels on short term contract allows for the opportunity cost associated with securing vessels for short-term restoration activities such as the solar radiation management or moving corals development pathways.

Future analyses will provide more refined estimates of vessel availability and penalty costings.

4.3.2 Method performance uncertainty

The other, and much larger source of uncertainty derives from a lack of validation of quantitative performance of options; in particular, the quantification of conversion rates between source inputs and success rates in the field. Examples include: the number of larvae collected and dispersed versus those that are grown into adult corals, or the number of aerosols released versus those that drift into a location where they are converted into a water droplet when intended to brighten clouds.

These uncertainties, and how they are addressed, are detailed in the following method-specific sections, and Table 13 presents an overview.

Table 13: Sensitivity efficacy parameters in concept costing models.

DELIVERY METHOD	SENSITIVE PARAMETERS
Translocation of larval slicks	Survival rates at all stages of the process (in particular the percentage deployed that recruit and grow into corals), number of days of vessel time, ability to decant slicks to reduce transport volumes.
Larval slick-device based settlement	
Assisted larval movement	
Asexual reproduction	Not costed
Cloud brightening	Required particle concentration (not finalised yet), choice of delivery method (aerial versus surface vessel), number of days of operation.
Misting	Required particle concentration (not finalised yet), number of days of operation.
Ultra-thin surface films	Cost of the formula and required volumes, retention of individual reefs.
Mixing and pumping	Required volume of water.
Grouting	Percentage of a target area that needs to be treated e.g. only a proportion of a specific area would need to be stabilised to sufficiently lock in place the residual area. That percentage is unknown at present.
Chemical bonding	
Mesh fixing	
Mars Spiders	
Gabion baskets	
Bioballs	
Reef hubs	
Artificial massive corals (coral-skinned shapes)	
3D printed structures	Not costed (however likely to be too expensive for practical use).
Rubble removal	Not costed.
Aquaculture	Survival rates at different life stages, capital and operational costs.

4.4 Moving corals

Three different delivery methods have been assessed to move corals (larvae or fragments) over different distances. These methods could be supporting restoration of a location and/or seeking to aid adaptation via assisted gene flow methods.

4.4.1 Moving corals: translocation of larval slicks (T)

Translocation entails finding and harvesting larval slicks, transporting these to receiver reefs and deploying as a larval cloud.

Larval translocation can be performed at different scales, depending on the methods and vessels used. For example, large-scale translocation can be performed using large vessels like a typical oil rig supply vessel used in the offshore oil and gas sector (Figure 4). While large vessels such as this have economies of scale, there are opportunity cost trade-offs in terms of sourcing a large vessel for only a few months of the year (during slick season) and problems with positioning large vessels close to coral reefs. Therefore, selection of the optimal vessel size for most—if not all—deployment methods can be complicated and are beyond the scope of this assessment.

The required vessel size for translocation is largely dictated by the volume of water required to be transported, which in itself is a function of the maximum stocking density of larvae. Ideally, methods would be developed to concentrate larvae through decanting slicks, without increasing mortality. The concentration and mortality rate that can be achieved is yet to be determined.

It is expected that slicks would be harvested in a technique similar to that used in purse-seine fisheries; where the slick is surrounded by a surface boom, or enclosed in a fine net, and the larvae pumped aboard the transport vessel.

Figure 4: Rig support tender as extensively used in the offshore oil and gas sector.

At this stage, it is not clear how the collected larvae would be dispersed at the target location, whether specific locations on a reef could be targeted, or the loss rate during redeployment. Therefore, it is difficult to reliably estimate the throughput rate of larval slick to redeployed one-year-old corals.

4.4.2 Moving corals: larval slick - device based settlement (LS)

Device-based settlement involves harvesting larval slicks and loading them aboard a transport vessel, similar to the translocation method. However, rather than simply transporting and redeploying larvae, in this approach the larvae are settled onto devices en-route.

The larvae might be settled as spat onto Choco boards (small settlement tiles) and these boards attached to devices for deployment (Figure 5, see RRAP report T11—Automated Aquaculture Production and Deployment for more details). The rationale behind this additional step is to increase survivorship, attempting to avoid the very high mortality expected to occur when larvae are deployed as clouds.

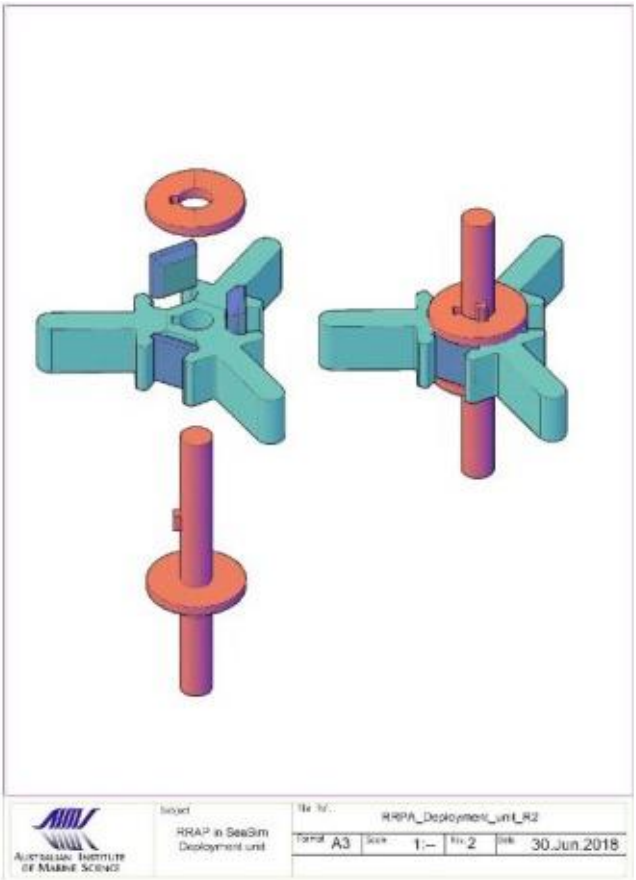

Figure 5: 3D view of erected deployment device – the slotted Choco boards are blue. Extracted from Figure 4-16 of T11—Automated Aquaculture Production and Deployment.

4.4.3 Moving corals: assisted larval movement (ALM)

The high costs associated with the translocation and device-based settlement methods are the result of the requirement for the large vessels needed to transport large volumes of water between reefs. In the assisted larval transport approach, these vessels are replaced by floating net enclosures, or larval pools; larval slicks are shepherded into floating enclosures, towed to receiver reefs and deployed when the larvae have the highest chance of survival.

The advantage of this approach is the expensive steel or aluminium vessels required for the previous two methods are replaced by flexible, and relatively inexpensive, net enclosures that are either self-propelled or towed by smaller tug vessels. The disadvantage of this approach is that these enclosures can only be towed very slowly, limiting the possible distance between the donor and recipient reefs.

The South Australian tuna ranching industry uses a similar approach to transport juvenile tuna, caught in the Great Australian Bight, to more permanent grow-out enclosures in the Spencer Gulf (Figure 6).

Figure 6: Towing a tuna pen in the Great Australian Bight (Image courtesy of www.smf.net.au).

The cost estimates for this delivery method have high uncertainty as the enclosures need to be developed and tested. Therefore, the costs for the enclosures have not been market-verified.

4.4.4 Moving corals: costed concept design

The costing models are configured to enable different types of deployment infrastructure to be used (Table 10). For each of the three moving corals delivery methods costed, a large number of costing scenarios were developed to understand the key cost drivers. The estimated deployment costs presented in this report for the first three moving corals delivery methods (see Table 25) were based on using medium-sized barges towed by small tug vessels, as these were found to be the most cost-effective.

In addition to specifying the type of deployment infrastructure, the three moving corals costing models require that the mortality rates (Table 14), and volume of water collected, are also specified as input parameters. The volume of water collected can then be iterated (by re-running the model) until the required number of one-year equivalent young coral is achieved (in the scenarios used here, this was two million one-year old equivalents).

The vessels that collect, transport and re-deploy larvae and spawn are needed for a total of 20 days per slick. Two slicks per year are targeted. This 20-days includes mobilising and demobilising, deployment to slick location and return transit from recipient reef location. The maximum vessel time required per slick event is governed by biological parameters. As larvae are not expected to be contained on the vessels for extended periods - vessel costings do not include comprehensive life support systems designed to sustain larvae for more than few days.

As spawning events can be relatively well predicted, bookings and procurement for required infrastructure could be planned years in advance, as could supporting logistics. One of the proposed projects in the Moving Corals R&D Sub-program is to develop slick-finding and prediction algorithms using numerical modelling and satellite imagery. These algorithms can also be incorporated in the operational decision support system being developed in the integrated logistics R&D sub-program, so day-to-day path planning can optimise day-to-day vessel logistics. Therefore, the concept design assumes spawn- and slick-finding operations will have a very high success rate in finding suitable slicks, and hence the costing does not include additional days beyond the specified 20 to search for slicks.

For the assisted larval transport delivery method, it is assumed that the enclosures would be collapsed and stored ashore when not used. Shore-based facilities are not included in the costing models, as the concept designs or quantities have not adequately been developed.

4.4.5 Moving corals: sensitivity analyses

Sensitivity analyses were undertaken to better understand the impact of efficacy uncertainty on deployment costs. Table 14 shows the key parameter values used for the high-, medium- and low-cost estimates for moving corals approaches to produce two million one-year old equivalent corals.

Table 14: Parameter values used for the moving corals sensitivity analysis (T – translocation of larval slicks, LS – Device based settlement, ALT – assisted larval transport).

SENSITIVITY RUN NAME	KEY ASSUMPTIONS							
	Mortality (%)					# slicks per year	Infrastructure	
	Collection and transport	Settlement on board	Larval discharge	Post settlement to one year	Total (1 in x survives)		Decanting Ratio	# days per slick per vessel
T low	80		95	90	1 000	2	1	20
T medium	86		99.5	95	28 571	2	1	20
T high	95		99.7	98	333 333	2	1	20
LS low	80	80		90	250	2	1	20
LS medium	86	90		95	1 429	2	1	20
LS high	89.5	90.5		98	5 013	2	1	20
ALM low	80		95	90	1 000	2	5	20
ALM medium	86		99.5	95	28 571	2	5	20
ALM high	95		99.7	98	333 333	2	5	20

The vessel rates can be found in Table 10 above. The other key parameter required for the modelling is the density of viable embryos per m^3 of slick. Initial modelling used the literature value of 230 000. However, based on the results of experiments performed in December 2018 by both Dr Russ Babcock (CSIRO) and Professor Peter Harrison (Southern Cross University), this value was tripled. As summarised in Table 7, the model logic involves specifying the volume of slick water harvested, the survival and decanting/concentrating rates (Table 14 above), and the type of infrastructure used for harvesting and transporting slicks. The model calculates the number of one-year-olds produced, and cost for producing this number. The volume of water collected can be iterated until the required number of one-year-old corals (two million in these scenarios) is achieved.

As identified in Table 14, the mortality rates are key sensitive parameters in the concept costing assessments. To this end, Table 15 below shows the literature-based estimates of natural mortality for comparison. Total survivorship from these estimates ranges from 1 in 17,422 to 1 in 4,166,667. The low-cost scenarios developed here apply lower mortality rates, reflecting the expected increase in survivorship as a result of active husbandry (Table 16).

Table 15: Estimates of natural larval mortality (provided by R. Babcock, CSIRO).

PARAMETER	RANGE OF VALUES (%)	SOURCE
Proportional mortality rates - embryo collection into vessel, or fertilisation in water column (up to 120 hours)	95.9 – 98.5	Pollock et al., 2017
Larval cloud mortality	95.0 - 99.2	Edwards et al., 2015; de la Cruz & Harrison, 2017
Post settlement mortality	97.2 – 99.8	Doropoulos et al., 2015; ter Hofstede et al., 2016; de la Cruz & Harrison, 2017

By comparison, corals reared in controlled aquaculture conditions (Table 16) show the values used in the independent assessment of aquaculture deployment costs (T11—Automated Aquaculture Production and Deployment); that were mostly derived from results obtained using the Australian Institute of Marine Science's SeaSim facility.

Table 16: Estimates of larval mortality rates in controlled conditions

PARAMETER	VALUE (%)	SOURCE
Fertilisation/larval rearing	10	T11—Automated Aquaculture Production and Deployment
Mortality during settlement	10	T11—Automated Aquaculture Production and Deployment
Post settlement mortality	31	T11—Automated Aquaculture Production and Deployment

Comparison of the estimates contained in Tables 15 and 16 reveal the dramatic differences in mortality in controlled aquaculture environments as opposed to in the wild. The mortality rates used in the costing scenario analyses are much closer to the wild or *in situ* rates. Therefore, there is great opportunity to increase the productivity of moving corals delivery methods if survival rates can get closer to those in aquaculture environments.

4.5 Cooling and shading

Cooling and shading primarily involves altering the local meteorological and oceanographic conditions during bleaching events, to reduce overall bleaching stress on reefs during these events. These delivery methods cluster into two categories:

- Solar radiation management
- Pumping and mixing

Solar radiation management seeks to reduce incoming or incident radiation, leading to cooling of ambient waters around reefs. Pumping and mixing acts to physically redistribute surface water and replace warmer waters with cooler water from nearby areas.

4.5.1 Cooling and shading: solar radiation management - marine cloud brightening

Marine cloud brightening is one of three solar radiation management delivery methods under consideration in the cooling and shading intervention strategy. These approaches seek to alter the local environment to reduce bleaching stress during critical bleaching periods.

Cloud brightening is somewhat similar to established methods of cloud seeding used to increase catchment rainfall in hydro-electric and agriculture catchments in many countries around the world; including in Australia (Figure 7). The challenge with cloud brightening, is the efficient generation of the right particle-size for discharge into the atmospheric boundary layer. If the wrong particle size is discharged, the effect will be minimal.

Figure 7: Example of a cloud seeding operation.

The costing of cloud brightening was developed on the assumption the coverage would be Great Barrier Reef-wide.

The costing models accommodate deployment through large fixed stations, or movable stations that can be relocated according to wind direction. The results presented here are based on a fleet of movable vessels. The costings are based on a per-nozzle basis, which is scaled up accordingly. Hence, there are no economics of scale represented in the model as these are presently unknown.

The costing is based on the existing snowmaker technology (Figure 8) with modified nozzles (still in development) and existing compressed air systems. Unlike existing snowmaking machines that direct the discharge at low incidence angles, in this application, the discharge would need to be directed at a much steeper angle into the lower atmosphere. Depending on the outputs of subsequent atmospheric models, it may be necessary to elevate these machines above mean sea level.

A large vessel such as that shown in Figure 4 could be used to support multiple spray machines.

Figure 8: Commercially available snow-making machines.

4.5.2 Cooling and shading: solar radiation management – misting

Misting is a variant on cloud brightening where a surface layer of mist is temporarily emitted, using technology similar to existing artificial fog- or mist-generating machines used for battlefield or theatrical purposes (Figures 9 and 10). In these machines, a fluid such as paraffin (biological products such as macroalgae extracts may be utilised) is atomised, and the fine spray discharged at the sea surface. The particles ultimately fall out of the atmospheric boundary layer and onto the sea surface. Their ultimate fate has not yet been investigated. While suspended in the atmospheric boundary layer, the particles reduce incoming solar radiation and hence local sea temperatures, thereby reducing local bleaching stressors.

Misting can be deployed from medium-sized surface vessels, or small aircraft such as crop-dusting airplanes.

Figure 9: US amphibious attack vehicles using misting technology while participating in the annual combined military exercise Cobra Gold 2010 at a Thai Navy base in Rayong province. (Image: AFP/Getty).

Figure 10: Commercially available local-scale misting system. (Image courtesy of Biogenesis: The Fog System).

4.5.3 Cooling and shading: solar radiation management - ultra-thin surface films

Ultra-thin surface films are the third delivery method for managing incoming solar radiation. Thin films are applied to the sea surface as a means of reducing radiation (see Figure 11).

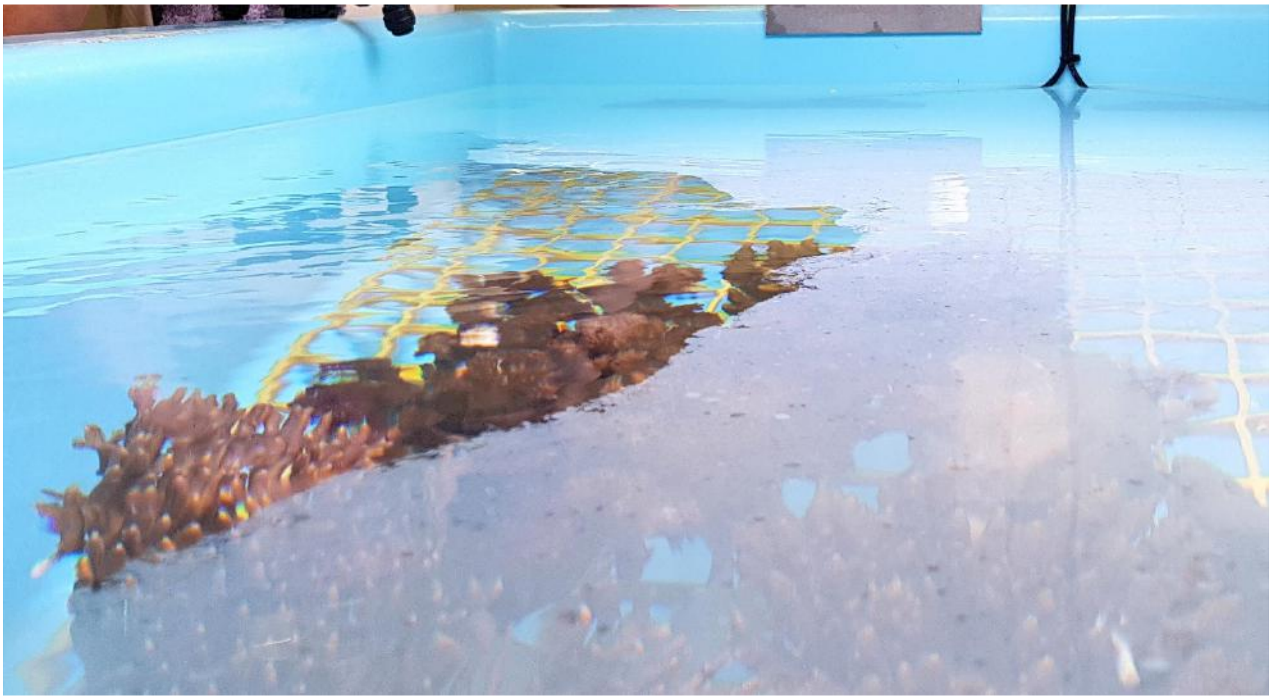

Figure 11: Ultra-thin surface films as applied in laboratory conditions (A. Negri).

Ultra-thin surface films have been assumed to be a local deployment method, either from small-to-medium vessels or planes. As with misting, daily deployment windows are envisaged, and it is expected that a surface area greater than the target reef area would be required to be covered. Modelling by Dr Mark Baird, CSIRO, suggests that around three times the reef area would need to be covered with film to account for tidal and non-tidal excursions of the surface waters off the target reef (see Figure 12). In the costing, this is accounted for by applying the retention parameter. For example, a retention parameter of 300 percent means that three times the reef area needs to be covered to account for advection and dispersion of surface water during the deployment cycle.

The retention multiplier crudely captures the effects of ocean circulation—driven by large-scale currents, tides and winds—on the time water stays on a reef. It is strongly affected by reef morphology, size and the target intervention area. To consider a variety of reefs, the eReefs Project's relocatable model was applied on more than 30 reefs, generating a spatially resolved residence time (age) and in-days (Figure 12). The retention parameter could be crudely considered as one/age.

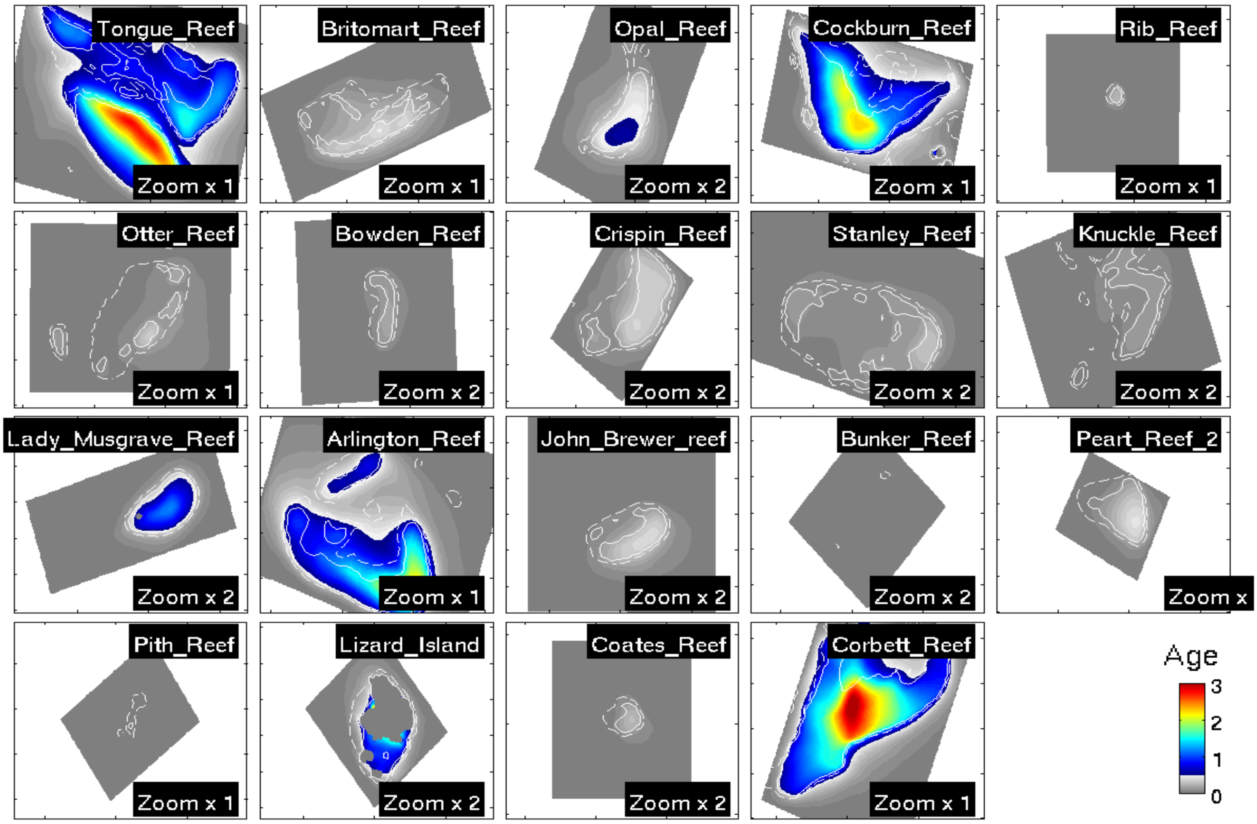

Figure 12: Spatially resolved residence time (or 'age') of 19 reefs calculated using 200m configurations of the eReefs relocatable ocean and coastal model (RECOM) for March 2017. Grey scaling is an age up to 0.5 d^{-1}. White lines are the 5m and 10m depth contours. All panels with a x1 zoom are equally scaled, while x2 have been magnified.

Reef areas with age greater than around three days, are likely to be lagoonal areas with low coral cover, due to little exposure to open ocean waters and the nutrients they contain. The success of inventions such as ultra-thin surface films partly depends on water retention over reefs, which can vary dramatically between reefs (Figure 12) Nonetheless, a retention multiplier of 300 percent would account for regions of age greater than say 0.5 d^{-1}, which exist on at least 10 percent of significantly-sized reefs.

4.5.4 Cooling and Shading: costed concept design

The solar radiation models operate by specifying the required concentration of particles or formula (in the case of ultra-thin surface films), weather conditions, and preferred deployment platforms. The models then calculate the number of deployment platforms required and their cost.

Therefore, the models require a set of input parameters to be specified. In the scenarios presented here, a number of these remain fixed, as shown in Table 17 below:

Table 17: Fixed parameter values used in the solar radiation management models.

PARAMETER	TYPICAL VALUE	COMMENTS
Single nozzle discharge	3×10^{12} particles/s	Supplied by Dr Daniel Harrison (Southern Cross University) and Professor Zoran Ristovski (QUT).
Fuel requirement per nozzle	0.025 l/h	Based on a CAT 330 HHA compressor.
Required swath width	Varies	Based on wind direction, used to determine the required spacing between stations. estimated in model.
Fuel cost	$3/litre	Fuel is required to power the compressors. The hourly fuel cost encompasses fuel delivery to the compressors. While the bowser cost may be around 1$/litre, the cost estimate includes the logistics of delivery to the discharge station.
Fuel + paraffin cost (misting)	$10/litre	'As delivered' cost encompassing cost to supply fuel and paraffin to the deployment vessels.
Coverage (ultra-thin surface films)	30 kg/ha	Supplied by A. Negri (AIMS).
Retention multiplier	300%	Additional area to be covered to account for local winds (confirmed by M. Baird CSIRO).
Formula cost (ultra-thin surface films)	$20/kg	'As delivered' cost encompassing cost to deployment vessel. Supplied by A. Negri (AIMS).

The input parameters that were varied in the long list of simulated scenarios include the type of deployment infrastructure (either relocatable or fixed platforms, vessels or planes) along with the minimum concentration of particles required in the atmosphere or sea surface (in the case of ultra-thin surface films).

The weather conditions for each simulation are also specified as an input parameter, as are the total number of days per year that solar radiation management is required.

For cloud brightening and misting, the number of deployment platforms required on any given day is partly a function of prevailing wind. This is because discharges from a point source deployment platform end up as buoyant plumes that propagate downwind. This is shown schematically in Figure 13 for the case of a north-easterly wind. Therefore, the positioning of the deployment platforms, and their spacing (which is calculated by the model), must consider local wind conditions.

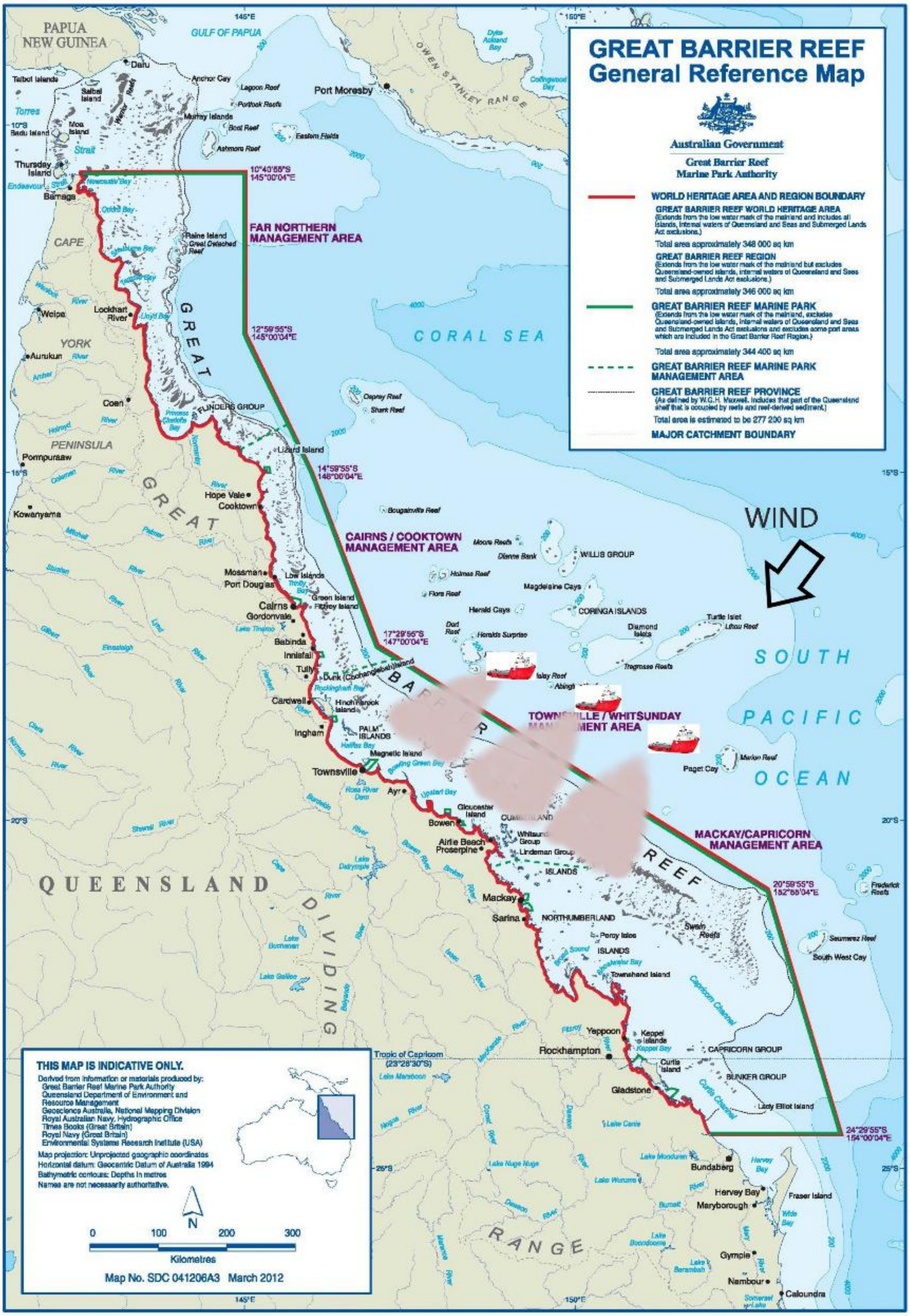

Figure 13: Schematic diagram of particle plumes generated by local and regional winds.

The marine cloud brightening and misting models are configured so that the required station spacing can be estimated using two different atmospheric dispersal formulations - a box model and a plume model. The cost estimates here used the plume parameterisation, where the horizontal scale of the plumes is estimated using the Eulerian conservation of mass formula (based on neutral atmospheric stratification):

> *Cross-sectional area of plume at any point downstream = (rate of particle emission)/(wind speed × particle concentration in downstream plume)*

In subsequent analyses, it is expected that plume models such as Plumes or the CSIRO TAPM model will be used. The regional atmospheric model presently being developed in the cooling and shading program will be applied when it becomes available.

The development of these plumes allows a high rate of particle emissions to be delivered from points upwind of the reef, and the subsequent plumes spread and join up over the reef to provide widespread coverage. The costing model calculates the spacing between the discharge points which are then used to determine the number of vessel of stations required, and the operational costs.

After these fixed and variable input parameters are specified, the model estimates the number of infrastructure platforms required, and the total annual deployment costs. For the marine cloud brightening and misting simulations presented here, the costing is based on a fleet of movable vessels. The ultra-thin surface film costings assume the formula is deployed via aircraft.

4.5.5 Cooling and shading: solar radiation management – sensitivity analyses

There is uncertainty around what concentration of particles or material will be required to be discharged to achieve the necessary reduction in solar radiation. The scenarios used for solar radiation management have therefore focused on exploring uncertainty in key efficacy or performance parameters and have constrained engineering uncertainty through specifying and holding constant the engineering assumptions; especially the cost and general arrangements of deployment platforms, such as vessels. These engineering assumptions were derived from the results of a separate set of sensitivity assessments undertaken to arrive at a reasonable set of engineering assumptions. The underpinning engineering assumptions are shown in Table 18:

Table 18: Cost-benefit analysis engineering assumptions used for marine cloud brightening

ASSUMPTION	VALUE	COMMENTS
Vessel type	40m work vessel	Deck space of 240m^2 (example in Figure 14) to accommodate 20 cloud brightening cannons (containing 7000 nozzles in total), powered by 7 screw compressors (97 kW Caterpillar 330HHA or equivalents). Each screw compressor feeds up to 1200 nozzles.
Vessel location	Relocatable - as required	Vessels able to be repositioned at night. Fixed stations not used in these scenarios.
Daily emission period	8	Particles emitted for 8 hours per day (allowing time to reposition vessels for following days' operations).
Cost of operating (in equivalent daily operational cost)	$10 500	Excludes penalty costs for lack of vessel availability (penalties are used in the analysis: for every vessel after the first 6, the daily cost is tripled). Vessel rates have been market-verified.

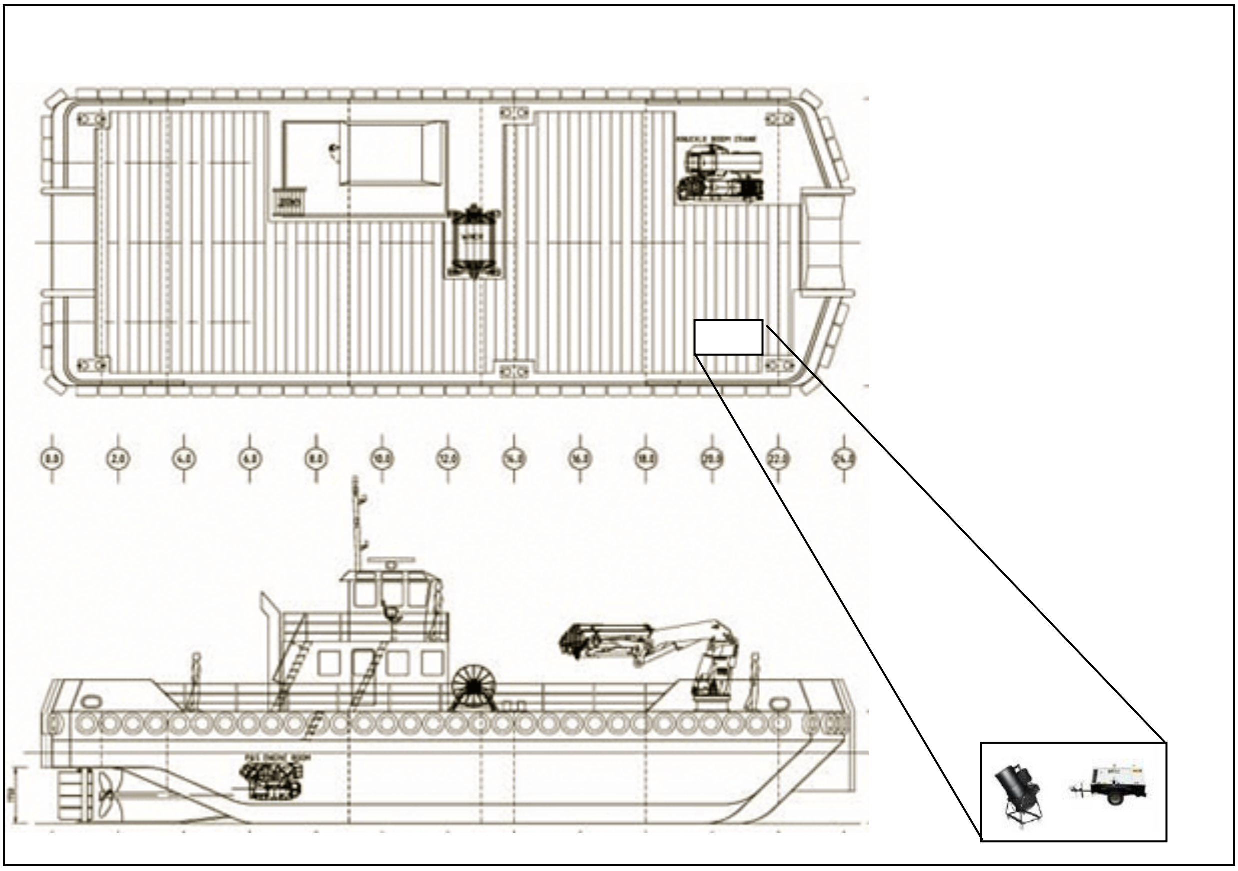

Figure 14: Example of a cloud brightening vessel. 40m vessel has deck space >240m^2, able to accommodate 20 cloud brighteners supported by seven compressors. Vessel has bunkering provisions for 20m^3 of compressor fuel. Daily requirement is 1400L, giving the vessel 14 days compressor fuel bunkering.

Table 19 shows the variables and values used for the sensitivity analyses of the solar radiation management methods.

Table 19: Parameter values used for the solar radiation management (MCB - marine cloud brightening, M – misting, SF - ultra-thin surface films) sensitivity analysis for solar radiation management.

COST SCENARIO	ASSUMPTIONS			
	Average wind direction and strength (km/h)	# days per year deployed	Coverage	
			Required concentration	Area of marine park protected (km^2)
MCB low	25 (SE)	90	200 (p/cm^3)	300 000
MCB medium	25 (SE)	90	300 (p/cm^3)	300 000
MCB high	25 (SE)	90	400 (p/cm^3)	300 000
M low	25 (SE)	90	0.01 (l/ha)	10 000
M medium	25 (SE)	90	0.02 (l/ha)	10 000
M high	25 (SE)	90	0.04 (l/ha)	10 000
SF low	Assumes 300% coverage required to account for tidal excursions	90	15 (kg/ha)	10
SF medium		90	30 (kg/ha)	10
SF high		90	60 (kg/ha)	10

The scenarios presented here use the same infrastructure but reflect uncertainties in the required particle or formula concentration.

In these calculations, misting is deemed to be a regional solar radiation management method and the scale used for the calculations are 10 000 km of reef area protected.

4.5.6 Cooling and shading: pumping and mixing

The final delivery method in the cooling and shading intervention strategy being considered is pumping and mixing. This involves physically transporting and dispersing cooler waters onto reefs during bleaching periods.

CSIRO (Dr Mark Baird) investigated the retention of several reefs on the Great Barrier Reef in order to identify which reefs might be the most suitable for the pumping and mixing delivery method (Figure 12). Of these, Lizard Island reef, which has as a high residence time for a small reef, and proximity to cooler water at depth, was deemed the most viable to model this intervention.

The modelling identified that in order to achieve cooling of 0.2°C or greater over 100ha required four outlets with flows of $5m^3s^{-1}$.

This estimate is underpinned by the following assumptions:

1. Flow is constant through rough pipes extending 3km to site at 40m depth, at which 27°C water is available.
2. There is no energy loss due to bends in the pipe.
3. Pipes are submerged at both ends, so lift is based on reduced density and not full mass.
4. Energy calculation includes friction, momentum loss and lifting.
5. Pipe cross-section is circular with a wall roughness of 0.025m, equivalent to rusted steel (a smooth pipe would reduce the friction loss, the major energy term, by a factor of four).
6. Assuming 1kWh costs $1.

For four outlets with $5m^3s^{-1}$ a pipe diameter of 1.5m brings the flow speed to 70 cm s^{-1}. The energy requirement for a set of four pipes is ~100kW. Energy cost per site is around $2 400 per day. With four sites, this rises to $9 600 per day. Running for say 40 days of the year ~$400 000, to protect the ~5 km^2 of reef area; which is equivalent to $80 000 per km^2 per year energy costs.

While the Lizard Island site maximises the impact of the cold water injection, engineering solutions such a larger pipe diameter for most of the 3km, for example, or pipe wall cleaning before each summer, could reduce the pumping costs.

Based on outrun costs from effluent discharge pipes, the capital cost is likely to be in the range $20-$50M per kilometre. Therefore, for four, 3km long pipes, the capital cost would be in the range of $240-$600M, amortised (without depreciation) over 25 years, gives an annual median cost of around $22M per year to capitalise the pipes.

Assuming maintenance requirements of 5 percent of the capital cost, then annual maintenance of the pipework is an additional $1.1M.

The pumps would be required to be submersible pumps, feeding 3m diameter pipes.

More comprehensive calculations can be found in **T12—Cool Water Injection**.

4.6 Reef structures and stabilisation

The subsea stabilisation contractor Subcon was contracted to provide deployment cost estimates for the existing technologies identified in the rubble stabilisation development pathway. The table below summarises the as-deployed costs of the 'fish habitat' creation options. Further details can be found in Appendix B.

Table 20: 3D structure method costs.

	GABIAN	REEF HUB	REEF DOME	MASSIVE CORAL
Total cost per structure ($)	1224	4093	3324	3662
Cost per m^2 surface area ($)	258	974	188	207
Cost per m^2 seabed coverage ($)	481	2316	1306	1439
Cost per m^3 of new reef ($)	1321	3474	1102	1214

If we compare these costs to creating new corals, assuming one young coral is equivalent to $1m^2$ of seabed habitat created, then we get the costs as detailed in the second row of the table below.

Table 21: 3D structure per coral estimated costs.

	GABIAN	REEF HUB	REEF DOME	MASSIVE CORAL
Cost per km^2 seabed coverage ($)	481M	2316M	1306M	1439M
Cost per coral ($)	481	2316	1306	1439

These costs are relatively consistent with the costs of small-scale restoration efforts identified in T4—Current Practices shown below (remembering that there are 100ha in a km^2):

Table 22: Global restoration costs.

RESTORATION TECHNIQUE	RESTORATION COST (2010 US$/HA)			
	n	Median (± SD)	Minimum	Maximum
Coral gardening	3	351,661 (± 136,601)	130 000	379 139
Coral gardening - nursery phase	5	5,616 (± 22,124)	2 808	55 071
Coral gardening - transplantation phase	2	761,864 (± 1,033,831)	30 835	1 492 893
Direct transplantation	21	73,893 (± 867,877)	4 438	3 680 396
Enhancing artificial substrates with an electrical field	0			
Larval enhancement	6	523,308 (± 1,878,862)	6 262	4 333 826
Substrate addition - artificial reef	15	3,911,240 (± 36,051,696)	14 076	143 000 000
Substrate stabilisation	8	467,652 (± 9,015,702)	91 052	26 100 000

Subcon also provided costs for grouting and other forms of stabilisation. These are shown in the first row in Table 23 below and in Appendix B.

The second row in Table 23 shows the costs if we assumed that each 5m 'strip' stabilises a 15m-wide strip (3:1 benefit ratio). Once again, assuming a coral density of 1 per m^2, the cost per coral would be as shown in the lower row of the table.

Table 23: Stabilisation costs

	MARS SPIDERS	GROUT INJECTION	WIRE MESH PINNIING
Cost per m of a 5m wide strip ($)	528	422	290
Stabilising cost per km^2 ($)	35M	28M	19M
Cost per coral ($)	35	28	19

4.7 Aquaculture

Costing for the aquaculture production and development has received the most scrutiny and contains more detail in comparison with the other implementation strategies. WorleyParsons was commissioned to develop a basis for design estimate of the quantities, concept designs and costings for both shore-based and field deployment infrastructure requirements (T11—Automated Aquaculture Production and Deployment).

The low, medium and high estimates were derived from the bottom-up costing supplied by WorleyParsons (T11—Automated Aquaculture Production and Deployment), with the base-case or medium estimate containing no contingency, the high case with contingency costs, and the low case the base-case minus the contingency costs (see T11—Automated Aquaculture Production and Deployment for details).

4.7.1 Aquaculture core scale drivers

The analysis of potential aquaculture (sexual or asexual) delivery methods included assessment of the core cost drivers and factors limiting production and deployment rates, and ultimately the overall scalability.

This identified several interrelated core drivers:

- **Post deployment survival** – the percentage of the corals deployed that survive to juvenile and ultimately sexually-reproductive adult corals.
- **Time in production** –production process length (intrinsically linked to post-deployment survival).
- **Automation and mass production** - the extent automation is used in the production, transport and deployment phases.
- **Production method** – land- versus sea-based, centralised and distributed.
- **Deployment logistics** – sea shipping and deployment methods.

Post deployment survival

In natural populations, corals follow a Type 3 survival curve (exponential decay), as illustrated in the diagram below.

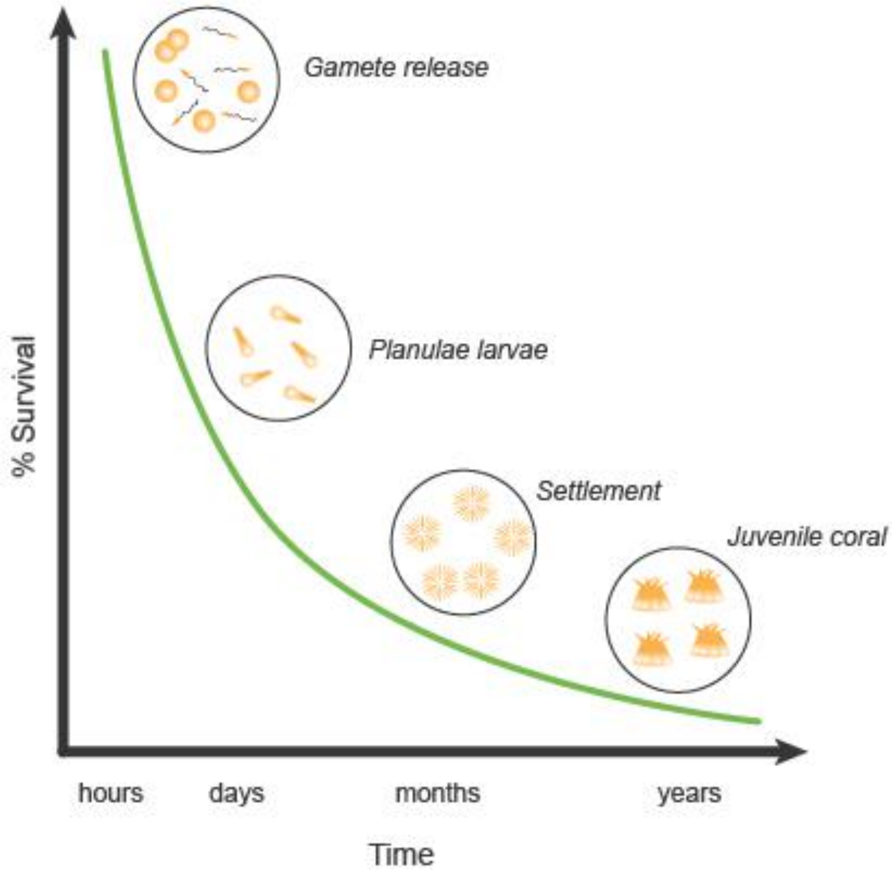

Figure 15: Schematic of survival curves for corals.

Without active management, the survival curve dictates that post-deployment mortality rates increase exponentially as the age of deployed corals is reduced. The older young corals are when they are deployed, the higher the survival rate per unit of time; represented by the change in gradient in Figure 15.

Time in production:

The longer the coral remains in the production process, the more expensive the cost of producing that coral. Even if labour costs are controlled, the longer a coral is in the process, the production system needs to be physically larger for any given throughput rate, and this increases cost. For example, the following table illustrates the number of corals in a production system required to produce a continuous stream of 100,000 corals per day as a function of time each coral stays in the production process.

Table 24: Production time/stock trade-off.

TIME IN PRODUCTION	NUMBER IN PRODUCTION SYSTEM AT ANY POINT IN TIME
1 sec	1.2
1 minute	69
1 hr	4,167
1 day	100,000
1 week	700,000
1 month	3,000,000
1 year	36,500,000
3 years	109,500,000

As the duration increases, the number in the system at any time increases and they each individually require more space (as they are growing). Ignoring the growth factor, assuming a 12-month production process, and a 0.5m^2 equivalent floor area for each coral (the holding area for the coral, and a pro-rata area for all of the other aspects of the facility - broodstock holding, spawning tanks, walkways, process areas, packaging and loading, offices, laboratories etc.) then 18km^2 of production area is required. If the production process is only one month in duration, then the area reduces to 1.5km^2, and costs reduce accordingly.

Automation and mass production

At the likely production rates being targeted by RRAP (upwards of tens of millions per year), the use of process automation and mass production methods to reduce labour requirements and increase throughput rates will be essential. High levels of automation are not feasible at small scales due to the capital investment overheads; however, these scales provide the opportunity to significantly reduce per-coral costs.

The exact requirements and opportunities for process automation are aquaculture system specific but would be expected to cover aspects of all process phases – production, transport, assembly (if required) and deployment.

One area of specific consideration is that of deployment. This is the most labour/time consuming/dangerous aspect of the process. Current methods are diver-based, and not viable or capable of achieving the target outcomes (by orders of magnitude) at the scales being considered.

Two alternative options were assessed:

A. **Automated attachment**: subsurface automated ‘planting’ delivery systems, akin to systems just starting to emerge in the precision agriculture sector. In this instance, corals (larvae, recruits, juvenile corals, fragments etc.) would be attached to the reef substrate. Conceptually, bottom crawling, submersible or surfaced-based planting systems can be envisaged, however these are expected to be complex to develop (very low current technology readiness level), expensive and environmental conditions constrained (likely to be limited to low current/calm conditions).
B. **Deployment device:** an alternative is to use a ‘delivery device” that holds the coral(s), is dispersed from a surface vessel, transports the coral to the substrate and aids in securing the coral in an appropriate position. For this method to be practical and cost effective, the payload (the coral in whatever form is selected) needs to be small, the upper limit is not

yet known, however corals or fragments equivalent in size to six to 12 months old would be a reasonable assumption.

For the remainder of the concept design process, the deployment device was used as the planning assumption. Note that automated planting has not been eliminated, and some research and development in this area is recommended.

Production method

Several options exist for production method, with two primary decision dimensions:

- Land versus sea-based facilities
- Centralised versus distributed facilities.

The analysis undertaken during the concept feasibility study focused on centralised, land-based aquaculture. This decision was based on a judgement that this option was the most scalable and low-cost and would therefore provide a design, cost and scale benchmark against which other options could subsequently be compared. At the scales being assessed, land transport costs become a small cost component, with factors such as access to labour markets and construction and operating costs the primary drivers. These all favour land-based operations.

Further analysis will be required to confirm these assumptions, and to factor additional dimensions such as ecology, genetic diversity or regional employment into the assessment.

Deployment logistics

Given the scale of the Reef, the large distances between reefs, and to the mainland (or islands with infrastructure to enable production and shipping), even if a highly distributed production system is used, the distances between production and deployment locations will still be considerable. Therefore, optimising deployment logistics becomes critical. Two specific aspects require management:

- If the deployment vessels need to operate over or close to the reef then small, shallow draft and highly manoeuvrable vessels are required.
- The larger the transport distance and volumes, the larger the vessel required to achieve required economies of scale and be less weather constrained.

This means a dual vessel approach is likely to be required. For example, small vessels operating from a shore-based staging point could carry limited product, in fair weather only, with most of its time spent travelling between port and worksite. At very small scales, this may be the best solution. However, as scale increases, it becomes more economic (and a logistical requirement) to operate these vessels from a staging point adjacent to the target reef. The exact configuration of this staging system will be context and deployment-rate specific. This is a common marine deployment requirement, with many potential models available. For example, using a site-based accommodation and restocking vessel which periodically returns to port to resupply, or remains onsite, resupplied by specialist transport vessels.

Optimising the design for RRAP deployment will be critical to minimising costs. It is also a common challenge for many of the proposed intervention delivery methods. It is likely that further cost savings can be achieved if different interventions/deployment methods use the same deployment infrastructure. These deployment logistics challenges are considered in S9—Systems Engineering and Integrated Logistics.

4.7.2 Conceptual design considerations

The following relationship model emerges if the factors of post-deployment survival, time in production, and automation are jointly considered (Figure 16).

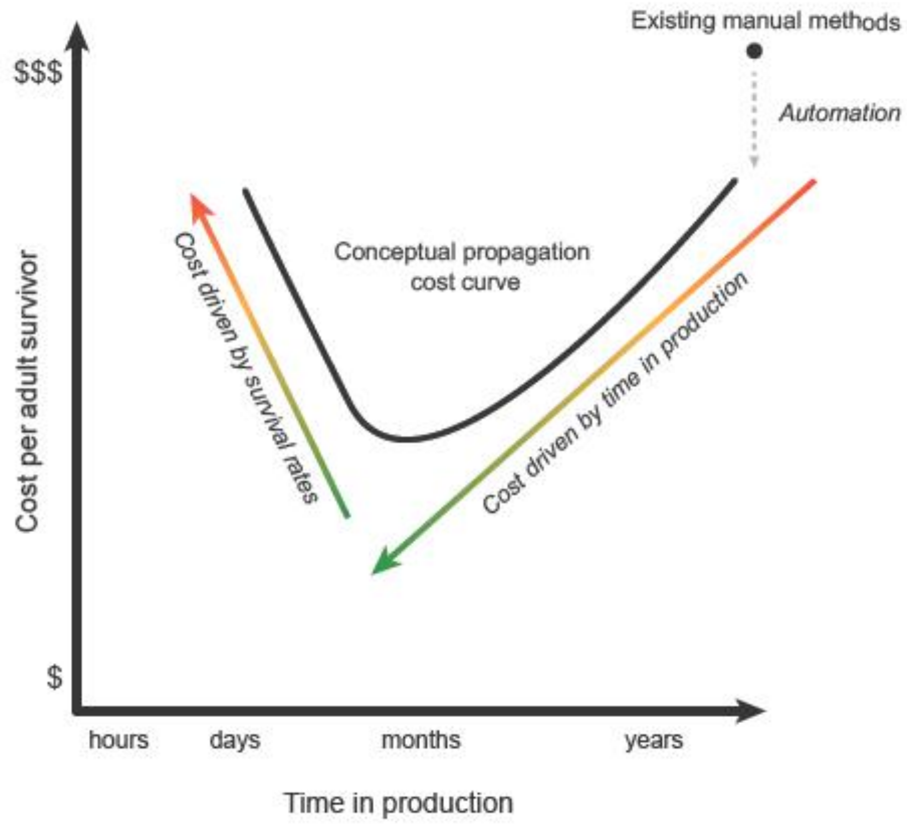

Figure 16: Schematic diagram showing trade-offs between production time and production costs.

In Figure 16, the cost per adult survivor is the total investment divided by the number of corals that survive to become adults. Time in production refers to the length of coral grow-out prior to deployment.

If a manual method is appropriately automated, the cost per adult will reduce. Similarly, as production time is reduced, cost per adult also reduces. However, as production time is reduced, post-deployment mortality increases, until increasing rates of mortality begin to dominate the cost curve, and further reductions in production duration result in increasing cost.

The actual shape and minimum point of the curve will be a function of many factors such as: the species, the production method (e.g. sexual, asexual, micro-fragmentation), the effective size/age of the coral as a function of time and receiving environmental factors that influence survival rates. However, the general principle will remain true.

With broad use of automation/mass production methods, and if post-deployment survival rates of small/young corals could be improved, the curve moves as follows and significant reductions in cost per coral could be achieved (Figure 17).

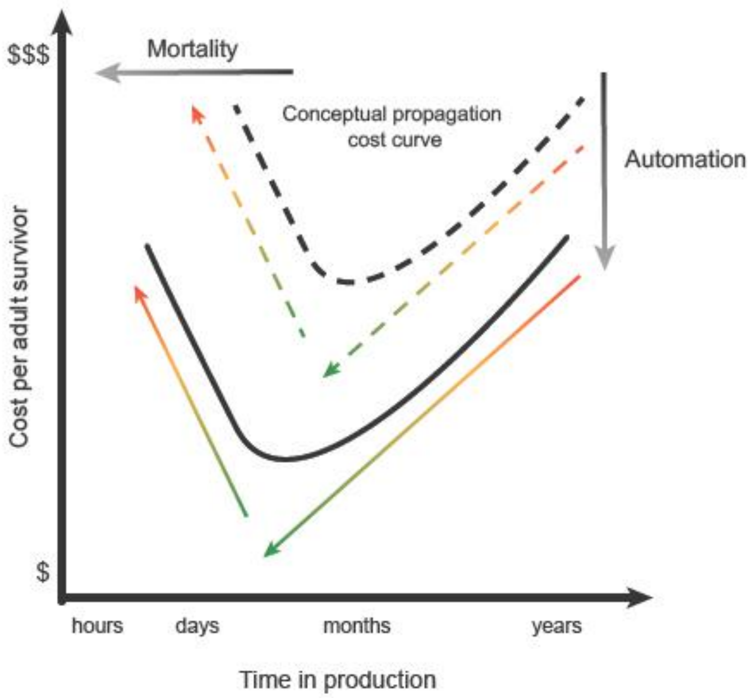

Figure 17: Family of curves for production cost trade-offs.

In reviewing this model, two questions arise:

1. Can aquaculture methods be developed that do not follow the standard age/size-related post-deployment coral survival curve?
2. How far can the concepts of mass production and automation be developed?

Consideration of these questions leads to the idea that a possible solution using a 'deployment device' can be envisaged. This device would allow coral to be firstly attached to and then deployed from the surface using automated methods. The advantage of this approach is that young corals would be given a helping hand in critical early life stages.

In reviewing the feasibility of this idea, two sources of information were uncovered:

- Australian Institute of Marine Science (AIMS) is trialling different coral larvae settlement tile shapes. In assessing settlement rates, ongoing survival rates were also recorded, indicating that ongoing survival rates were much higher than larvae settling onto natural benthos.
- International organisation SECORE is in the process of testing different diver deployment shapes designed to "lock into the substrate" and allow the deployment of young coral recruits while maintaining acceptable survival rates.

In both cases, the research and development were early phase but promising. Based on this assessment, SECORE was contracted into the RRAP Concept Feasibility Study and a collaboration was formed between AIMS, SECORE and multinational engineering company WorleyParsons to further develop and assess these methods.

4.7.3 Aquaculture basis of costing

The following four scenarios were selected to quantitatively assess the factors driving cost and scalability and determine if the required levels of cost reduction (two to three orders of magnitude over current methods) and deployment scale (assumed to be tens to hundreds of millions per year) are feasible.

Table 25: Aquaculture delivery methods

DELIVERY METHOD	METHOD CHARACTERISTICS	
	aspect	description
Current methods	Production duration/coral age	Long (1-3 years)
	Production automation	Manual
	Deployment automation	Manual diver deployment
	Deployment device sophistication	N/a
Medium automation	Production duration/coral age	Short (30-90 days)
	Production automation	Partial
	Deployment automation	Partial
	Deployment device sophistication	Passive design
High automation and mass production	Production duration/coral age	Short (30-90 days)
	Production automation	Full
	Deployment automation	Full
	Deployment device sophistication	Passive design
Larvae/polyp method	Production duration/coral age	Very short (larvae/polyp)
	Production automation	Full
	Deployment automation	Full
	Deployment device sophistication	Active design

A detailed concept design and costing of the 'high automation and mass production' methodology, assuming a centralised, land-based production model, was completed by WorleyParsons, with technical and design advice from AIMS, SECORE and Queensland University of Technology (QUT). The detailed report is provided in T11—Automated Aquaculture Production and Deployment.

This method was selected on the basis that:

- It targeted large-scale (36.5M corals per year), sufficient to represent the 'commodity rate[1]' based on the full use of automation and mass production methods. Further scale increases using this method would not result in additional economics of scale and unit cost reductions.
- It did not use methods technologies that had wide uncertainty margins such as post-deployment survival rates and deployment device performance.
- It provided a framework for value engineering processes to estimate potential outcomes for other methodologies, such as those described as medium and very large in Table 25.

[1] The commodity rate refers to the point at which economies of scale drivers are exhausted. Per unit costs no longer reduce as production scale increases.

5. COSTING RESULTS

5.1 Overall findings

A key objective of this study is to develop the 'first-cut' estimates of the possible and probable operations operational costs to deploy many of the interventions being considered in RRAP.

The estimated concept-level deployment costs can be seen in Tables 26 and 27. Table 26 shows the cost rate estimates where deployment costs can be estimated on a per unit basis or are rate-based. For example, the reef structures and rubble stabilisation methods have been costed on a per unit deployed, or area restored, basis. Similarly, the coral-based interventions can be costed on a per unit basis, where the unit is a one-year-old coral.

By contrast, other interventions such as solar radiation management are more appropriately costed on an annual protection basis. These can be found in Table 27.

it is difficult to compare the costs of the interventions considered here as a result of the different approaches, methods and scales of the concepts investigated. In addition, it is likely that a suite of interventions, or combinations of interventions, will be deployed together, when they become operational. Consideration of synergies or leverage gained by deploying combinations of interventions is beyond the scope of this concept-level report and will be addressed in subsequent reports delivered in the integrated logistics R&D sub-program in the next, research and development, phase of RRAP.

The high-, medium- and low-cost estimates presented, map onto the sensitivity assessments described in the previous section.

Table 26: Results: cost-estimating assessments – unit rates.

DEVELOPMENT PATHWAY	DELIVERY METHOD	UNITS	UNIT RATES ($) Low	Medium	High
Moving corals (reproduction and recruitment)	Translocation of larval slicks	Per one-year-old coral	$0.30	$18.00	$213.00
	Larval slick-device based settlement		$1.18	$4.71	$12.71
	Assisted larval movement		$0.68	$12.10	$50.08
	Fragging - asexual reproduction		Not assessed		
Cooling and shading (primarily solar radiation management)	Cloud brightening		Only assessed as scenarios		
	Misting				
	Ultra-thin surface films				
	Mixing and pumping	Assessed as unviable			
Reef structures and stabilisation	Rubble removal	Per m of a 5m wide strip	Not assessed		
	Biological bonding		Not assessed		
	Grouting			$422	
	Chemical bonding			$422	
	Mesh fixing			$290	
	Mars Spiders			$528	
	Gabion baskets	(Per m^2 seabed coverage)		$481	
	Bioballs				
	Reef hubs			$2316	
	Artificial massive corals (coral-skinned shapes)			$1439	

	3D printed complex structures		Not assessed		
Aquaculture	Shore-based facilities with offshore deployment	Per one-year-old coral	$1.5	$3.0	$4.5
	Treatments	Incorporated into above cost/coral			

In Table 25, the figures in round brackets, show the estimated number of vessels/vehicles required for each scenario. The figures in square brackets, are the results from diagnostic calculations. These figures represent the average annual cost per vessel. In many cases, vessel costs dominate the overall cost, hence the diagnostic keeps track of this. These diagnostics results show annual vessel costs for larger vessels centre around $2M per annum, and for the small vessels around $0.4M per annum. This is the expected range, given the penalty costs identified and the number of days required, as shown.

Table 27: Results: cost-estimating assessments – scenarios. Figures in round brackets show the estimated number of vessels/vehicles required for each scenario, while the figures in square brackets are the results from diagnostic calculations (average annual cost per vessel).

DEVELOPMENT PATHWAY	**SCENARIO**	**Scenario description (*primary uncertainty*)**	**ANNUAL DEPLOYMENT COST (numbers in brackets are # deployment vessels)**		
			Low	**Medium -base case**	**High**
Moving corals (reproduction and recruitment)	Translocation of larval slicks	Based on deploying two million one-year-old corals. This scale represents the likely limit using charter vessels and seasonal workers. Beyond this, costs would increase significantly. *Uncertainty driven by post-deployment survival rates.*	**$0.6M** (1) [$0.6M]	**$36M** (21) [$1.7M]	**$427M** (242) [$1.7M]
	Larval slick-device based settlement		**$2.36M** (2) [$1.2M]	**$9.4M** (6) [$1.6M]	**$25.4M** (15) [$1.7M]
	Assisted larval movement		**$1.37M** (4) [$0.3M]	**$23.7M** (79) [0.3M]	**$101M** (336) [$0.3M]
	Asexual reproduction	Difficult to cost as requires extensive automation research and development.			
Cooling and shading (primarily solar radiation management)	Cloud brightening	Annual cost of protecting Great Barrier Reef, (300 000 km^2). *Uncertainty driven by different levels of required particle concentrations.*	**$107M** (34) [$3.1M]	**$158M** (50) [$3.1M]	**$338M** (109) [$3.1M]
	Misting	Based on protecting from 10 000 km^2. *Uncertainty driven by different levels of required particle concentrations.*	**$1.97M** (1) [$2.0M]	**$4.93M** (2) [$2.4M]	**$7.89M** (3) [$2.6M]
	Ultra-thin surface films	Based on protecting from 10 km^2 delivered by small planes. *Uncertainty driven by different levels of required particle concentrations.*	**$29.26M** (5)	**$58.52M** (11)	**$2117.04 M** (21)
	Mixing and pumping	Deemed unfeasible			
Reef structures and stabilisation	Biological bonding	Cost to stabilise 10km^2 of rubble, assuming a 3:1 benefit ratio (every m^2 installed stabilises 3m^2), at an average rate of $400 per 5m strip. *(Uncertainty driven by extent to which economies of scale would reduce costs).*	Not costed		
	Rubble removal		Not costed		
	Grouting		**$120M**	**$260M**	**$260M**
	Chemical bonding				
	Mesh fixing				
	Mars Spiders				
	Gabion baskets	Cost to install 10km^2 of 3D structure, assuming a 1/10 density ratio (devices are deployed in clusters with gaps	**$600M**	**$1 200M**	**$1 200M**
	Bioballs				
	Reef hubs				

	Artificial massive corals (coral-skinned shapes)	between). Rate is based on $\$1300/m^2$ for 3D structure. *(Uncertainty driven by extent to which economies of scale would reduce costs).*			
	3D printed complex structures		Not costed, however it will be considerably more expensive		
Aquaculture	Optimised existing nursery methods		Not costed		
	Medium-scale shore-based aquaculture				
	Large-scale shore-based aquaculture	Annual costs are to deploy 36.5 million one-year-old corals.	$54M	$110M	$158M
	Very large-scale breakthrough larval/polyp-based aquaculture		Not costed		

Estimating implementation costs for the concept solutions revealed key results in terms of scalability of the interventions, and the key challenges to increasing the efficacy of interventions. These are summarised in Table 28.

Table 28: Key findings: scalability, cost drivers and key challenges.

DEVELOPMENT PATHWAY	DELIVERY METHOD	SCALABILITY	KEY CHALLENGES
Moving corals (reproduction and recruitment)	Translocation of larval slicks	Medium	• How to achieve, and what can be achieved in reducing volume of water transported, and lowest possible mortality
	Larval slick-device based settlement		
	Assisted larval movement		
	Asexual reproduction	Small unless highly automated then medium	• How to automate • Composition of required adhesive
Cooling and shading (primarily solar radiation management)	Cloud brightening	Very large	• Required particle concentration • Optimal source material • Efficacy of method • Design, efficiency and energy requirements of sprayers
	Misting	Large	
	Ultra-thin surface films	Small, possibly medium	• Required formula concentration and recipe • Efficacy of method
Reef structures and stabilisation aquaculture	Rubble removal	Medium	• Efficacy of methods • When to apply which method • How to optimise methods
	Biological bonding		
	Grouting		
	Chemical bonding		
	Mesh fixing		
	Mars Spiders		
	Gabion baskets	Small	
	Bioballs		
	Reef hubs		
	Artificial massive corals (coral-skinned shapes)		
	3D printed structures		

Aquaculture	Optimised existing nursery methods	Micro	• Methods to optimise husbandry, brood stock management • Ways to automate specific tasks in shore facilities • Optimal vessel design and fleet configuration • Optimal deployment methods, including design of deployment device
	Medium-scale shore-based aquaculture	Small	
	Large-scale shore-based aquaculture	Medium	
	Very large-scale breakthrough larval/polyp-based aquaculture	Large	

In summary, the cost estimating exercise revealed:

- Deployment costs are substantial. This is not unexpected given the size of the estate under consideration, and general costs for operating marine infrastructure.

- The extent to which a method can be deployed at scale is driven by cost per unit (or area) and available funding. An objective of the intervention R&D sub-programs is to drive this cost down as far as practical. However, even considering potential cost reductions identified in the sensitivity analyses, there remains two distinct cost profiles.

- The range between the low and high cost estimates in the sensitivity analysis is indicative of the compounding uncertainty in key parameters such as survival rates and efficacy of different methods. For example, in the larval slick capture and movement methods, the cost per coral ranges from less than $1 to more than $100, depending on assumptions. In this instance, the uncertainty was primarily a result of post-deployment larval recruitment and survival rates. This uncertainty will need to be reduced as a matter of priority.

- There are significant opportunities to reduce deployment costs through optimising deployment methods: both within each method, and through sharing infrastructure. For example, the same vessel can potentially be used for multiple intervention approaches at different times of the year, increasing the utilisation of marine infrastructure.

5.2 Aquaculture findings

Key findings from the detailed high automation and mass production aquaculture model assessment were:

- The cost per coral at one year of age (i.e. factoring post-deployment mortality to this age) ranged between $1.50 and $4.50, with an expected outcome around $3.
- The method (and the associated degree of automation etc.) has a likely deployment scale range of 10 million to 100 million corals per year. Any smaller and the overheads of complex automation systems would be too high, and the cost per coral would increase; any larger and logistics become unrealistic.
- Capital investment requirements would be high, most likely limiting the useful range of this method to the lower end of this scale.
- Post-deployment survival rates, and the performance of the deployment device, were the areas of highest uncertainty. Research and development would be required to test and optimise these areas.
- Most automation and mass production systems could be adapted from existing systems, however automated deployment would require a R&D sub-program to understand the

exact level of performance possible, and to develop aspects of the required systems not available off-the-shelf.
- At this scale, the optimum deployment logistics option was a pair of accommodation/work platform barges, with one continuously onsite, servicing several smaller deployment vessels.

Based on the outcomes of the concept design and assessment, it was also possible to make commentary around the medium- and very large-scale methods.

Medium automation:

- This would likely have a scale range between one million and 10 million corals per year, depending on the exact degree of automation.
- Costs would likely be in the $5-$10 per coral range.
- A system such as this could be designed, built and operated immediately with relatively low failure risk. It would, however, need to be matched with a focused R&D sub-program designed in parallel, to address knowledge gaps relating to the biology, ecology and genetics of the aquaculture process and post-deployment survival.

Larval/polyp method:

- There are potentially still significant improvements to be made in reducing per coral cost, for example, the large-scale design did not push the boundaries of deployment age or deployment device design. Several breakthrough ideas have been identified that, if successful, would enable extremely short production timeframes (and deployment at the larvae/polyp age) while maintaining high post-deployment survival rates. These ideas remain commercial-in-confidence, but broadly span the areas of:
    - Deployment devices that are active (bonding, predation control, health and growth) and shape-optimised (designs to lock to specific substrates)
    - Optimised device placement systems (right device design, right species in the right location)
    - Systems using larvae, or very early recruits, with the deployment devices (including leveraging technologies developed in the pharmaceutical industry)
    - Asexual fragmentation methods that only involve a small number of polyps
    - Integration of cryo-preservation into the process (for example providing a buffering capability between production and deployment or facilitating integrated aquaculture/wild stock production models).

- If innovations that achieve step-change in production cost and deployment success can be developed, there will be significant flow-on effects to the type and scale of required production and deployment infrastructure systems. This could reduce the cost (particularly the capital investment requirements) of medium- to large-scale deployments and make very large-scale deployments affordable and logistically feasible.

- Further work is required to accurately quantify likely costs per coral, however less than $0.50 per survivor to one year of age seems a credible target, and is consistent with production costing for other species, as identified in the out-turn costs estimates provided in the RRAP report T11—Automated Aquaculture Production and Deployment.

Deployment scale range

The assessments completed to date indicate the various aquaculture methods have economic scale ranges (where the method would be more cost-effective relative to the other methods) (Table 29).

Table 29: Aquaculture scale ranges.

METHOD	INDICATIVE SCALE RANGE (TARGETED NUMBER OF ADULTS PER YEAR IN MILLIONS)	COMMENTS
Current methods	0 to 1	Incremental improvements to reduce labour requirements could feasibly increase the output of these methods to perhaps one million per year, before logistics become infeasible.
Medium automation	1 to 10	Beyond this scale, logistics and costs would likely limit deployment. It would be more cost-effective to increase the level of automation if larger scales are required.
High automation	10 to 100	Technically and logistically feasible, capital cost likely to limit it to the lower range.
Larvae/polyp method	1 to 100+	This method should be highly scalable and could be applied at small-scale through to very large-scale. At the smaller end of this range, lower levels of automation would be expected.

Technology readiness level and development risk

Based on the analysis of the high automation model (T11—Automated Aquaculture Production and Deployment) an assessment of the tech readiness and development risk was undertaken (Table 30).

Table 30: Aquaculture development risk.

Hatchery: *Broodstock holding to growout*	All required technology is at high technology readiness level (in use), a high throughput facility could be built using existing equipment. There are several areas where automation would be required, however, all are considered relatively simple, and would be a design task only. Areas requiring development and intellectual property would be the process flows, facility design and biological know-how underpinning coral breeding and health in captivity. The National Sea Simulator provides the closest existing global proxy to the technology and automation systems that would be required.
Transportation and holding – land/sea	All required technology is at high technology readiness level (in use). Specialist systems would need to be developed. This would be an engineering design task, using existing technology. Research and development would be required to develop appropriate standards under transportation.

Deployment device design *(Design and manufacture)*	This is at low technology readiness level and will be a focus of research and development. There is little knowledge as to: • What shapes and materials provide the highest retention, and where? • Material design for optimal growth and survival of corals • Materials and designs to minimise environmental impact /carbon debt • Manufacturing methods and costs.
Assembly **(Corals-to-deployment device)**	Specialist systems would need to be developed. This could be done using off-the-shelf automation systems.
Device deployment	Methods to 3D-scan reefs, and to auto-determine where, and the most effective shapes to deploy, are at medium technology readiness level. Likely performance is uncertain and needs to be assessed early in the R&D program as it will impact the viability of aquaculture methods. Assuming surface deployment, while specialist systems would need to be developed, these could be constructed using off-the-shelf automation systems. If surface deployment is not feasible (insufficient device retention and survival rates), an automated 'planting' system would need to be developed. Suitable technologies and methods are at very low technology readiness level and would require an extensive R&D sub-program. This would be a highly complex and difficult project.

Development risk was not assessed and quantified; however, developed risk increases as the degree of method complexity increases. Qualitative estimates of likely developed success, based current knowledge/uncertainty and an appropriate R&D sub-program, are speculated to be:

Table 31: Aquaculture success likelihood.

Method	Success likelihood	Comments
Current methods	Very high (90+%)	The requirements to reduce labour are well known and being actively targeted by the global coral restoration community.
Medium automation	Very high (80+%)	This is largely based on established technology. The risk lies in the unique application, and small number of low TRL areas.
High automation	High (70+%)	As above, it is largely based on established technology, however the additional levels of automation assumed are less developed, and performance assumptions less tested.
Larvae/polyp method	Medium (50+%)	In general, the targeted breakthrough areas are untested and require research and development. However, some research and development has occurred, and not all identified breakthroughs need to be delivered for benefits to be achieved.

The findings have significant strategy implications, both for aquaculture and moving coral-based (larval slick) delivery methods, as well as for the ecological program.

Aquaculture implications:

- Significant aquaculture method design evolution is still possible, with significant potential benefits, irrespective of the deployment scale ultimately needed and targeted. These breakthrough technologies and methods should be explored as a matter of priority.
- Research and development into facilities and systems design should be limited to areas that are either critical paths or required to assess efficacy and performance. Broadscale research and development relating to a specific production and deployment methodology should be delayed, subject to the outcomes of the above assessment.
- All research and development in the broader areas of aquaculture should continue in parallel as these are critical paths, not sensitive to the breakthrough aspects being investigated.
- Aspects such as decentralised versus distributed systems, and integrated deployment logistics, should progress early in the R&D sub-program. These are yet to be assessed and could significantly impact overall strategies and designs.

Moving corals implications:

The larval slick capture methods being developed under the moving corals area functionally mesh well with aquaculture. Aquaculture is strong in ‘hardy corals’ and production reliability and scale, and weaker with species and genetic diversity. In contrast, the larval slick capture and redeployment methods have the inverse strengths and weaknesses. Functionally, it makes sense to develop and use both methods.

However, for this model to work well, the scale of larval slick capture and redeployment would ideally need to be increased. Logistics and cost constraints mean it is unlikely to be feasible to increase scale simply by increasing the number of systems operating in parallel; however, if the conversion ratio of collected larvae to adult corals could be improved, scale would be effectually increased. Currently this ratio is very low (less than one percent), with major scope for improvement.

If methods to attach larvae or deploy very young recruits could be developed for aquaculture, they could also be used to improve the performance of the larval slick methods and increase the impact of these methods.

Hybrid aquaculture/larval slick methods

- As discussed above, there are ecological benefits in combined use of methods. The larval/polyp-based method would facilitate this occurring, with common use systems and deployment infrastructure.

- If cryogenic preservations can be developed, it would also open a pathway to additional mixed models; for example, combing aquaculture sperm with field-sourced eggs. This opens the possibility of merging assisted evolution and genetic modification methods (and the associated climate change performance improvements being targeted) into the larval slick methods.

Deployment logistics:

Deployment logistics are critical to all proposed interventions. The distances and volumes involved, and the need to operate adjacent to or over reefs, will be challenging to manage. However, there appears to be options to combine deployment infrastructure associated with different interventions. Combined options would provide major cost savings and have significant impact on the method concepts. These options need to be explored early in the R&D program.

6. OTHER COST CONSIDERATIONS

The outlined program will not only require direct on-water and facility costs, but also program management and its associated costs. At this stage, it is unclear if these management costs will be incorporated into the RIMReP (Reef 2050 Integrated Monitoring and Reporting Program).

If deployment of these interventions is outsourced, presumably management costs would be incorporated into the outsourced providers overall contracted costs.

The concept costing has also not yet considered the capital or operational costs of specific equipment such as compressors and spraying equipment for the solar radiation management interventions. This next level of detail will be considered in the next RRAP phase of the program, which will involve preliminary design-level costings.

7. MAJOR COST DRIVERS AND PATHWAYS TO REDUCE DEPLOYMENT COSTS

The calculations performed in this assessment reveal the major deployment cost drivers for each approach; summarised in Table 32.

Although there is some commonality in the cost drivers (for example marine infrastructure), the individual deployment methods often have specific key cost drivers.

Table 32: Major cost drivers

TREATMENT/ METHOD	MAJOR COST DRIVERS
Translocation of larval slicks	• Deployment vessel and infrastructure costs, compounded by episodic timing of slicks and lack of availability of suitable vessels • Mortality/survivorship • Volume of water being transported
Larval slick-device based movement	
Assisted larval movement	
Asexual reproduction	• Underwater labour costs using existing methods • Lack of available automation and adhesive technology
Cloud brightening	• Deployment vessel and infrastructure costs • Deployment equipment energy costs • Permitting cost
Misting	• Deployment vessel and infrastructure costs • Misting source material costs • Deployment equipment energy costs • Permitting cost
Ultra-thin surface films	• Cost of formula • Deployment vessel costs • Permitting cost
Mixing and pumping	• Infrastructure capital and operating (energy, maintenance) costs
Grouting	• Underwater labour and costs • Deployment vessel costs • Manufacturing and fabrication costs
Chemical bonding	
Mesh fixing	
Mars Spiders	
Gabion baskets	
Bioballs	
Reef hubs	
Artificial massive corals (coral-skinned shapes)	
3D printed structures	
Rubble removal	
Aquaculture	• Shore-based facility capital and operating (including husbandry) costs • On-after deployment costs including vessel capex and operating costs • Mortality at each stage of the production process • Brood stock management requirements

The results generated in this concept costing assessment can also be used to identify methodological changes that could substantially reduce operational deployment costs. These are summarised in Table 33, clustered according to deployment strategy.

Table 33: Methodological improvements that could lead to cost reductions for individual interventions.

TREATMENT/ METHOD	METHODOLGICAL IMPROVEMENTS
Translocation of larval slicks Larval slick-device based settlement Assisted larval movement	• Reduce volume of water required to be transported • Improve survival rates, particularly the conversion rate of release larvae to juvenile corals • Maximise slick location, harvesting, transport and deployment operations through vessel/fleet design, decision support and automation
Asexual reproduction	• Underwater automation to harvest and redeploy fragments • Fragment adhesive
Cloud brightening	• Develop dry powder material (possibly $CaCO_3$) for aerial deployment • Develop efficient nozzle for saltwater surface discharge operations • Optimise application through better understanding of efficacy • Develop operational decision support • Design optimised deployment infrastructure
Misting	• Identify best material to discharge (possibly paraffin) • Optimise application through better understanding of efficacy • Develop operational decision support • Design optimised deployment infrastructure
Ultra-thin surface films	• Reduce the cost and mass of formula
Mixing and pumping	• Unclear how cost could be substantially reduced
Grouting Chemical bonding Mesh fixing Mars Spiders Gabion baskets Bioballs Reef hubs Artificial massive corals (coral-skinned shapes) 3D printed structures Rubble removal	• Improve understanding of the efficacy of rubble stabilisation methods to optimise deployment • Design and materials refinement • Fabrication and deployment automation
Aquaculture	• Reduce per coral cost through optimised husbandry and operations in shore-based facilities • Optimise deployment operations to reduce mortality and increase productivity

There is also a significant cross-methodology cost improvement opportunity through sharing marine infrastructure and deploying suites of interventions.

The information contained in Table 26 can be incorporated into the individual research planning documents with a view to optimising the overall operational costs of implementing tools developed in RRAP.

8. DELIVERY METHOD DEPLOYMENT SCALE

8.1 Assessment overview

The following is an additional assessment undertaken to apply the findings of delivery method scale and cost to each of the identified interventions.

Using information from this costing and scale assessment and findings from the intervention R&D program development process, each of the interventions (where data is available) have been assessed and categorised against a series of additional criteria:

1. Feasible Usage Scale: Estimated feasible deployment quantities and the areas these might impact.
2. Development Risk: What is the likelihood that method could be developed (technical risk) and deployed (approvals risk) at the scale indicated.
3. Time to Full Deployment: An estimation of the total time to undertake R&D, then construct and commission and then ramp production to the annual rates being targeted.

In reading this assessment, it should be noted that:

- It is not an assessment of intervention "efficacy" and to what extent ecological, social or economic benefits would occur if deployed at the scales described.
- The values are based on the available information, much of this has high uncertainty levels. The majority of interventions are early in their assessment and development lifecycle with limited quantitative data available. The findings should consider indicative and assessed for trends and general comparisons only.

8.2 Feasible deployment scale

The scale of utilisation for each intervention will depend on the cost-benefit circumstances at that time. The decision factoring aspects such as the reef state, the extent of benefits being targeted, other interventions occurring in parallel and overall costs and benefits.

As such "absolute" assessments of deployment scale cannot be made at this time. However, their applicability to be deployed at four scales was assessed in order to see relative differences between the different interventions and provide indicative feasible usage scales.

Two key parameters needed to be estimated in order to make these assessments:

1. The relationship between deployment quantity (for example the number of corals deployed) and scale of benefit; noting that this will be highly variable and a function of reef state, other interventions and the degree of impact being targeted.
2. The level of financial investment made into each intervention. At this time a cost-benefit method cannot be utilised, therefore a simple annual investment cut-off was utilised for interventions were there are not logistics or other factors that constrain the intervention to

a specific scale range. For example, Cloud Brightening only works at large scale, and surface films are logistically constrained to small areas, however other interventions are s are only limited by annual investment. In these instances, it was assumed that no more than $200m per year would be invested in any one intervention.

The estimation around both parameters has high uncertainty. However, as the scale ranges being assessed are a log scale (order of magnitude differences in scale between the four scenarios), the estimating errors have less impact in categorising interventions into scale ranges.

Table 34 shows the quantity to scale relations that were assumed.

Table 34: Quantity scale relations assumed.

Deployment Scale		**Number of reefs where benefits are being targeted**	**Assumed annual quantities required for delivery method to have benefit at the nominated scale**
Micro	Represents current restoration method levels	Small areas in limited sites	0.1 million corals per year 0.01 km^2/yr rubble stabilised
Small	A scale that could retain/protect tourism and other key sites if required	50 Tourism scale sites	1 to 10 million corals per year 1 km^2/yr rubble stabilised 50 by 0.02km^2 sites shaded
Medium	A scale that could support several clusters of key reefs to support ecosystem function in key areas	50 Reefs	10 to 100 million corals per year 10km^2/yr rubble stabilised Five multi-reef areas shaded
Large	A scale that would target retaining broader GBR ecosystem function and core economic and social values of the GBR	200+ Reefs	100 million corals per year plus 100km^2/yr rubble stabilised Full GBR shaded

Other factors considered:

- For seasonal usage interventions (slick capture and movement, surface films, misting), the scale is capped at the point where charter/reef industry vessels are likely to be fully consumed. If these methods are scaled beyond this point then cost increases significantly (between half and a full order of magnitude) as the method must then absorb the full ownership cost of the infrastructure, while only having very low utilisation factors.
- Cloud Brightening and Fogging/Misting, while seasonal, require significant dedicated infrastructure and so their scale is capped based on cost.
- A number of interventions are underpinned by different aquaculture delivery methods. The alternative methods designed to target different deployment scales, and so the nominated scales relate to the range over which that method is likely to be the most cost-efficient compared to the other aquaculture delivery methods.

The assessment outcomes for each intervention are summarised below. Where low, medium and high costing information was available this has been included. This costing spread indicating the extent of costing uncertainty. Where there are very large cost spreads (for example ER2 and ER3) this is typically driven by technical performance rather than engineering cost uncertainty.

Table 35: Intervention deployment scales and annual costs.

Estimated feasible usage scale	Possible feasible usage scale	Infeasible usage scale	Eliminated based on risk

Code	Intervention Title	Micro	Small	Med	Large	Commentary	Feasible Deployment Scale
		Annual Cost $M					
		Low **Med** High	Low **Med** High	Low **Med** High	Low **Med** High		
C1	Cooling by mixing					Micro scale only	N/A
C2	Cooling by pumping					Micro scale only	N/A
C3	Shading by cloud brightening				107 **158** 338	Cost is to protect entire Reef (300 000 km2).	Large
C4	Shading by fogging			20 **50** 80		Not yet costed, however estimated to be 2 times the cost of misting (higher energy and more units required).	Medium
C5	Shading by misting			10 **25** 40		Medium scale is based on protecting from 10 000 km2, however as there are five assumed sites the costs are higher than a single site as infrastructure needs to be duplicated. The low case is based on 5 boats, the medium on 10 and the high on 15.	Medium
C6	Shading by surface films		15 **30** 59			Small scale has been directly costed; medium scale is a simple extrapolation based on area	Small
C7	Shading by micro-bubbles		15 **30** 59			Not yet costed, but assumed to be similar to surface films	Small
C8	Shading by structure					Micro scale only	N/A
C9	Shading by algae					Not yet assessed, but expected to be micro scale only	Micro
C10	Ocean fertilisation					Eliminated based on risk	N/A
C11	Cooling by high altitude aerosols					Eliminated based on risk	N/A
S1	Stabilisation by natural bonding					Not yet quantitatively assessed, however in theory this is the most scalable of the stabilisation interventions. This is to be assessed in the R&D program.	Medium
S2	Stabilisation by chemical bonding		12 **26** 52	120 **260** 520		Costing based on industry quotes for a single barge operating on a continuous basis. The medium scale costs are based on the rates quoted for small scale, it is possible economics of scale would reduce these costs.	Small
S3	Stabilisation by mesh		12 **26** 52			As above, however logistics of this method make it impractical and medium scale	Small
S4	Stabilisation by removal					Not yet costed and no similar intervention to estimate from.	Small
S5	Structure by consolidation		30 **60** 120			Costing based on industry quotes for a single barge operating on a continuous basis.	Small
S6	Structure by 3D frames		60 **120** 240			Costing based on industry quotes for a single barge operating on a continuous basis.	Small
S7	Structure by concrete shapes		60 **120** 240			Costing based on industry quotes for a single barge operating on a continuous basis.	Small
S8	Structure by massive corals		120 **240** 480			Not yet costed but assumed to be a minimum of twice the cost of other 3D options due to the additional cost of growing coral cover over the structure.	Small
S9	Structure by 3D printed shapes					Not yet costed, however expect to be too expensive for practical use.	Micro

ER1	Coral seeding by *in situ* movement					Micro scale only	
ER2	Coral seeding by assisted larval movement		4 **60** 253			Practical usage scale driven by limited window of opportunity each year, weather and logistics. Costing is based on 5 million corals per year; however, logistics currently indicate a limit of around 2 million assuming the post deployment survival rates for the medium cost scenario. If the post deployment survival rates factored into the "low cost scenario" can be achieved, then the 5 million is feasible, and potentially larger scales also.	Small
ER3	Coral seeding by larval slick translocation		2 **90** 1068			Practical usage scale driven by limited window of opportunity each year, weather and logistics. Costing is based on 5 million corals per year; however, logistics currently indicate a limit of around 2 million assuming the post deployment survival rates for the medium cost scenario. If the post deployment survival rates factored into the "low cost scenario" can be achieved, then the 5 million is feasible, and potentially larger scales also.	Small/ medium
ER4	Coral seeding by larval slicks settled on devices			75 **150** 219	150 **300** 439	This delivery method seeks to convert a higher percentage of collected larvae into coral recruits. If this occur, then scale is increased. This has not yet been individually costed as it is a very early phase idea. It is assumed that the costs would be similar to the high automation aquaculture cost, as while the infrastructure costs will be less, there are increased field costs to collect larvae. Large scale may be feasible, but it would require large scale cryopreserving and the polyp aquaculture method to be successfully developed.	Medium
ER5	Coral seeding by *in situ* harvested fragments					Scale limited by underwater labour requirement unless large-scale automation is developed. It is not yet costed as a concept outline and performance estimates have not yet been developed.	Micro
ER6	Coral seeding by nursery aquaculture					Micro scale only	N/A
ER7	Coral seeding by semi-automated aquaculture		15 **30** 44			This could be built now based on National Sea Simulator expertise and systems, combined with deployment methods utilised internationally. It would still require a parallel R&D program to refine deployment methods and performance. Cost has been extrapolated from automated aquaculture (ER8), but the per coral rate assumed to be 200% higher due to reduced automation and economics of scale.	Small
ER8	Coral seeding by automated aquaculture			75 **150** 219		Automation could scale out aquaculture. Assumes some but limited new technologies and methods. Cost for 50 million corals per year have been extrapolate from the detailed design undertaken for 36.5 million.	Medium
ER9	Coral seeding by larval/polyp aquaculture				150 **300** 439	An extension the automated aquaculture that pushes the design envelope using several conceptual but unproven ideas. If feasible would likely increase scale/reduce cost by a further half to full order of magnitude. However, these are early phase concepts with R&D required. Cost extrapolated from automated aquaculture (ER8) using a conservative unit cost reduction of 50%.	Large

B1	(Bio)-control of macro algae					Scale limited by underwater labour requirement unless large-scale automation is developed. Not yet costed, concept outline and performance data not yet available	Small?
B2	Biocontrol of species with negative impacts					Scale limited by underwater labour requirement unless large-scale automation is developed. Not yet costed, concept outline and performance data not yet available	Small?
F1	Application of field treatments to enhance coral survival					Scale limited by underwater labour requirement unless large-scale automation is developed. Not yet costed, concept outline and performance data not yet available	Medium?
EE1	Seeding enhanced corals from existing stock by larval slick translocation.		2 **90** 1068			Refer to ER3	Small (Medium?)
EE2	Seeding enhanced corals from existing stock by settlement of larval slicks on devices			75 **150** 219	150 **300** 439	Refer to ER4	Medium (Large?)
EE3	Seeding enhanced corals bred from existing stock with semi-automated aquaculture		15 **30** 44			Refer to ER7	Small
EE4	Seeding enhanced corals bred from existing stock with automated aquaculture			75 **150** 219		Refer to ER8	Medium
EE5	Seeding enhanced corals bred from existing stock with larval/polyp aquaculture				150 **300** 439	Refer to ER9	Large
EN1	Seeding enhanced corals bred from engineered stock with semi-automated aquaculture		15 **30** 44			Refer to ER7	Small
EN2	Seeding enhanced corals bred from engineered stock with automated aquaculture			75 **150** 219		Refer to ER8	Medium
EN3	Seeding enhanced corals bred from engineered stock with larval/polyp aquaculture				150 **300** 439	Refer to ER9	Large

9. DELIVERY METHOD DEVELOPMENT RISKS AND TIMELINES

Development risk refers to the technical risk to successfully develop an intervention and obtaining regulatory approval. Its factors achieving the functional objective (for example to cool water) but does not factor if this will result in the benefits being targeted. It is assessed against the estimated feasible deployment scales.

As each of the interventions are early in their development lifecycle and lack of quantitative data a simple qualitative assessment process has been utilised. It has been simplified down to low, medium and high and should be used for comparative purposes only. Two factors have been assessed and combined into an overall rating. The technical risk describes the risks to the ability of specific interventions to be able to be developed and made operational at the scale targeted, while approvals risk describes the possible or probably difficulties is acquiring approvals for both developing the delivery methods and for operations once methods have been developed.

The technical and approvals risk ratings have been combined into an overall rating as per Table 36.

Table 36: Implementation risk ratings.

Implementation Risk		**Technical Risk**			
		Very low	**Low**	**Med**	**High**
Approvals Risk	**Very low**	low	Low	Medium	High
	Low	Low	Medium	Medium	High
	Med	Medium	Medium	Medium	High
	High	High	High	High	High

The assessment outcomes are provided for each intervention in

Table 37 below.

Table 37: Assessment outcomes for each intervention.

Code	**Intervention Title**	**Assumed Deployment Scale**	**Technical Risk (Rating / Key Drivers)**		**Approvals Risk (Rating / Key Drivers)**		**Overall Rating**
C1	Cooling by mixing	Eliminated and not assessed					
C2	Cooling by pumping	Eliminated and not assessed					
C3	Shading by cloud brightening	Large	H	Low TRL of nozzles, energy requirements and uncertainty RE suitable atmospheric conditions for method to work	M	Uncertain as to what unwanted impacts might occur (e.g. weather patterns, coastal rainfall), stakeholder concerns	H
C4	Shading by fogging	Medium	M	Energy requirements and nozzle design	M	Driven by visual amenity and stakeholder concerns	M
C5	Shading by misting	Medium	VL	Existing technology	M	Risk driven by visual amenity and ecotoxicology concerns and stakeholder concerns	M
C6	Shading by surface films	Small	M	Surface film material, deployment quantities and ability to retain in required location	L	Small scale, low toxicity, low risk	M

C7	Shading by micro-bubbles	Small	L	Technology and efficacy need to be tested	M	Risks uncertain	M
C8	Shading by structure	Not assessed					
C9	Shading by algae	Small	Not yet assessed				
C10	Ocean fertilisation	Eliminated and not assessed					
C11	Cooling by high altitude aerosols	Eliminated and not assessed					
S1	Stabilisation by natural bonding	Medium					
S2	Stabilisation by chemical bonding	Small	L	Many alternative delivery methods, low risk one or more will not be viable	L	Some delivery methods already in use	L
S3	Stabilisation by mesh	Small					
LS4	Stabilisation by removal	Medium					
S5	Structure by consolidation	Small					
S6	Structure by 3D frames	Small					
S7	Structure by concrete shapes	Small	M	Cost will limit use; risk is that unit costs cannot be reduced	L	Some delivery methods already in use	M
S8	Structure by massive corals	Small					
S9	Structure by 3D printed shapes	Small					
ER1	Coral seeding by *in situ* movement	Eliminated and not assessed					
ER2	Coral seeding by assisted larval movement	Small/	M	Availability of slicks, and post release survival rates	L	Approved at R&D scale	M
ER3	Coral seeding by larval slick translocation	Small	M	Availability of slicks, collection and shipping systems and post release survival rates	L	Already approved at R&D scale	M
ER4	Coral seeding by larval slicks settled on devices	Med/large	H	Translocation risk, plus requires breakthrough larval recruitment methods	L	Already approved at small scale	H
ER5	Coral seeding by *in situ* harvested fragments	Eliminated and not assessed					
ER6	Coral seeding by nursery aquaculture	Eliminated and not assessed					
ER7	Coral seeding by semi-automated aquaculture	Small	L	Extension of proven methods developed by AIMS and SECORE	L	Research scale already approved	L
ER8	Coral seeding by automated aquaculture	Med	M	Strong concept developed with relatively few uncertain performance areas	L	Approved at research scale, should be able to demonstrate OK at small scale	M
ER9	Coral seeding by larval/polyp aquaculture	Large	H	Requires performance break thoughts in two areas, both have identified options, but R&D required to develop and test feasibility	L	Similar risk to other aquaculture methods	H
B1	(Bio)-control of macro algae	Small	M	Micro scale manual methods well developed, unknown as to how these might be scaled.	M	Risks associated w biocontrol	M
B2	Biocontrol of species with negative impacts	Small	M	Methods still needs to be developed	M	Risks associated w biocontrol	H
F1	Application of field treatments to enhance coral survival	Medium	H	Product and deployment methods need to be developed	M	Uncertain regulatory framework	H

EE1	Seeding enhanced corals from existing stock by larval slick translocation.	Small	H	As with ER3, plus assisted gene flow method needs to work,	M	At scale translocation of corals has risk that need regulatory approval	H
EE2	Seeding enhanced corals from existing stock by settlement of larval slicks on devices	Medium	H	As with ER4, plus assisted gene flow method needs to work	M	At scale translocation of corals has risk that need regulatory approval	H
EE3	Seeding enhanced corals bred from existing stock with semi-automated aquaculture	Small	M	As per ER7, plus functional benefits of enhanced corals need to be confirmed	M	Research scale already approved	M
EE4	Seeding enhanced corals bred from existing stock with automated aquaculture	Med	M	As per ER8 plus functional benefits of enhanced corals need to be confirmed	M	Approved at research scale, should be able to demonstrate OK at small scale	M
EE5	Seeding enhanced corals bred from existing stock with larval/polyp aquaculture	Large	H	As per ER9 plus functional benefits of enhanced corals need to be confirmed	M	Similar risk to other aquaculture methods	H
EN1	Seeding enhanced corals bred from engineered stock with semi-automated aquaculture	Small	H	As per ER7, plus engineered corals to be developed and functional benefits of enhanced corals need to be confirmed	H	Pathway to regulatory approval extensive and unchartered.	H+
EN2	Seeding enhanced corals bred from engineered stock with automated aquaculture	Med	H	As per ER8, plus engineered corals to be developed and functional benefits of enhanced corals need to be confirmed.	H	Pathway to regulatory approval extensive and unchartered.	H+
EN3	Seeding enhanced corals bred from engineered stock with larval/polyp aquaculture	Large	H	As per ER9, plus engineered corals to be developed and functional benefits of enhanced corals need to be confirmed.	H	Pathway to regulatory approval extensive and unchartered.	H+

10. SUMMARY AND KEY FINDINGS

The concept costing exercise revealed:

- Deployment costs are not insubstantial. This is not unexpected given that size of the estate under consideration and general costs of operating marine infrastructure.
- The deployment costs for the intervention approaches considered in this report range over several orders of magnitude; from less than $1 per coral to between $1 and hundreds of dollars per coral for the high-cost scenarios for some delivery methods. This range is a primarily a result of fundamental parameter uncertainty; which will be reduced with further research.
- In some cases (for example the moving corals approaches), the costs are commensurate with other deployment approaches; however, the vessel requirements make some of these scenarios unrealistic.
- The range between the low- and high-cost estimates in the sensitivity analysis indicates there remains high uncertainty in the cost estimates. This is a result of the compounding uncertainty in key parameters such as survival rates and efficacy of different methods. A key objective of RRAP should be to reduce this uncertainty.

- There are significant opportunities to reduce deployment costs through optimising deployment methods, by both sharing infrastructure, and deploying multiple intervention delivery methods. For example, the same vessel can potentially be used for multiple intervention approaches at different times of the year, increasing the utilisation of marine infrastructure. It is likely a suite of interventions will be applied over different scales. This integrated approach will be explored in detail in the proposed integrated logistics R&D sub-program.

11. NEXT STEPS

This report represents the concept costings along with the areas of uncertainty affecting the accuracy of key assumptions and estimates. The stage in the assessment of options requires the development of greater definition and detail for each option and incorporate new estimates of key parameter values as they are determined through the research program. The specific tasks required for each deployment method are detailed in Table 38.The priorities are based on reducing uncertainty as quickly as possible, so high priority actions are directed towards reducing key uncertainties that have large impacts on deployment cost estimates.

Table 38: Methodological improvements that can lead to cost reductions.

TASK	TREATMENT/METHOD	PRIORITY	COMMENTS
1	Translocation of larval slicks	High	• Develop specific vessel use cases to refine infrastructure requirements (CSIRO and Southern Cross University experiments in late 2018 should provide updated parameter estimates. Investigate use of settlement devices in more detail - based on T11—Automated Aquaculture Production and Deployment) • Quantify post-deployment efficacy • Incorporate into preliminary logistics costing model
2	Larval slick-device based settlement		
3	Assisted larval movement		
4	Fragmentation - asexual reproduction	Low	• Assess technology development costs • Develop infrastructure use case • Incorporate into preliminary logistics costing model
5	Cloud brightening	High	• Numerical modelling (regional atmospheric model and local plume models) to estimate coverage and plume behaviour • Define preliminary specifications for material requirements (wet and dry) • Define preliminary specifications for spray infrastructure • Develop infrastructure use case • Incorporate into preliminary logistics costing model
6	Misting		
7	Ultra-thin surface films	Low	• Laboratory experiments to develop updated coverage and material cost estimates • Define preliminary specifications for material requirements • Define preliminary specifications for deployment infrastructure • Develop infrastructure use case • Incorporate into preliminary logistics costing model
8	Mixing and pumping	Medium	• Develop understanding of efficacy • Develop possible use cases and supply chains requirements • Incorporate into preliminary logistics costing model
9	Grouting		
10	Chemical bonding		
11	Mesh fixing		

12	Mars Spiders		
13	Gabion baskets		
14	Bioballs		
15	Reef hubs		
16	Artificial massive corals (coral-skinned shapes)		
17	3D printed complex structures		
18	Aquaculture	High	• Develop economic impacts assessment (focus on shore facilities) which will consider the costs and benefits of centralised versus de-centralised shore facilities • Finalise specifications for deployment infrastructure • Incorporate into preliminary logistics costing model
19	Cross-cutting	High	• Identify and quantify synergies and opportunities to share marine infrastructure through development and application of the integrated logistics costing model

The analyses presented here do not encompass the integrative delivery of multiple interventions as this is within the scope of subsequent analyses as described in the integrated logistics research and development plan. Understanding these will be critical for forward research and operational planning.

APPENDIX A – RRAP DOCUMENT MAP

Reef Restoration and Adaptation Program

APPENDIX B – REEF STRUCTURES AND STABILISATION COST ESTIMATES

The following are extracts from a costing and deployment feasibility assessment completed by Subcon Limited. Subcon is a specialist Australian marine services company with offices in Australia, Netherlands, Belgium, China and Singapore. They specialise in marine grouting, scour protection, stabilisation and artificial reefs.

Costing assessment

A unit cost comparison and production estimation has been completed for each of the rubble stabilisation and fish habitat options. The rates are determined by using one barge at full production rate for fabrication and installation. One day sail for mobilising/demobilising the barge to the installation site is accounted for. Further details of the assumptions for each of the options is presented in sections 0 to 0. These installation rates are then used to score each of the options for this section of the quantitative assessment. The total installation rates can be scaled up by increasing the number of barges in operation. As the Medusa grout has not been fully developed yet, pricing is not available. It has been scored equal with standard grout injection as the installation method is very similar and the material costs will likely be similar too.

Table B1: Rubble stabilisation cost comparison.

	Rubble stabilisation options			
Item	**Mars spiders**	**Grout injection**	**Medusa grout injection**	**Wire mesh pinning**
Cost per m² deployed	$106	$84	N/A	$54
Cost per m of a 5m wide grout strip	$528	$422	N/A	$290
Total length of 5m strip per year (km)	47	70	70	52
Total area per year (m²)	233 600	350 400	350 400	281 571

Table B2: Fish habitat cost comparison.

	Fish habitat options			
Item	**Gabion**	**Reef hub**	**Reef dome**	**Massive artificial corals**
Total cost per module	$1224	$4093	$3324	$3662
Cost per m² of surface area deployed	$258	$974	$188	$207
Cost per m² deployed	$481	$2316	$1306	$1439
Cost per m³ of reef deployed	$1321	$3474	$1102	$1214
Total modules per year	13 936	4615	7483	7483
Total surface area installed per year (m²)	66 241	19 382	132 440	132 440
Total seabed coverage per year (m²)	35 464	8155	19 041	19 041
Total reef volume per year (m³)	12 917	5436	22 567	22 567

Gabion baskets

- Tidal access of 5 hours per day. Installation barge requires to run over top of reef to install modules.
- 400 total modules on barge (40x10m working area)
- 10 Modules installed per hour
- 50 modules installed per day.

Reef hub

- Tidal access of 8 hours per day. Barge does not need to sit directly over reef for installation.
- 200 total modules on barge (40x10m working area)
- 2 modules installed per hour
- 16 modules installed per day

Reef dome

- Tidal access of 8 hours per day. Barge does not need to sit directly over reef for installation.
- 125 total modules on barge (40x10m working area)
- 4 modules installed per hour
- 32 modules installed per day

Artificial massive corals

- Tidal access of 8 hours per day. Barge does not need to sit directly over reef for installation.
- 125 total modules on barge (40x10m working area)
- 4 modules installed per hour
- 32 modules installed per day

Mars spiders

- Tidal access of 5 hours per day. Installation barge requires to run over top of reef to install modules.
- 700 spiders per 20’ container
- 26 x 20’ containers on barge (40x10m working area)
- 240 modules installed per hour. Installed in two chains
- 1200 modules installed per day
- 145m of 5m wide strip deployed per day

Grout injection

- Tidal access of 8 hours per day. Barge does not need to sit directly over reef for installation.
- 400Te of dry materials on barge (40x10m working area)
- 15m^3/ hr grout pumping rate
- Grout thickness within rubble of 0.5m
- 320m of 5m grout strip deployed per day

Medusa grout injection

- Tidal access of 8 hours per day. Barge does not need to sit directly over reef for installation.
- 400Te of dry materials on barge (40x10m working area)
- 15m^3/ Hr grout pumping rate
- Grout thickness within rubble of 0.5m
- 320m of 5m grout strip deployed per day

Wire mesh pinning

- Tidal access of 5 hours per day. Installation barge requires to run over top of reef to install modules.
- 36 x 30m long rolls of wire per 20' container
- 26 x 20' containers on barge (40x10m working area)
- 40m of wire installed per hour
- 200m of 5m wire strip installed per day

Table B3 Cost qualitative assessment.

Ecosystem Component	Gabion Basket	Reef Hub	Reef Domes	Artificial Massive Corals	Mars Spiders	Grout Injection	Medusa Grout Injection	Wire Mesh Pinning
Cost	7	3	7	7	3	3	3	7

Table B4: Cost scoring matrix.

	0	3	7	10
Cost	Significant cost of installation of modules. Installation not feasible.	Relatively high cost of installation and fabrication compared to other methods.	Relatively low cost of installation and fabrication compared to other methods.	Significantly cheaper installation and fabrication cost compared to other methods.

Scalability

The scalability component is component is judged on how readily each of the installation techniques could be scaled up from a small-scale trial to a large-scale installation on the Great Barrier Reef. Table & Table below show the reasoning behind the scoring for each technique.

Table B5: Scalability scoring matrix.

	0	3	7	10
Scalability	Significant installation times and/or significant production rates. Scaling of the method not feasible.	Slow installation and/ or production rates limit the benefits of scaling the method.	High installation and production rates. Some cost benefits from scaling the method.	Very high installation and production rates. Significant cost benefit from increasing to a large scale.

Table B6: Scalability qualitative assessment.

Ecosystem Component	Gabion Basket	Reef Hub	Reef Domes	Artificial Massive Corals	Mars Spiders	Grout Injection	Medusa Grout Injection	Wire Mesh Pinning
Scalability	7	3	3	3	3	7	7	3

Installation risk (safety)

This category is used to judge the safety risks of the different installation modules. All habitat restoration modules were given the same risk score, as they all require similar lifting operations while offshore. These lifting operations are standard and are not deemed to be high risk. The Mars spiders and wire mesh methods scored the lowest, as these methods both require divers to complete the installation.

Table B7: Installation risk (safety) scoring matrix

	0	3	7	10
Installation risk (safety)	Almost no risk of personnel injury from installation method	Small level of high-risk activity involved in installation method	High level of high-risk work involved during the installation (diving, lifting)	Safety risk of installation too great to complete works

Table B8: Installation risk (safety) assessment.

Ecosystem Component	Gabion Basket	Reef Hub	Reef Domes	Artificial Massive Corals	Mars Spiders	Grout Injection	Medusa Grout Injection	Wire Mesh Pinning
Installation risk (safety)	7	7	7	7	3	7	7	3

Installation risk (economic)

This section is used to judge the different techniques on the economic risk of their installation. The risk is based on how weather dependent the installation methodology is. If the methodology is very weather depended then there is a greater risk of delays, which would result in the installation budget being greater than expected. The installation of the reef gabions only requires the modules to be lifted around the deck of the barge, whereas the installation method of the reef dome, artificial massive corals and reef hub require the crane to lift the modules to the seabed. The Mars spiders and wire mesh pinning options are more weather-dependent then the grouted stabilisation options.

Table B9: Installation risk (economic) scoring matrix.

	0	3	7	10
Installation risk (economic)	Installation method very reliant on weather conditions. Unproven and untested installation method.	Proven installation method that is dependent on weather conditions.	Proven installation method that is less dependent on weather conditions.	Limited vessel operations that are not weather dependent.

Table B10: Installation risk (economic) assessment

Ecosystem Component	Gabion Basket	Reef Hub	Reef Domes	Artificial Massive Corals	Mars Spiders	Grout Injection	Medusa Grout Injection	Wire Mesh Pinning
Installation risk (economic)	7	3	3	3	3	7	7	3

Fabrication risk (safety)

This category is used to judge the safety risks that are associated with the fabrication of the different methods. The gabion baskets have scored the highest as they are the simplest of the fish habitat modules to fabricate. All the rubble stabilisation methods have limited safety risk of fabrication.

Table B11: Fabrication risk (safety) scoring matrix.

	0	3	7	10
Fabrication risk (safety)	All structures require a high level of manual labour to be produced.	High level of manual labour and heavy equipment required for production.	Low level of manual labour required. Minimal large equipment required to be operated.	Mass produced structures that do not require any manual labour to be produced.

Table B12: Fabrication risk (safety) assessment.

Ecosystem Component	Gabion Basket	Reef Hub	Reef Domes	Artificial Massive Corals	Mars Spiders	Grout Injection	Medusa Grout Injection	Wire Mesh Pinning

Fabrication risk (safety)	7	3	3	3	7	7	7	7

Fabrication risk (economic)

Each of the fish habitat modules are relatively simple to fabricate and have been scored as such. The artificial massive corals have been scored the lowest due to the additional labour and risks involved in out planting the coral onto the structure prior to deployment. All the rubble stabilisation options been scored equal for this section due to the limited fabrication processes involved.

Table B13: Fabrication risk (economic) scoring matrix.

	0	3	7	10
Fabrication risk (economic)	Complex production method that require a high level of man labour to construct. No previous fabrication history.	Complex production method requiring manual labour. Limited production history.	Relatively simple structures that require manual labour to produce. Some previous production history.	Simple structures that can be mass produced on a production level scale. Proven production history.

Table B14: Fabrication risk (economic) assessment

Ecosystem Component	Gabion Basket	Reef Hub	Reef Domes	Artificial Massive Corals	Mars Spiders	Grout Injection	Medusa Grout Injection	Wire Mesh Pinning
Fabrication risk (economic)	7	7	7	3	7	7	3	7

Summary

The figure below shows the results for the qualitative assessment.

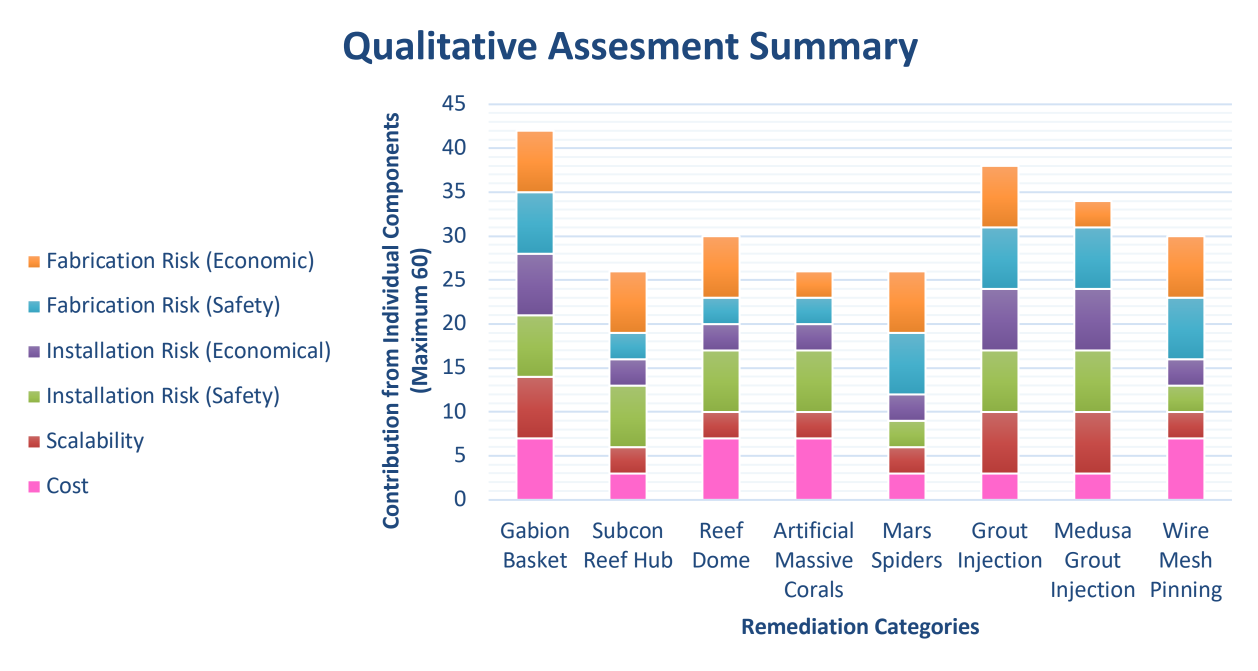

Figure B15: Qualitative assessment summary.

Reef Restoration and Adaptation Program

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Reef Restoration and Adaptation Program, a partnership: