Effective and Efficient Pathways for Investment in Improved Water Quality in the Great Barrier Reef

Final Report

12 June 2019

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We extend our deepest respect and recognition to all Traditional Owners of the Great Barrier Reef as First Nations Peoples holding the hopes, dreams, traditions and cultures of the Reef.

This report was produced for the partnership between the Australian Government's Reef Trust and the Great Barrier Reef Foundation.

EXECUTIVE SUMMARY

This Investment Pathways Project, funded by the Great Barrier Reef Foundation (GBRF), provides a key input into a broader decision making process associated with the development of GBRF's Five Year Investment Strategy (and Annual Workplan) for the Water Quality Component of the Reef Trust Partnership (RTP). Specifically, this project aimed to develop a quantitative assessment of the most cost-effective catchment management actions (built to collectively form a scenario or investment pathway) in 46 reporting basins within the Great Barrier Reef (GBR) catchments, and a data visualisation tool to support the comparison of the investment scenarios. Importantly, the project was supported throughout its duration by the GBRF's Project Working Group and Peer Review Panel.

The overall approach adopted during this project is summarised in the following paragraphs. Firstly, the project assimilated key background information. This included key foundational information such as the Reef 2050 Water Quality Improvement Plan and the recently derived, basin specific, Ecologically Relevant Targets for Water Quality (Centre for Tropical Water & Aquatic Ecosystem Research, 2017). This work also built upon the previous modelling and costing information produced during the original Reef Costings Project (Alluvium, 2016). The project also utilised the Paddock to Reef (P2R) program modelling used to generate the 2016 Report Cards, and wherever possible took into account relevant information (particularly costs and efficacies of catchment management actions) from recent federal and state government investments in the reef space including those projects funded by the Reef Trust, the Queensland Regional Natural Resource Management Investment Program and the two current Major Integrated Projects.

Secondly, and using the additional information from a range of key practitioners in the reef space, it was agreed that the project develop 10 management intervention approaches focussed on three primary pollutants, namely nutrients (particularly Dissolved Inorganic Nitrogen- DIN), fine sediments (FS) and pesticides. Each approach was summarised into a Solution Set Statement document outlining their scope and extent, the management actions they contained, the costs and efficacy of those actions, the necessary assumptions and limitations used and a summary of the relevant results. The solution sets investigated were as follows:

1. Practice change – Cane
2. Practice change – Grazing
3. Practice change – Pesticides
4. Practice change – Irrigation
5. Practice change – Horticulture (bananas)
6. Catchment remediation – Gullies
7. Catchment remediation – Streambanks
8. Catchment remediation – Treatment systems
9. Point source WWTP management
10. Landuse change.

Each of the solution sets were then individually modelled across the 46 agreed GBR catchment basins, to allow comparisons of cost-effectiveness between options and to establish efficient investment pathways – the investment required to mitigate one unit of pollution (e.g. \$/kg DIN). For each solution set, this Cost Effectiveness Analysis (CEA) process was undertaken across all key efficacy parameters, all cost parameters, and other risk and uncertainty parameters (particularly non-cost risks related to adoption and efficacy) where required. To allow for different types of costs (establishment/capital, refurbishment, operations and maintenance, and opportunity costs) and different timings of costs, the cost-effectiveness for each solution set was discounted to present value terms. However, for the purposes of the costs included in the investment scenarios developed later in the project, the 5-year actual costs are used, as these reflect the cost to GBRF of their investment. Finally, significant sensitivity analyses using Monte Carlo simulations were utilised to establish a range of CEA estimates for each solution set.

The fourth key component of this project involved the generation of agreed investment scenarios. This involved working collaboratively with GBRF and the Project Working Group and Peer Review Panel to develop and assess a range of scenarios quantitatively, in parallel to the qualitative values assessment work undertaken in parallel by Aurecon (Aurecon 2019). At total of 12 initial scenarios were developed to capture a broad range of potential interventions, and these were based on different approaches to allocating funding as follows:

- between basins (e.g. based on priority level, NRM region)
- between target pollutants (e.g. giving greater or lesser priority to a particular pollutant)
- between intervention types (generally the most cost-effective option was adopted, but in some instances, for example, practice change might be prioritised over other interventions, or vice versa).

Note also that for pesticides there remains some uncertainty around costs, which will be informed by current projects underway in GBR catchments. For this reason, the funding for this pollutant was capped at $15m, and was generally split evenly between the three priority basins identified in the Reef 2050 Water Quality Improvement Plan. In relation to cane and irrigation practice change, where an intervention involved a landholder moving from ‘D’ practice to ‘C’ practice, then this cost is assumed to be met by the landholder (i.e. not paid for by GBRF), on the basis that this is a now a regulatory requirement.

The 12 scenarios selected for assessment by both this project and the values-based process are summarised in the table below.

Scenario number	Scenario name	Scenario description
1.	Very High priority (VHP) Locations Only	- VHP basins only - $15m pesticides - Roughly even split between FS and DIN - Based on most cost-effective interventions available in VHP basins
2.	VHP and High Priority (HP), balanced portfolio (with pesticides)	- VHP and HP basins only - Roughly even split between basins (greater $ to VHP basins) - Roughly even split between FS and DIN - $15m pesticides
3.	VHP and HP, balanced portfolio (no pesticides)	- As above, without pesticides
4.	All NRM regions	- Split by NRM region, with regard to priorities - Wet Tropics and Burdekin $35m each - Mackay Whitsunday, Fitzroy, Burnett Mary $20m each - Cape York $5m - Funding in each based on priority locations and cost effectiveness
5.	DIN Only	- VHP, HP and MP basins only - DIN only - Includes practice change to A. However, assumes a landholder moves no more than 2 steps in practice change (i.e. D-B, or C-A, but no D-A)
6.	FS Only	- As above, but FS instead of DIN
7.	VHP for FS; balance for DIN and pesticides	- VHP basins only for FS, $40m - HP, VHP basins for DIN, $85m - HP, VHP basins only for pesticides, $15m
8.	VHP only for DIN, balance for FS and pesticides	- VHP basins only for DIN, $40m - HP, VHP basins only for FS, $85m - HP, VHP pesticides, $15m
9.	Limited practice change	- VHP and HP basins only - $30m for practice change, balance for other intervention types - No pesticides
10.	Majority practice change	- VHP and HP basins only - $110m for practice change, balance for other intervention types - No pesticides

Scenario number	Scenario name	Scenario description
11.	Most cost effective options in HP and VHP basins	- VHP and HP basins only - Even split between FS and DIN - $15m pesticides - Interventions based on most cost effective intervention
12.	Most cost effective option any location	- Any location - Even split between FS and DIN - $15m pesticides - Interventions based on most cost effective

The final project output developed was a visualisation tool, the purpose of which was to take the outputs of the very detailed modelling (outlined in the solution sets) and provide a user-friendly approach to assess user-defined investment scenarios. The interface and supporting computational processes were developed based on inputs from a range of stakeholder needs analyses, with the final format agreed followed a range of testing with GBRF, the Project Working Group and Peer Review Panel. A short User Manual for the tool was also produced.

Additional work was conducted external to this project to examine a range of values that may influence the selection of specific investment approaches (Aurecon 2019). Key outcomes from the Structured Decision Making (SDM) values assessment process were that:

- there was strong support for the inclusion of pesticides in the preferred scenario
- there was also strong support for a significant investment in practice change
- cost effectiveness of interventions were highly favoured
- water quality outcomes should be favoured above all other considerations, and as such they need to have regard for identified WQIP priorities.

In short three scenarios ranked the highest from this process (scenarios 2, 11 and 12). It was agreed that scenario 12 did not meet the principles in the RTP grant agreement “that investments seek to address highest priority threats in the highest priority locations”. It was therefore not considered further. As such an amalgam of scenarios 2 and 11 was adopted as the final scenario to be analysed in further detail using the modelling.

In terms of funding that could be directed to any preferred scenario, the RTP includes $201M of funding for water quality improvement activities. While the final allocations of funding had not been finalised at the time of this report, it was likely that a final investment amount of approximately $141M in regionally focussed interventions would be potentially available after other funding commitments had been satisfied. This was used as the upper bound for the scenario investment totals. In addition, a scenario reflecting a total of $250M of investment (in a situation where additional funding would be secured from other funding partners) in water quality management interventions was investigated to compare the impact on water quality targets, but this is not reported further here.

The final scenario for analysis was therefore as follows:

- Total scenario investment value of approximately $141m
- Funding allocation
  - $15m for pesticides – on basis that the SDM process identified value in investing in pesticides, but that there is greater uncertainty with respect to pesticide interventions, cost, and efficacy, and due to the relative loads across the three priority pollutants
  - $62.1m and $63.9m for each of DIN and FS, respectively - on the basis that the SDM process identified each as of relatively equal importance
- Only VHP and HP locations under the WQIP (for the relevant pollutant)
- For pesticides:
  - $11m in Mackay Whitsunday - Plane Ck ($7m, VHP) and Pioneer ($4m, HP)

- $4m in Lower Burdekin (HP)
- For DIN
  - Available funding allocated within VHP and HP basins on basis of most cost-effective intervention available
  - Practice change capped at 40% of available area of farms at the practice levels being changed, on assumption that it is not feasible to shift more that this % over the 5-year window.
  - For irrigation practice change, program to fund max of 10% of up-front costs based on this intervention generally being a highly cost-effective action when the 30-year NPV is considered, generating long-term benefits to landholders.
  - Land use change capped at 1% of available area, to minimise impacts on productivity and viability of cane industry
  - No practice change beyond B to be included
- For FS:
  - starting point of scenario 11
  - Cap at 20% of gully areas for Type 1 and 40% of gully areas for Type 2. These values to be adjusted on catchment-by-catchment basis recognising capacity constraints.
  - Wherever possible, gully restoration and grazing practice change to be linked together – i.e. both interventions to be adopted in same catchment. Average cost-effectiveness across the 2 intervention types to be considered.
  - Cap total expenditure on FS in the Burdekin at approximately $30m, having regard to capacity to deliver. Further adjusted where required to provide for appropriate load reductions and linkage to grazing practice change.
  - If apportioning between basins with same priority and interventions with similar cost-effectiveness, then look to apportion with consideration for (i) delivery capacity in each basin and (ii) the total load reduction targets for the basins, i.e. with greater funding to basins with a greater load reduction target.
- Identify for DIN and FS what and where the next most cost-effective interventions would be, i.e. where the final decision points are as we approach the limit of the available funding.
- When selecting the most cost-effective action, these are to be based on 30-year NPV
- Consider exclusion of interventions if the size of the intervention available is sufficiently small that the cost-effectiveness will be significantly reduced due to (fixed) program costs. As part of this consider if the intervention can be linked with other interventions.
- For Regulations:
  - For Cane - assume that 40% of cane under D class practice has moved to C at no cost to GBRF (due to regulation compliance) and is available for practice change from C-B. Load associated with D to C to be included in overall progress towards targets, but to be accounted for separately
  - For Grazing – allow for program to fund D to C.

The final results obtained for the above scenario constraints are shown in the tables below.

The work from this project was utilised as an input into finalising GBRF's Five Year Investment Strategy (and Annual Workplan) for the Water Quality Component of the Reef Trust Partnership.

Table 1. Final Scenario - DIN

Region	Basin	Priority	Pollutant	$	Intervention	Cost effectiveness (5yr) ($/kg)	DIN Reduction (t)	DIN Target (t)	% to DIN target	Reduction due to regulation (D to C) (t)
Wet Tropics	Herbert River	VHP	DIN	$1,890,000	Cane C to B	$70.58	26.8	641.0	4%	
Wet Tropics	Herbert River	VHP	DIN	$8,080,000	Cane D to B	$168.40	159.8	641.0	25%	52.1
Wet Tropics	Herbert River	VHP	DIN	$6,260,000	Cane to conservation	$690.98	9.1	641.0	1%	
Wet Tropics	***Herbert River***			***$16,200,000***			***195.7***	***641.0***	***31%***	
Wet Tropics	Johnstone River	HP	DIN	$2,090,000	Cane C to B	$48.36	43.2	471.4	9%	
Wet Tropics	Johnstone River	HP	DIN	$2,530,000	Cane D to B	$105.67	79.6	471.4	17%	26.0
Wet Tropics	Johnstone River	HP	DIN	$2,300,000	Cane to conservation	$428.95	5.4	471.4	1%	
Wet Tropics	***Johnstone River***			***$6,920,000***			***128.2***	***471.4***	***27%***	
Wet Tropics	Mulgrave-Russell River	HP	DIN	$1,050,000	Cane C to B	$55.19	19.0	336.7	6%	
Wet Tropics	Mulgrave-Russell River	HP	DIN	$3,100,000	Cane D to B	$136.10	75.7	336.7	22%	24.7
Wet Tropics	Mulgrave-Russell River	HP	DIN	$2,060,000	Cane to conservation	$500.77	4.1	336.7	1%	
Wet Tropics	***Mulgrave-Russell River***			***$6,200,000***			***98.8***	***336.7***	***29%***	
Wet Tropics	Tully River	HP	DIN	$1,000,000	Cane C to B	$43.80	22.8	249.7	9%	
Wet Tropics	Tully River	HP	DIN	$2,130,000	Cane D to B	$108.14	65.5	249.7	26%	21.3
Wet Tropics	Tully River	HP	DIN	$1,570,000	Cane to conservation	$401.86	3.9	249.7	2%	
Wet Tropics	***Tully River***			***$4,690,000***			***92.2***	***249.7***	***37%***	
Burdekin	Lower Burdekin	VHP	DIN	$9,310,000	Cane D to B	$673.93	26.7	585.3	5%	26.1
Burdekin	Lower Burdekin	VHP	DIN	$7,100,000	Irrigation C to B Level 2	$1,493.73	47.5	585.3	8%	
Burdekin	***Lower Burdekin***			***$16,400,000***			***74.3***	***585.3***	***13%***	
Mackay/Whitsundays	Plane Creek	HP	DIN	$8,710,000	Cane D to B	$376.39	65.2	230.5	28%	38.6
Mackay/Whitsundays	Plane Creek	HP	DIN	$2,940,000	Cane C to B	$441.06	6.7	230.5	3%	
Mackay/Whitsundays	***Plane Creek***			***$11,700,000***			***65.2***	***230.5***	***28%***	

Table 2. Final Scenario – Fine Sediment (FS)

Region	Basin	Priority	Pollutant	$	Intervention	Cost effectiveness (5yr) ($/kg)	FS Reduction (kt)	FS Target (kt)	% to FS target
Burdekin	Bowen Bogie	VHP	FS	$6,130,000	Grazing D to C	$0.03	196.8	426	
Burdekin	Bowen Bogie	VHP	FS	$1,960,000	Gully Type 1 Treatment	$0.04	44.9	426	
Burdekin	Bowen Bogie	VHP	FS	$19,300,000	Gully Type 3 Treatment	$0.21	89.9	426	
Burdekin	***Bowen Bogie***			***$27,300,000***			***331.6***	***426***	***78%***
Burdekin	East Burdekin	VHP	FS	$1,040,000	Grazing D to C	$0.07	15.5	75	
Burdekin	East Burdekin	VHP	FS	$489,000	Gully Type 1 Treatment	$0.09	5.4	75	
Burdekin	***East Burdekin***			***$1,530,000***			***20.9***	***75***	***28%***
Fitzroy	Fitzroy River	HP	FS	$5,970,000	Grazing D to C	$0.34	17.4	201	
Fitzroy	Fitzroy River	HP	FS	$9,990,000	Streambank repair	$0.37	27.3	201	
Fitzroy	***Fitzroy River***			***$16,000,000***			***44.7***	***201***	***22%***
Wet Tropics	Herbert River	HP	FS	$1,040,000	Grazing D to C	$0.17	6.0	95	
Wet Tropics	Herbert River	HP	FS	$2,410,000	Streambank repair	$0.37	6.5	95	
Wet Tropics	***Herbert River***			***$3,450,000***			***12.5***	***95.***	***13%***
Fitzroy	Mackenzie	HP	FS	$3,610,000	Grazing D to C	$0.59	6.1	63	
Fitzroy	***Mackenzie***			***$3,610,000***			***6.1***	***63***	***10%***
Burnett Mary	Mary River	HP	FS	$9,400,000	Streambank repair	$0.33	28.3	132	
Burnett Mary	***Mary River***			***$9,400,000***			***28.3***	***132***	***22%***
Burdekin	Upper Burdekin	VHP	FS	$2,560,000	Grazing D to C	$0.11	22.7	245	
Burdekin	***Upper Burdekin***			***$2,560,000***			***22.7***	***245***	***9%***

Table 3. Final Scenario – PSII Pesticides

Region	Basin	Priority	Pollutant	$	Intervention	Cost effectiveness (5yr) ($/kg)	Pest reduction (kg)	Pest anthropogenic load (kg)	% of anthropogenic load
Mackay Whitsunday	Plane Creek	VHP	Pesticides	$7,000,000	Pesticides C-B	$52,312	133.8	1271.4	11%
Mackay Whitsunday	Pioneer	HP	Pesticides	$4,000,000	Pesticides C-B	$46,307	86.4	737.7	12%
Burdekin	Lower Burdekin	VHP	Pesticides	$4,000,000	Pesticides C-B	$109,723	36.5	1318.7	3%

Table 4. Final Scenario – NRM Region Summary

	DIN	Pesticides	Fine Sediment	Total
Wet Tropics	$34,000,000		$3,450,000	$37,500,000
Burdekin	$16,400,000	$4,000,000	$31,400,000	$51,800,000
Mackay Whitsunday	$11,700,000	$11,000,000		$22,700,000
Fitzroy			$19,600,000	$19,600,000
Burnett Mary			$9,400,000	$9,400,000
	$62,100,000	**$15,000,000**	**$63,900,000**	**$141,000,000**

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1 Introduction

The Great Barrier Reef Foundation (GBRF) engaged Alluvium Consulting Australia (Alluvium), in partnership with Natural Capital Economics (NCE), Truii and Central Queensland University, to provide a robust and defensible scientific basis for the GBRF to plan and implement the Water Quality Component of the Reef Trust Partnership.

This work forms one of several inputs to the decision-making process associated with the development of the GBRF Investment Strategy. A separate project (Prioritisation Support Consultancy, Aurecon 2019)for GBRF helped to establish an overall Structured Decision Making (SDM) process that assisted the GBRF develop and assess scenarios for future investment. That process utilised a Multi Objective Decision Analysis (MODA) approach to ultimately help develop Investment Scenarios, a set of options for combined actions across catchments that use value drivers and their relative success factors to test for optimum value; and guide program decision-making. The relationship of the two projects and the development of the Investment Strategy is outlined in Figure 1 below.

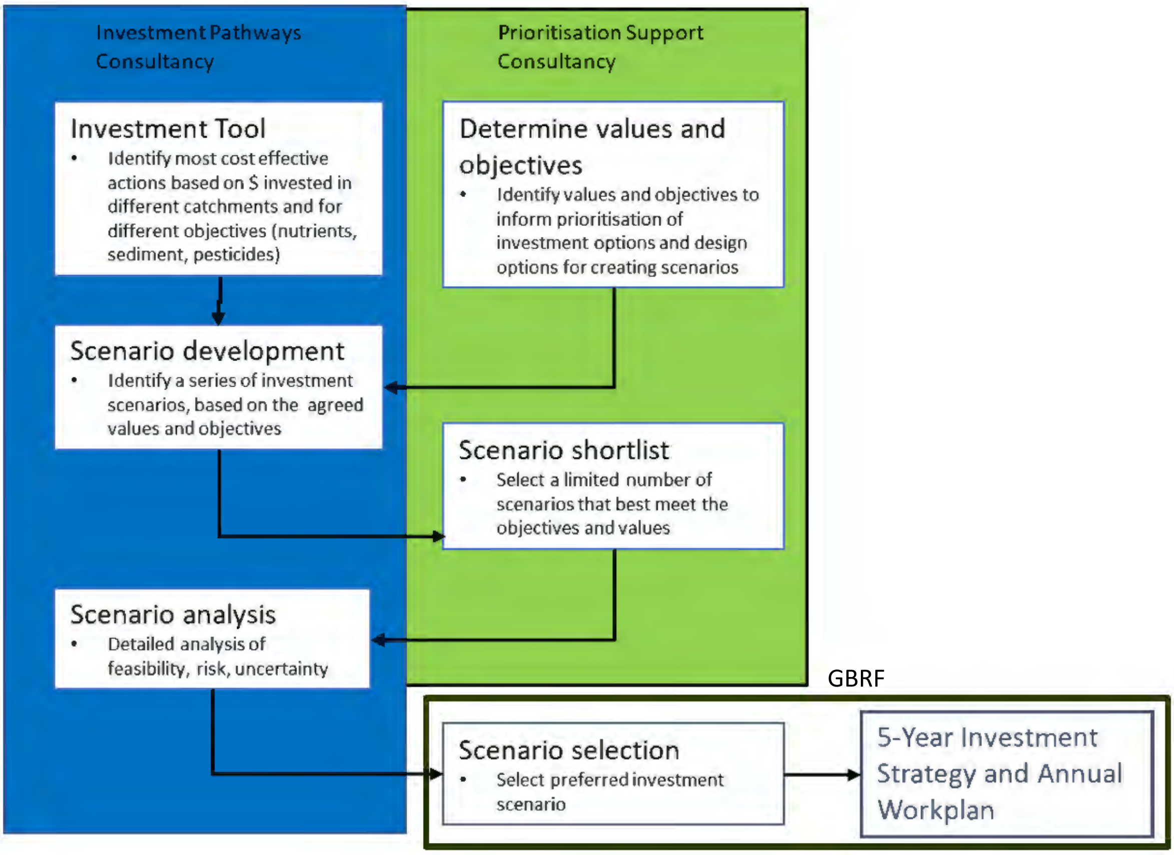


Figure 1. *Relationship of Investment Pathways Project and Prioritisation Support Consultancy and the GBRF Investment Strategy*

1.1 Study overview and objectives

This Investment Pathways Project aimed to develop a quantitative assessment of the most cost-effective catchment management actions in 46 reporting basins within the GBR catchments, and a data visualisation tool to support the comparison of investment scenarios.

Specifically, the study aimed to:

- Establish and apply integrated science and economics to identify and test effective and efficient investment pathways for pollutant load reduction to the GBR. In conjunction with assessments of key

GBR assets (e.g. specific reef ecosystems), investments to enhance the GBR's resilience can be maximised within constrained budgets, and/or the most efficient investment pathways to improve ecosystem resilience can be established.

- Build on and enhance the cost effectiveness analysis previously undertaken across 5 regions in the GBR to now identify the most efficient investment pathways for the planned $141M expenditure in reducing water quality impacts on the reef.
- Show how these investments will enable appropriate actions to work towards Reef 2050 Plan targets for each of the 46 priority basins, for up to 10 different management interventions (Policy Solution Sets).
- Develop the tools and analysis needed to properly inform prioritisation of investment in the actions and locations that are likely to have the most significant impact in reducing pollutant loads to the Reef thereby improving ecosystem health and reef resilience.

This report summarises the work completed by Alluvium and its partners in delivering the Investment Pathways project. An outline of both the broad project phases and the detail associated with these tasks is shown in Figure 2 and Figure 3. Components of Phase 4 and 5 were led by GBRF with our team providing data, information and consultative support where required.

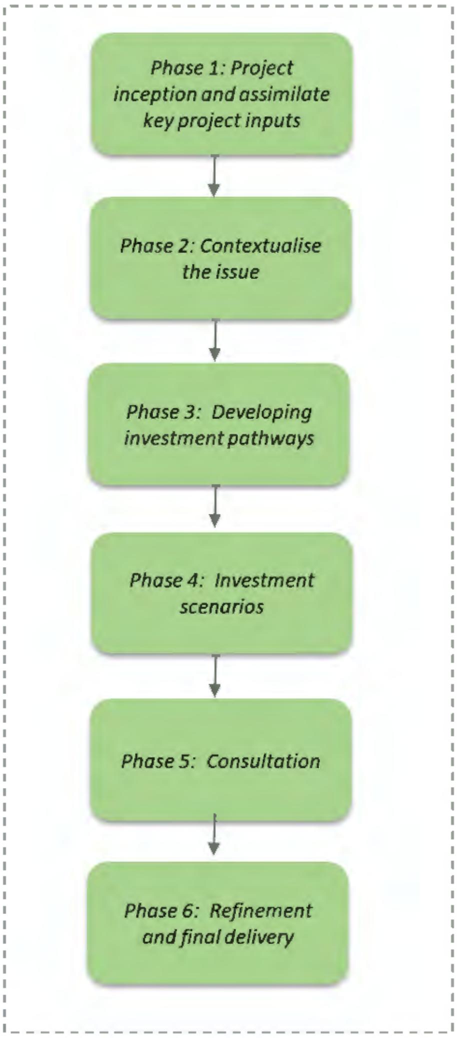


Figure 2. *Phases of the Investment Pathways Project*

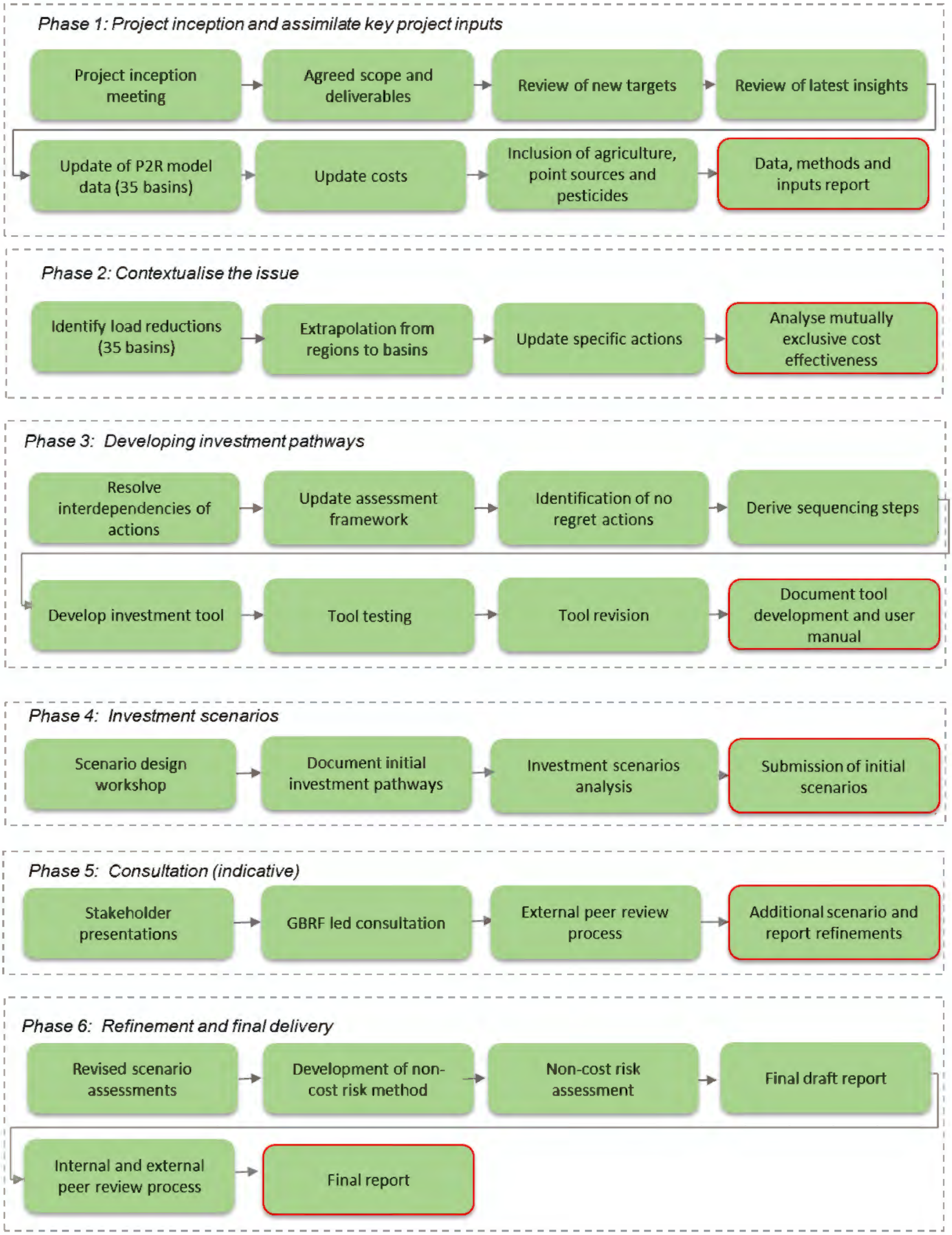


Figure 3. *Project tasks*

1.2 Report content and structure

This report is structured as follows:

- **Section 2** provides an overview of the contemporary information sources used to develop the methods and provide inputs into the quantitative analysis.
- **Section 3** provides an overview of framework utilised to develop the method for the broader project, and details the processes used to synthesise the information for future use in the broader project and includes information on the assumptions and decisions in analysis so far and the methodologies intended for subsequent phases.
- **Section 4 – cost effectiveness input data** sets the scene for the analysis and tool development through an overview of the solution sets that are assessed in each relevant basin, the locations of the basins and the regions within which they lie, and an overview of the water quality baselines and targets (detailed coverage of baselines and targets is provided in Appendix C).
- **Section 5 – the visualisation tool** provides an overview of the data visualisation tool, outlining agreed objectives and user requirements, describing data processing methods and giving an overview of the user interface, which will be explained in more detail in a User Manual. This is to be completed following the development, testing and finalisation of the scenarios to be analysed in the next phases of this project.
- **Section 6 – discussion of results** provides an overview of the cost-effectiveness results, giving an indication of what might be useful to further explore in the investment scenarios using the data visualisation tool. This is broken down by constituent pollutant.
- **Section 7 – scenario development** outlines the process undertaken to develop and assess a range of scenarios and the preparation of a final investment pathway scenario.
- **Section 8 – non-cost risks** discusses the assessment of risks to adoption and achievement of modelled efficacy.
- **Section 9 – next steps** outlines the few remaining project tasks.
- **Attachment A – list of management actions** provides a detailed list of management actions assessed within each solution set.
- **Attachment B – solution sets** are a series of documents (one for each solution set assessed). These include the approach and data used in the solution sets, the range of costs parameters used, the range of efficacy parameters used and some summary reporting of cost effectiveness (including between and within regions). It is the very detailed modelled outputs of the solution sets that provide the major data inputs for the scenario development and data visualisation tool.
- **Attachment C – baseline pollutant loads and targets** outlines the quantitative ecologically relevant targets and loads for each region, their basins, and each constituent pollutant.

2 Project inputs

This project was highly reliant on existing information to support the determination of cost-effectiveness of management actions. Given the importance of the GBR, there have been continuing efforts to improve the scientific understanding of poor water quality impacts occurring on the Reef and the performance of management interventions to address those impacts. There has also been a considerable focus on the implementation of actions across the NRM regions within the GBR catchments so that additional information around the costs and application issues was also available.

In the first phase of the project, we focussed on identifying sources of information that have become available since the previous Reef Costings Study in addition to the information obtained in that study, further details of which are outlined below.

2.1 Primary information sources

2016 Reef Costings Study
In 2016 the Great Barrier Reef Water Science Taskforce was asked to consider the costs to achieve ambitious reef water quality targets (up to an 80% reduction in nitrogen runoff and a 50% reduction in sediment run off) from key catchments by 2025. Alluvium Consulting, in partnership with a number of entities, was commissioned to investigate seven policy solution sets to determine which would be most cost effective in reducing the impacts associated with sediment and nitrogen run-off across key GBR catchments. The work undertaken during the initial costings study, including the models developed and the economic analyses undertaken (Alluvium 2016), form an important input to this project. Specifically, the solution sets statements, information regarding individual cost elements for each of the steps in the solution sets and the data obtained around time lags have all been reviewed and recollated for this study. We have also updated relevant costing information to AU$2018 where we intend to use that directly (i.e. the data is not likely to be updated with new information).

Since the previous costings report, a significant volume of work has continued in the broader reef space, most of which is aligned to the federal and state governments ongoing implementation of the Reef 2050 Plan. A summary of some of the key outputs in recent times is provided below.

Reef 2050 Plan – Investment Framework (2016)
This framework not only outlines current investment in protection of the GBR, it also determined investment priorities for the future. This prioritisation was informed by both the Reef 2050 Advisory Committee and the Independent Expert Panel and includes consideration of investment sequencing. Six priority areas for future investment were identified, and strategies to boost funding were also considered in the process. The six areas for future funding included:

- Reef Water Quality Protection Plan actions – focuses on continuing to make improvements to water quality from broadscale landuse as identified by the 2013 Reef Water Quality Protection Plan Actions
- Field Management Program Actions – this area focusses on management actions that ensure well-functioning marine and island ecosystems
- Reef 2050 Integrated Monitoring and Reporting Program Actions – focusses on tracking progress towards targets and includes the eReefs and Paddock to Reef programs. The modelling from the latter is particularly relevant to this project.
- Crown-of-Thorns Starfish (COTS) Actions – focuses on improving water quality and direct control program to manage COTS numbers on high value reef sites.
- Traditional Owner Actions – this program has several aspects, but at its core is improving Traditional Owner participation in governance and management arrangements for the reef.
- Fisheries Actions – strong focus on reviewing the regulatory structure of the Queensland fishing industry to ensure its long-term sustainability.

2017 Scientific Consensus Statement (2017)
This statement updated the previous 2013 statement and reviewed the current hazards and pressures facing the GBR, assessing each of their relative risks and as a result provided recommendations including the following relevant to this project:

- Developing strategies to manage impacts of future landuse changes (coastal development and land retirement)
- Improving the management of wetlands, rivers and floodplains and their connectivity to the GBR
- Utilising the catchment-specific pollutant targets to guide actions linked to water quality (see below)
- Prioritising agricultural sources of pollutants while at the same time assessing other potentially important pollutant sources such as urban, industrial and port areas
- Urgently implementing more targeted and substantial effort to improve GBR water quality
- Developing more cost-effective techniques for a range of management responses such as gullies and riparian erosion
- Implementing broader practice change programs
- Developing a more comprehensive and costed water quality improvement plan
- Undertaking finer scale spatial prioritisation of management effort.

Basin Specific Water Quality Targets (2017)
This project developed basin-specific, Ecologically Relevant Targets (ERTs) for water quality across all 35 basins in the GBR regions. The study built on the existing 2013 Scientific Consensus Statement to incorporate the most recent science and to support the 2017 update of the Reef Water Quality Protection Plan. In addition, the project drew on previous work undertaken to develop ERTs for a number of the Water Quality Improvement Plans (WQIPs) in reef regions. The work was founded on the eReefs hydrodynamic, sediment transport and biogeochemical modelling and monitoring data sources. Targets have been developed for sediment and nutrients, and pesticides. These targets formed a critical input for the current study.

Reef 2050 Water Quality Improvement Plan 2017-2022 (2018)
This plan updated previous plans compiled in 2003, 2009 and 2013. It includes all source of land-based pollutants and sets Whole-of-Reef, Regional and Catchment-based water quality targets. It also provides an update of long-term progress toward the 2025 water quality targets, and provides a series of land management, catchment management and human dimensions (social, cultural, institutional and economic) targets to be achieved.

Report Card 2016
The outputs of the Paddock to Reef modelling form the basis for annual report cards on catchment loads for the GBR. The report card documents themselves provide useful information on the estimated load reductions achieved to date, but in addition, the detailed technical documents and the model results are one of the key inputs into this project. From the modelling undertaken for the 2016 Report Card (RC2016), we have been provided with results for all 5,583 sub-catchments down to individual constituent, generation, delivery and area level for all "functional units" (i.e. land uses) across the 6 GBR regions for which models have been constructed. Further technical reports from previous years were also reviewed (McCloskey et al 2017).

Additional Investment

Since the 2016 costings study, a range of programs delivering investment in improvements in water quality entering the GBR lagoon have continued, some of which are summarised below. Projects delivered since 2016 will provide a range of important information (costs, efficacies etc) relevant to this current study.

The Reef Trust is a $700 million federal government program focused on improving water quality, restoring coastal ecosystem health and enhancing species protection. There are currently 6 phases of the program, with the most recent phase (Phase VI) investing up to $15 million for four projects targeting on-ground actions to improve the health and resilience of the Great Barrier Reef. This includes:

- $3.5 million, complementing $3.7 million from the Queensland Government, to help sugarcane farmers improve their fertiliser use efficiency.
- $5 million matched with $5 million raised by the Great Barrier Reef Foundation, to restore and conserve Reef island ecosystems.
- $5 million to clean-up and prevent marine debris entering the Great Barrier Reef.
- $1.5 million for an 'Innovation Challenge' run in collaboration with the Queensland Government to seek innovative solutions to boost coral abundance on the Great Barrier Reef.

A range of other federal government programs including those linked to disaster relief (e.g. Natural Disaster Relief and Recovery Arrangements (NDRRA)) have also provided ongoing investment into reef related projects, including those focussed on reducing sediment loads into rivers and streams to improve water quality flowing into the GBR lagoon.

The current Queensland Regional Natural Resource Management Investment Program (the program or QRNRMIP) has been in place since 2013 and concluded in July 2018. This stream of investment involved $80 million over five years, including $30 million to support initiatives to protect the Great Barrier Reef (see for example, DNRME 2017). This is one of many programs investing additional funding to improve water quality in GBR catchments.

The Queensland Government is also investing in two Major Integrated Projects (MIPs), a key recommendation of the Great Barrier Reef Water Science Taskforce report in May 2016. The stated aim of these multi-million dollar projects is to work closely with groups of landholders in identified priority areas. The current MIPs focus in the following areas:

- the Bowen-Broken-Bogie sub-catchments of the lower Burdekin River catchment in the Dry Tropics (focused on reducing sediment loads from grazing regions)
- the Tully and Johnstone basins in the Wet Tropics (focussed on reducing nutrient and pesticide loads, predominantly in sugar cane growing regions).

The MIPs, along with other projects that have resulted from investment in the GBR catchment management space, provided important sources of updated information in relation to costs (establishment, operational and maintenance costs and their variability) and efficacies of practices relevant to the scenarios investigated as part of this project.

2.2 Differences between this project and the previous 2016 Reef Costings report

In undertaking this project, we were well aware of a range of factors that influenced the development of the cost-effectiveness results during the 2016 Reef Costings Report (Alluvium 2016). There were some key differences between that work and the current study. These include:

a) Overall, this project was not focussed on the costs to achieve targets, but the most cost-effective group of actions in key priority basins for a given level of investment. This meant that poorer cost-effectiveness actions did not have to be implemented if not required for the level of investment.
b) This study includes all GBR regions, including Cape York. The previous study did not include the Cape.

c) This study includes 3 constituents; fine sediment, DIN and pesticides. The previous study did not include pesticides.
d) In the previous work, the amount of a particular action and the range of solution sets were constrained to those previously identified in various WQIPs in the regions. In this project, additional data was available to consider increasing the range of solution sets, and there were no constraints on the amount of an action that could be implemented.
e) The current study examines 10 solution sets where the previous work examined 7. Some of the solution sets also were changed (e.g. urban stormwater was not considered as a solution set given the poor cost-effectiveness in comparison to rural practices).
f) The previous 2016 study had blanket water quality targets to be achieved (80% reduction in anthropogenic DIN, 50% reduction in fine sediment). This project uses the updated Ecologically Relevant Targets which vary across basins according to the relevance of the target to the reef ecosystem. Overall, the targets reduced in most basins and this subsequently reduced the amount of effort required to achieve targets and therefore the costs to achieve them.
g) This project also considered bananas as a land use for potential investment.

3 Broad framework

3.1 Approach

As outlined in the project proposal, the approach for this project has the basis in the original Reef Costings Study, though we adapted it to ensure there was sufficient flexibility in the way that potential investments may be undertaken through the application of the GBRF funding for water quality projects. The figure below, as reproduced from the proposal, provides a visual indication of how the different elements of the information and data sources link together.

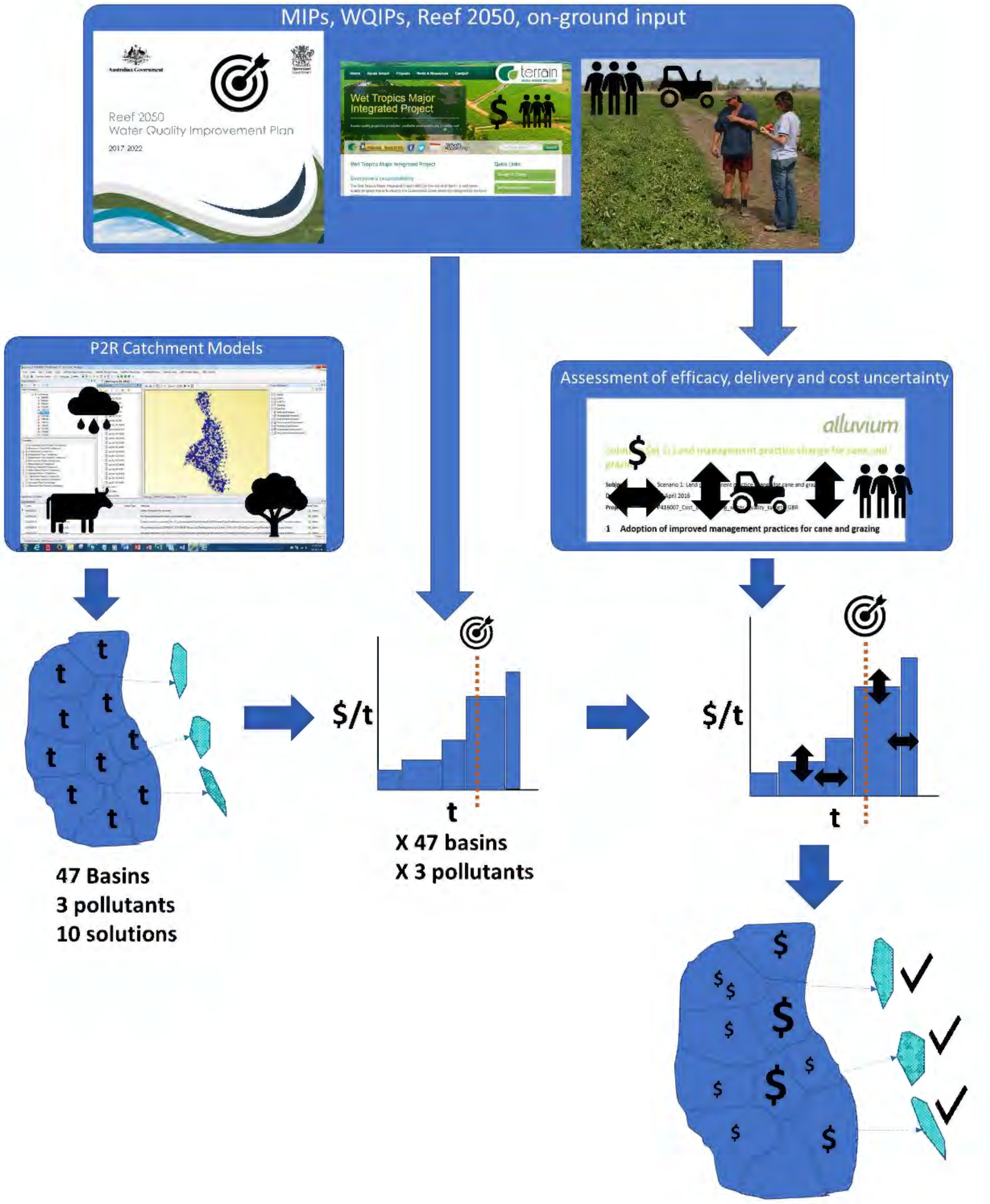


Figure 4. *Broad framework*

This was modified from the original proposal to reflect that we identified practices for the 46 reporting basins (47 reporting regions without Curtis Island -see below) reported to the Federal Government rather than the original 35 basins as outlined in the project proposal and in the list of Ecologically Relevant Targets (ERTs) that form part of the Reef 2050 Plan WQIP. In effect, this expansion is to ensure consistency with other reporting and while the ERTs exist for only the 35 basins, we have extended previous work in the Burdekin WQIP and Scientific Consensus Statement reports to subdivide the Burdekin ERT into sub-basin targets. In the Fitzroy, similar work does not yet exist, so scaling of the targets according to anthropogenic contribution in sub-basins has been done as part of this project and is discussed in subsequent sections. It should also be noted that the targets themselves are not as critical for this project as they were for the previous reef costings work, but provide an indication of the magnitude of effort required in each of the reporting regions.

What is important to understand from the figure above is that the methodology was driven by the outputs of the Paddock to Reef models, and integrated with cost and efficacy data from the primary information sources outlined in the previous chapter. This allowed us to identify the groups of actions needed to address the target loads. The process that we will apply will be:

1. Determine the loads needed to achieve the ERTs in each of the 46 basins based on updated Report Card 2016 Model results (the latest available), using the % reductions outlined in the ERTs applied to updated anthropogenic loads to calculate the mass load reductions (in tonnes) required. Pesticides were dealt with separately to this process as information regarding targets was not directly applicable to the loads produced from the Report Card 2016 Model results.
2. Determine the performance of actions to date in reducing those loads – a number of different methods have been used to develop appropriate load reductions and these are outlined in the Solution Statements.
3. Calculate the remaining mass load to achieve the ERTs in the 46 basins.
4. Determine the groups of solution sets available in each of the 46 basins (obviously not all actions in each solution set will be applicable in each basin).
5. Determine the steps needed for each solution set. For example, moving practice from D to C, C to B and B to A are all separate steps which can be costed and have the efficacy determined.
6. Identify the costs and performance for each step.
7. Identify the cost-effectiveness of each step.
8. Analyse the most cost-effective group of steps across all solution sets to achieve the targets or scenario requirements.
9. Determine the correct sequence of actions to achieve the targets or scenario requirements.
10. Align the sequences and cost-effectiveness so that the most cost-effective sequence of actions for a given expenditure can then be determined.

3.2 Potential Solution Sets

The Terms of Reference for this project outlined the need to investigate 10 potential policy solution sets (intervention types). These were to include the 7 solution sets from the 2016 costings study as a minimum, as well as three additional interventions that were subsequently identified as being potentially significant (horticulture and grains, major point sources (Wastewater Treatment Plants - WWTPs) and pesticides). Importantly all 35 GBR basins (46 reporting regions) were included in the current study.

On 24 September 2018, a workshop was held involving project team members, GBRF staff and members of both the Project working Group and Peer Review Panel. The workshop focused on reaching agreement on the scope and extent of the solution sets to be applied in the current study. A summary of the outcomes from the workshop are provided below in Table 5 below. Departures from the 2016 study have been highlighted in bold. The workshop also concluded that given their relative size, additional sub-basins in the Fitzroy and Burdekin River catchments needed to be considered in the study. This increased the total number of basins being investigated to 46 (as noted above, there is no Paddock to Reef modelling for Curtis Island in the Fitzroy Region in the datasets we have received, and as such has not been included in the analysis, leaving a remaining 46 reporting catchments).

Linked to this, the project team required assistance to ensure the relevant targets were both available and able to be incorporated into the modelling analyses. It was also agreed that the solution sets would utilise as similar format to those presented in the 2016 costings work. These included the following broad areas of content:

- Definition
- Background
- Management actions
- Costs
- Efficacy of actions
- Detailed results
- Assumptions and limitations.

Table 5. Solution sets considered for current study, with key differences from the 2016 costings study highlighted in bold.

Proposed Solution Sets	Part of 2016 costings study?	Retain for current study?	Extent	Comments
1. Practice change – cane and grazing	Yes	**Retain but split as follows:** **1a: Cane (nutrient)** **1b: Grazing (sediment)** **1c: Pesticides**	**Cane and grazing to be applied over all relevant basins** **Pesticides to be considered, but only in the 5 agreed priority catchments**	Given the scale of this solution set it needs to be more clearly split
2. Improved irrigation practices	Yes	Retain	As per previous study	Need to be cognisant of issues associated with separate vs combined efficacy
3. Gully remediation	Yes	**Retain but split as follows:** **3a: Alluvial gullies** **3b: Hillslope gullies**	**Apply over all relevant basins**	Need to recognise the different characteristics, contributions and potential interventions linked to the two major gully types and address separately in methodology. Significant new data from MIPs and other recent investments e.g. NDRRA, Reef Trust, NESP. NB Further analysis showed that these could not be resolved as separate gully components and were combined as one
4. Streambank repair	Yes	Retain	**Apply over all relevant basins**	Significant new data from MIPs and other recent investments e.g. NDRRA, Reef Trust, NESP
5. Treatment systems	Yes	Retain	**Apply over all relevant basins**	Significant new data emerging from MIPs, also now includes other treatments so solution set was renamed “Treatment Systems” to reflect engineered treatments (Constructed Wetlands,

					Landscape Wetlands, Bioreactors, Recycle Pits)
6.	Landuse change	Yes	Retain	**Apply over all relevant basins**	Need to be cognisant of the influence of fluctuating cane prices and how these are selected/utilised in any analyses
7.	Urban s/water management	Yes	**Not to be considered further in the current study**		Available data similar to that utilised in 2016 study. Not therefore considered necessary to include given findings of previous work.
8.	Bananas and grains	No	**Include in current study but modify to:** **8: Horticulture: bananas**	**Focus to be the Wet Tropics region**	Grain not included as limited data availability, comparably small spatial extent and current practices already relatively well advanced.
9.	Point source WWTP management	No	**Include in current study**	**Major urban centres only**	
10.	Pesticides	No	**Include in current study but incorporate into Solution set 1 (see above)**		

In summary, this means we have evaluated 10 solution sets. After further discussions with GBRF on 8 October 2015 linked to a presentation of this report and subsequent discussions, the final solution sets to be investigated are as follows:

1. ***Practice change – Cane***
2. ***Practice change – Grazing***
3. ***Practice change – Pesticides***
4. ***Practice change – Irrigation***
5. ***Practice change – Horticulture (bananas)***
6. ***Catchment remediation – Gullies***
7. ***Catchment remediation – Streambanks***
8. ***Catchment remediation – Treatment Systems***
9. ***Point source WWTP management***
10. ***Landuse change***

Another issue the project team considered was the planned implementation of the proposed updated reef protection regulations. Current regulations exist for sugarcane and grazing properties in the high priority catchments Wet Tropics, Burdekin and Mackay Whitsundays, and legislation introduced in March 2019 proposes broadening and enhancing the existing guidelines based on the recent findings of the 2017 Scientific Consensus Statement. Discussion have therefore been held with relevant OGBR staff about the potential minimum compliance standards for cane, grazing and bananas to be set linked to the new regulations. These minimum standards set an important baseline and the solutions sets considered in this study have evaluated the practices that focus on activities above this proposed baseline.

3.3 Reporting areas

The basin specific ERTs (Centre for Tropical Water & Aquatic Ecosystem Research 2017) have been set for 35 major basins within the six NRM regions. Given the relatively large area that several of these basins cover, this study has assessed management scenarios against baseline loads for 46 'reporting catchments' as shown in Figure 6.

The 5583 Paddock to Reef (P2R) sub-catchments have each been assigned by the P2R team to the 46 reporting catchments in addition to the 35 basins. It should be noted that the boundaries for the Lower Burdekin and Fitzroy reporting catchments do not perfectly align with basin boundaries. An example is provided in Figure 5, where the Lower Burdekin reporting catchment contains sub-catchments within the Burdekin, Don and Haughton basins. For consistency, we have used the assigned reporting catchment (46), however given that anthropogenic load estimates and target load reductions are reported at the basin (35) scale, we have disaggregated the targets in the Burdekin and Fitzroy major basins and this is discussed further in the following sections.

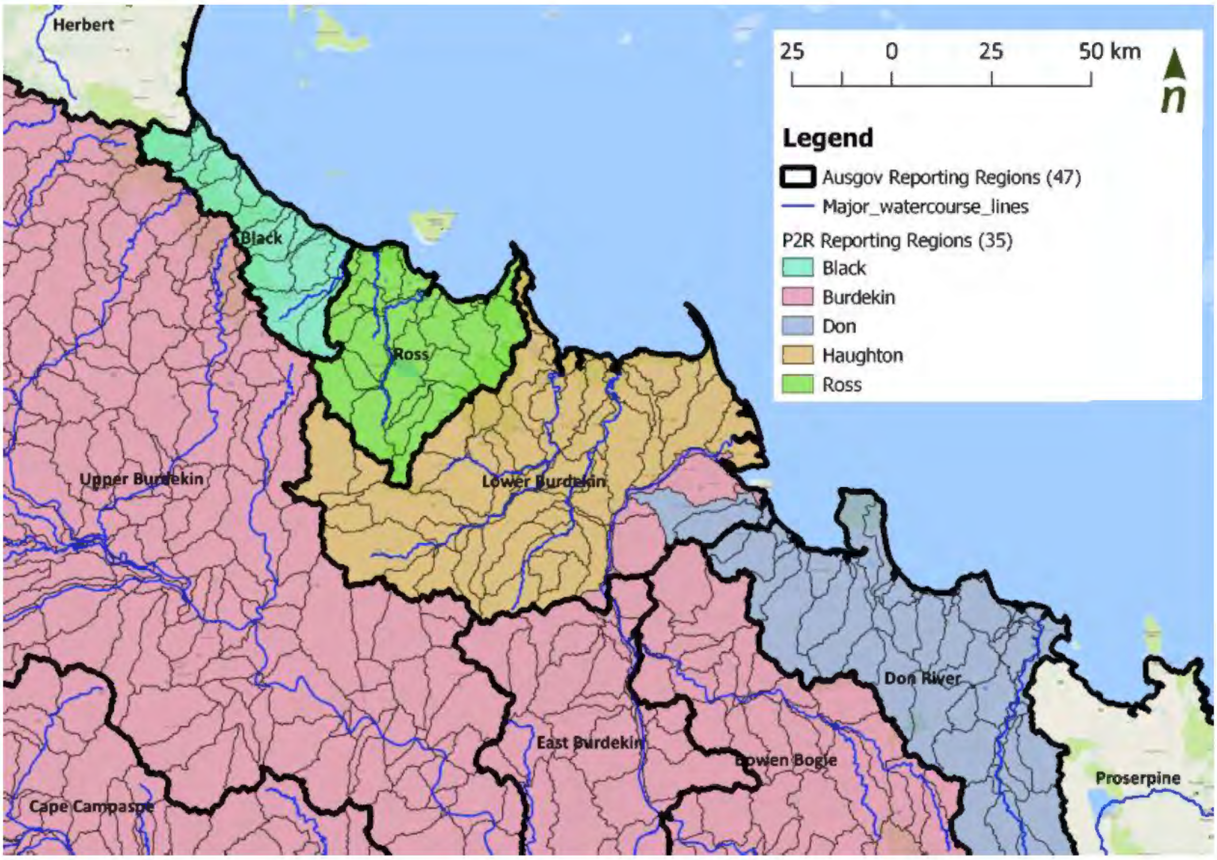


Figure 5. *Reporting catchment boundary alignment*

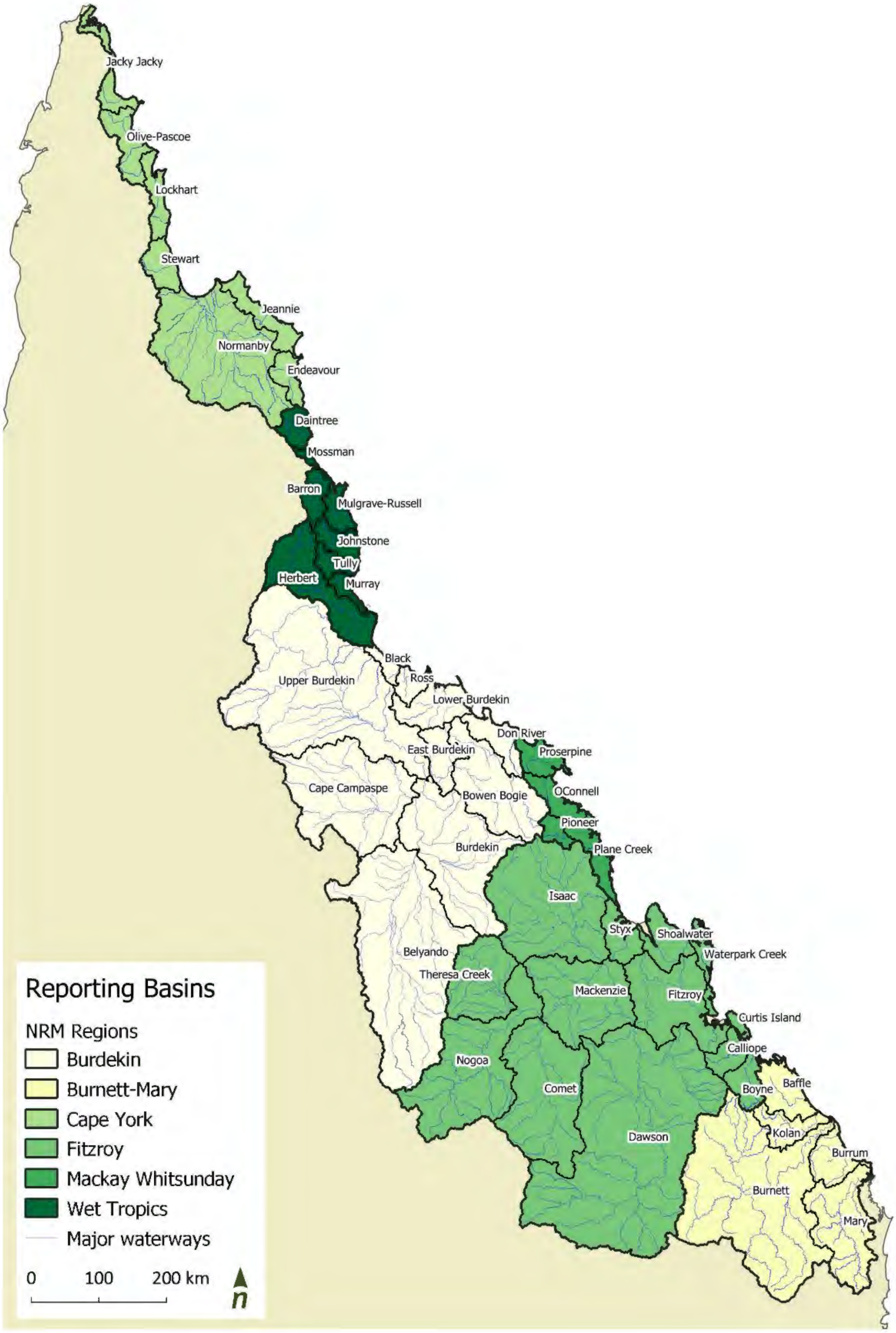


Figure 6. *Map of 47 reporting catchments and the P2R sub-catchments (derived from P2R GIS datasets)*

3.4 Measuring water quality improvement

Baseline

Water quality data from the Paddock to Reef modelling for the 2016 Report Cards was provided by the P2R team for use in this project. The data provided the modelled annual baseline load for dissolved inorganic nitrogen (DIN), fine sediment, and pesticides (5 PSII herbicides), attributed to a specific land use type and pollution source for each of the 5583 modelled sub-catchments.

The most recent and applicable water quality targets (Centre for Tropical Water & Aquatic Ecosystem Research 2017) report baseline total and anthropogenic loads which were used to generate 2025 target load reductions based on 2012-2013 model outputs. In this study however, the baseline loads from the 2016 Report Card model outputs were used, which reflect the best available modelling and science.

The Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (P2R program) uses a baseline scenario which represents 2013 land management practices. As modelling practices have been further developed and applied to the P2R models, the baseline loads for each region have been found to increase or decrease as a result of these changes. While there are arguments for maintaining a consistent baseline by which to measure progress, reported progress in the annual report card is measured against the most up to date revision of the baseline.

The P2R data provided has been assessed to compare the 2016 baseline total and anthropogenic loads with the 2012-2013 loads reported in the basin specific water quality targets (Centre for Tropical Water & Aquatic Ecosystem Research 2017). We note that there are some differences at the catchment and region level between that originally used for determining the target mass loads and the 2016 data, however our approach was to use the 2016 data and the % reduction ERTs to determine the mass load reductions required in each of the 46 basins as being the most recent and best available information.

Targets

The basin specific ERTs (Centre for Tropical Water & Aquatic Ecosystem Research 2017) have been set for 35 basins within the six NRM regions as a percentage reduction and subsequent load reduction when applied to the 2012-2013 baseline anthropogenic load. These targets have also been adopted as the load reductions required in the Reef 2050 WQIP so are therefore the current targets being used in program design and assessment as noted further in Section 4.2.

To be consistent with best available science and modelling, the percentage reduction for each basin has been applied to the 2016 Report Card baseline data. Where a basin has been further divided into several reporting catchments, the target percentage reduction for that basin has been applied to the baseline anthropogenic load for that catchment. We developed a table of the differences in loads from the ERT work and the 2016 Report Card as shown in Table 6 below.

Table 6. Comparison of mass loads for the WQIP Ecologically Relevant Targets and Report Card 2016.

Region	Ausgov reporting basin	WQIP ERT catchment/basin	Dissolved Inorganic Nitrogen (t/y)								Fine sediment (kt/y)							
			WQIP ERT					Report Card 2016			WQIP ERT					Report Card 2016		
			Tonnes	% reduction	Baseline load	Anthropogenic load	Target load reduction	Baseline load	Anthropogenic load	Target load reduction	Kilo-Tonnes	% reduction	Baseline load	Anthropogenic load	Target load reduction	Baseline load	Anthropogenic load	Target load reduction
Cape York	Jacky Jacky Creek	Jacky Jacky Creek	MCL	MCL	67	0	0	67	0	MCL	MCL	MCL	52	43	0	32	4	MCL
	Olive Pascoe River	Olive Pascoe River	MCL	MCL	98	1	0	98	1	MCL	MCL	MCL	72	54	0	62	12	MCL
	Lockhart River	Lockhart River	MCL	MCL	49	0	0	49	0	MCL	1	2	67	54	1	74	3	0
	Stewart River	Stewart River	MCL	MCL	30	0	0	31	0	MCL	2	6	49	41	2	33	7	0
	Normanby River	Normanby River	MCL	MCL	105	9	0	111	16	MCL	15	10	186	151	15	139	103	10
	Jeannie River	Jeannie River	MCL	MCL	35	0	0	35	0	MCL	2	6	42	31	2	40	7	0
	Endeavour River	Endeavour River	MCL	MCL	40	1	0	41	2	MCL	3	10	59	27	3	60	17	2
Regional Total					**423**	**11**	**0**	**431**	**19**	**0**			**526**	**400**	**23**	**440**	**153**	**13**
Wet Tropics	Daintree River	Daintree River	MCL	MCL	478	135	0	482	138	MCL	MCL	MCL	103	28	0	142	47	MCL
	Mossman River	Mossman River	52	50	160	104	52	167	111	56	MCL	MCL	17	6	0	18	4	MCL
	Barron River	Barron River	52	60	152	87	52	180	115	69	MCL	MCL	55	32	0	63	38	MCL
	Mulgrave-Russell River	Mulgrave-Russell River	300	70	934	423	296	992	481	337	16	10	253	156	16	214	87	9
	Johnstone River	Johnstone River	350	70	1059	499	349	1,233	673	471	100	40	379	260	104	304	161	64
	Tully River	Tully River	190	50	777	384	192	892	499	250	17	20	157	83	17	136	47	9
	Murray River	Murray River	120	50	414	232	116	489	307	154	8	20	74	39	8	71	26	5
	Herbert River	Herbert River	620	70	1522	886	620	1,552	916	641	99	30	478	331	99	484	317	95
Regional Total					**5496**	**2750**	**1678**	**5987**	**3241**	**1977**			**1516**	**936**	**243**	**1431**	**727**	**183**
Burdekin	Black River	Black River	ND	ND	97	21	ND	94	22	ND	ND	ND	62	34	0	61	33	ND
	Ross River	Ross River	74	60	180	123	74	180	129	78	ND	ND	62	49	0	62	49	ND
	Lower Burdekin	Haughton River*	640	70	1016	914	639	965	826	578	MCL	MCL	183	157	0	176	150	MCL
	Bowen Bogie	Burdekin River*	100	60	1104	171	103	175	23	14	840	30	3260	2783	836	1,655	1,420	426
	East Burdekin							85	11	0						293	251	75
	Upper Burdekin							451	60	0						953	818	245
	Burdekin River							90	12	0						88	75	23
	Cape Campaspe							75	10	0						42	36	11
	Belyando							61	8	0						59	51	15
	Don River	Don River*	MCL	MCL	177	68		106	43	MCL	55	30	213	183	55	212	181	54
Regional Total					**2574**	**1297**	**816**	**2283**	**1144**	**670**			**3781**	**3209**	**891**	**3601**	**3065**	**850**
Mackay/Whitsundays	Proserpine River	Proserpine River	110	70	310	157	110	248	143	100	MCL	MCL	131	75	0	125	67	MCL
	O'Connell River	O'Connell River	130	70	325	186	130	265	177	124	96	40	314	241	96	242	167	67
	Pioneer River	Pioneer River	140	70	256	193	135	251	203	142	35	20	227	173	35	168	117	23
	Plane Creek	Plane Creek	260	70	464	366	256	401	329	230	MCL	MCL	146	99	0	119	71	MCL
Regional Total					**1355**	**902**	**631**	**1165**	**853**	**597**			**818**	**589**	**131**	**654**	**422**	**90**
Fitzroy	Styx River	Styx River	MCL	MCL	91	10	0	90	10	MCL	MCL	MCL	104	94	0	99	91	MCL
	Shoalwater Creek	Shoalwater Creek	MCL	MCL	100	5	0	99	5	MCL	MCL	MCL	67	59	0	63	56	MCL
	Waterpark Creek	Waterpark Creek	MCL	MCL	65	4	0	65	4	MCL	MCL	MCL	65	57	0	64	56	MCL
	Fitzroy River	Fitzroy*	MCL	MCL	799	159	0	284	57	MCL	390	30	1507	1292	388	733	660	198
	Mackenzie							61	12	0						236	212	0
	Isaac							236	47	0						135	122	0
	Dawson							139	28	0						195	176	0
	Comet							41	8	0						24	22	0
	Nogoa							22	4	0						7	6	0
	Theresa Creek							17	3	0						11	10	0
	Calliope	Calliope*	MCL	MCL	47	6	0	47	6	MCL	15	30	57	50	15	52	46	14
	Boyne River	Boyne River	MCL	MCL	37	3	0	37	2	MCL	6	40	24	16	6	17	15	6
Regional Total			**MCL**	**MCL**	**1140**	**186**	**0**	**1138**	**186**	**0**	**411**		**1824**	**1568**	**409**	**1636**	**1473**	**218**
Burnett Mary	Baffle Creek		16	50	58	32	16	57	31	16	11	20	75	53	11	76	53	11
	Kolan River		34	50	78	68	34	73	63	31	6	20	40	30	6	40	30	6
	Burnett River		150	70	246	207	145	234	196	137	85	20	528	426	85	341	246	49
	Burrum River		93	50	199	186	93	179	166	83	3	20	26	17	3	25	16	3
	Mary River		180	50	459	361	181	421	324	162	130	20	770	666	133	769	658	132
Regional Total					**1040**	**854**	**468**	**965**	**780**	**429**			**1459**	**1192**	**238**	**1250**	**1004**	**201**
GBR Total					**12028**	**5999**	**3594**	**11968**	**6223**	**3672**			**9925**	**7894**	**1935**	**9012**	**6843**	**1554**

Management priority					
	Very high		Moderate		Minimal
	High		Low		Not assessed

MCL = maintain current load

*Refers to catchments with inconsistent boundaries, final baseline, anthropogenic and target loads yet to be finalised

Scenarios

The method applied for the 2016 Reef Costings Study (Alluvium 2016) to estimate water quality improvement from various management scenarios was used for this study with updated data where available. This method interacts with the model results without having to re-run the model for each management scenario.

Updated input data included the latest understanding of efficacy for different management interventions, including a 'minimum', 'most likely' and 'maximum' annual reduction in pollutant load.

For the scenarios looking at changes in practices, the most recent estimates for percentage of land within each basin being managed with practices at different water quality risk states (i.e. the previous ABCD framework) has been applied (McCosker pers comm 2018).

3.5 Estimating relative solution set costs – cost effectiveness analysis

Cost-effectiveness analysis (CEA) compares the relative costs to the outcomes (effects) of two or more courses of action, in this case alternative investments to achieve reductions in pollutants. CEA measures costs in a common monetary value (present value of all costs) and the effectiveness of an option in terms of physical units (e.g. kg DIN).

Each of the solution sets were individually modelled to allow comparisons of cost-effectiveness between options and to establish efficient investment pathways – the investment required to mitigate one unit of pollution (e.g. $/kg DIN). Because each solution set has different types of costs (establishment/capital, refurbishment, operations and maintenance, and opportunity costs.) and different timings of costs, the cost effectiveness for each solution set required costs to be discounted to present value terms.

All costs were estimated in real terms and discounted to a present value using agreed discount rates. A discount rate of 7.0% (real) was used, with sensitivity analysis at 4.0% and 10% (real) as per the Queensland Treasury guidelines. A 30-year time frame was used for the analysis of each solution set with costs for 5 year investments (cash costs) and 15 year (Net Present Value) quantified to assist with scenario and investment pathway development.

Relevant costs

The key costs considered into the modelling for each solution set are outlined in

Table 7 including comments and sources of data. Further details of the results of these are provided in each of the Solution Statements attached to this report.

Table 7. Key cost categories for inclusion in each solution set

Cost category	Description	Comments and sources of data
Program administration	The cost of any administering any solution set by delivery partners	This costs typically occurs in year 1 of any program. Data was sourced from the recent evaluation of NRM programs in Queensland (Alluvium 2018) and relevant information from the Commonwealth (e.g. Reef Trust tender projects).
Establishment costs	This is the design and capital cost associated with solution sets	This is the capital cost of projects (e.g. earthworks for gully erosion, equipment for practice change such as hooded sprayers etc.). For most solution sets, data was sourced and updated from the previous costings project (Alluvium 2016), data from programs run since 2016, and through consultation associated with this project.
Opportunity cost – production foregone (to be incorporated into establishment cost)	The cost of the loss of productive land use	For some solution sets, productive land use may be foregone (e.g. wetland construction). Where necessary, the opportunity cost of foregone production have been estimated (based on the present value of gross margins foregone, or similar) and incorporated as part of the establishment cost. Data was sourced from the literature and the use of existing models (e.g. the FEAT gross margin models developed by Qld DAF for sugarcane cropping regions).[1]
Capital asset renewal / refurbishment	The cost of periodic refurbishing and replacing capital equipment	Some solution sets will require periodic replacement of capital equipment (e.g. pumps for enhanced irrigation practices). However, only the incremental (addition) costs of capital equipment should be included (e.g. if a pump required replacement as business as usual irrigation practices, if would not be included in the analysis). Data was sourced from the previous costings project (Alluvium 2016), data from programs run since 2016 such as the QFF energy audit, recent work undertaken by the consulting team, and through consultation associated with this project.
Annual operations and maintenance (net change)	The ongoing cost of the solution set.	This is the ongoing cost of operations (e.g. labour, energy) and maintenance (e.g. routine maintenance of pumps) required for any given solution set. This should be a net change (costs net of benefits) as some solution sets actually deliver costs savings to farmers (e.g. fertiliser practice change or water use efficiency initiatives reduce fertilise or water/electricity operational costs). For 5 year cash costs, only costs (not net of benefits) were assumed. Data was sourced from the previous costings project (Alluvium 2016), data from programs run since 2016, recent work undertaken by the consulting team, and through consultation associated with this project.

The degree to which the above-mentioned categories of costs were included for each solution set depended on the specific elements of that solution set. Where information on the geographical differentiation of solution set efficacy or costs was available, this was also included into the modelling for each of the reporting areas. Further details on these costs are provided in the Solution Statements.

Sensitivity analysis to establish a range of CEA estimates for each solution set

In establishing the efficient investment pathways, investors will be interested in both the more likely relative efficiency of alternative solution sets (e.g. $/Kg DIN) as well as the potential range of estimates (i.e. the variability/risk associated with each solution set) and the feasibility of scaling up actions.

[1] See https://www.daf.qld.gov.au/business-priorities/plants/field-crops-and-pastures/sugar/farm-economic-analysis-tool

For each cost category, there will be a range of information sources and subsequently a range of cost parameters. Based on the information available, for each solution set and each relevant cost category parameters, low, more likely and high cost parameters were established. These parameters effectively became the input parameters for the CEA modelling.

The project team then completed significant sensitivity analysis using Monte Carlo simulations to establish a range of CEA estimates for each solution set. Monte Carlo simulation performs risk analysis by using different input parameters and their distribution bounds in multiple iterations to find the range and probabilities of outputs of interest. The numerous iterations utilise a different set of random values from the probability functions. This enabled the establishment of probability distribution-like estimates of the CEA of alternative solution sets.

For each solution set, this process was undertaken across all key efficacy parameters, all cost parameters, and other risk and uncertainty parameters where required.

An example of the outputs from a Monte Carlo simulation from a previous project is shown in the figure below. This analysis provides a number of important information sources for investors, including:

- A mean estimate of the CEA for the solution set. This provides the initial key information to inform efficient investment pathways.
- Minimum, maximum, and confidence intervals of the range of CEA estimates for the solution set. The range provides investors with insight into the likely investor risk (from a cost perspective) and how reliable the estimates are likely to be for investment and decision-making.

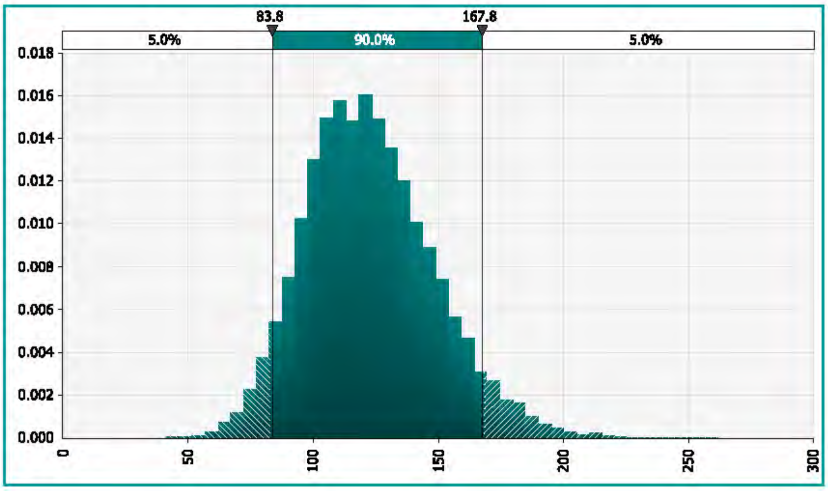


Figure 7. *Example of a Monte Carlo simulation to estimate a 90% range of outputs*

When multiple solution sets are compared, this analysis then provides insight into the degree of confidence that two alternative solution sets do actually have different levels of efficiency. For example, where there is no cross-over between the 90% confidence interval range of CEA, it is very likely that the CEA of one solution set is superior to the other. Where there is significant cross-over between the 90% confidence intervals, it is less certain that the one solution set is clearly more cost effective than the other.

The output of the Monte Carlo simulations can also be used to gain insight into which input parameters of the CEA calculations (e.g. capital costs, efficacy estimates) have the greatest impact on the estimates of CEA. An example of this type of analysis is shown in Figure 8. This figure shows the variability in capital costs has the highest effect on the estimated model output.

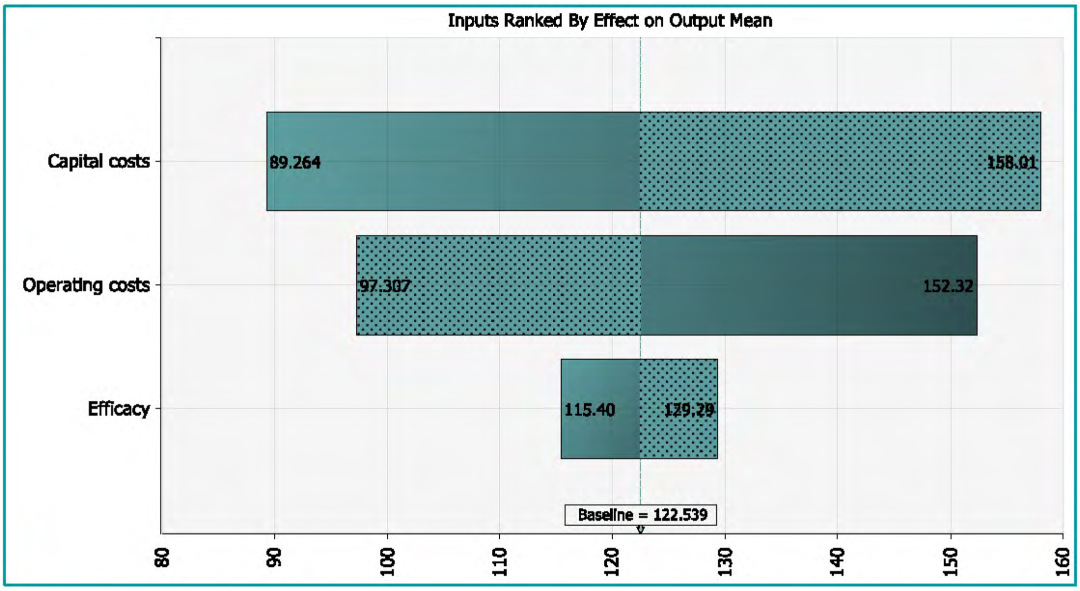


Figure 8. *Example of a Monte Carlo simulation to identify input parameters explaining the variance in estimates*

This information provides valuable insight for future investment including:

- Focusing future research or analysis to better understand the variability and uncertainty in key parameters.
- On-ground program design. For example, if the majority of the variance in CEA for a solution set is attributable to the opportunity cost of land, significant efficiency gains could be gained by using price discriminatory approaches (e.g. reverse tenders) to allocate incentives.

Monte Carlo simulations were undertaken for all major input parameters and for each individual solution set.

4 Cost-effectiveness input data

For the purposes of this study, a range of data was required as input to the Investment Pathways assessment process (this project), as summarised in Table 8.

Table 8. Types of input data required for the Investment Pathways project

Data	Description	Methods
Solution Sets	The 10 solution sets each contain a group of management actions which seek to achieve the same objective	As agreed by the Project Working Group and the Peer review panel
Management actions	These are individual management actions with sufficient data available to be able to establish cost and efficacy	Largely drawn from the water quality risk frameworks for practice change, supplemented by other actions identified through literature and previous studies.
Baseline pollutant loads	Baseline loads of dissolved inorganic nitrogen (DIN), fine sediment, and pesticides (PSII) for each of the 46 basins, attributed to each land use	Determined from the 2016 Report Card Paddock to Reef data sets
Available area	The maximum area available for each management action to be applied within each basin	Determined from the 2016 Report Card Paddock to Reef data sets
Efficacy	The estimated reduction in pollutant load resulting from a given management action, providing an uncertainty range where available	Determined from a range of data sources
Cost	The estimated life cycle cost of a given management action over a 30 year period (includes capital and operational costs, 7% discount rate), accounting for uncertainty through a low, medium and high cost. Final costs presented as 5 year cash cost (investment cost required), 15 year and 30 year net present values.	Determined from a range of data sources
Targets	Ecologically Relevant Targets at the basin level	Derived from Ecologically Relevant Targets and Scientific Consensus Statement

4.1 Solution Sets

It was originally intended to use the data provided to determine the cost-effectiveness of management actions within 11 solution sets, as agreed by the Project Working Group and the Peer review panel. As noted in the previous sections, Wetland Construction was renamed Treatment Systems and Catchment Remediation; for Alluvial and Hillslope Gullies, while originally intending to be separated, were combined due to a lack of data available that discretely related to each of these gully types. The list of solution sets is provided in Section 3.2.

A full list of management actions and the NRM regions for which they apply can be found in Attachment A. We note that that the analyses completed were undertaken for solutions where costing and efficacy data were available and supported by a reasonable evidence base. This does not preclude other technologies, practices or actions from future funding but this work does provide a basis by which their cost-effectiveness can be examined (i.e. if their cost-effectiveness could be shown to be equal or better than actions assessed in this project, it would strengthen their further consideration).

A Solution Statement has been produced for each solution set which outlines:

- A description of, and context for, each solution set, including the list of individual management actions
- The approach adopted for capital and ongoing costs associated with each individual action, accounting for uncertainty by providing a low-high range of costs, and varying regionally where applicable
- The method used to assess efficacy of the action in reducing pollutant loads, providing a range of efficacy values where available, and varying regionally where applicable
- The area available for an action to be implemented within each of the 46 reporting basins
- A high level summary of cost-effectiveness
- Any assumptions and limitations used in the approaches outlined above
- Key sources of data and information used in the analysis.

The Solution Statements for the 10 solution sets can be found in Attachment B. A brief overview of each solution set is provided below.

Solution Sets 1 – 5 Practice change – cane, grazing, pesticides, irrigation, horticulture (bananas)
The practice change solution sets each compile the data to assess the cost-effectiveness of improved practices across different agricultural land types; sugarcane, grazing and horticulture. The management actions within each solution set refer to a transition from High (D), to Moderate (C), to Moderate-low (B) to Lowest (A) risk practice level. The Water Quality Risk Frameworks (Reef 2050 Water Quality Improvement Plan) for each land use were used to determine the likely management practices within each practice level which could be costed individually to produce an overall lifecycle cost for changing practice level. The average pollutant loading rate for each practice level under a given land use type within each NRM region was provided by the Queensland Government Department of Environment and Science (DES) modellers and was used to determine the efficacy of transitioning to an improved practice level.

Solution Set 6 Catchment remediation – Alluvial and hillslope gullies
These solution sets use the results of the Reef Trust Gully and Streambank Toolbox work being undertaken by CSIRO in addition to studies undertaken by Alluvium and other agencies within Queensland on gully remediation. This work focuses on both alluvial and hillslope gullies across a number of catchments in Cape York, Burdekin and Fitzroy NRM regions but also is able to be applied wherever gullying is a significant source of fine sediment. The efficacy and cost data are mostly derived from the Gully and Streambank Toolbox work, though further studies and projects are currently underway and where this data is relevant, it was used to provide better estimates of the ranges of costs and efficacies.

Solution Set 7 Catchment remediation – Streambanks
Streambank remediation has been a major focus of a number of National Disaster Relief and Recovery Arrangements (NDRRA) projects post Cyclone Debbie. There have also been other studies (Baheerathan et al 2017) investigating streambank contributions to fine sediment in other catchments. This work is providing the basis of the extent, costs and efficacies of streambank remediation in this solution set. Compared to the previous Reef Costing project, the extent of streambank remediation has expanded considerably, and this is being incorporated where suitable data exists.

Solution Set 8 Catchment remediation – Treatment systems
This solution set provides the costs and efficacies for four specific management actions related to treatment systems (formerly referred to as wetland construction). These are 1) Dry weather (tailwater) recycle pits, 2) Wet weather recycle pits, 3) Wetlands and 4) Bioreactors. For the purposes of this study, costs and efficacy have only been determined for areas of cane. It is proposed that these actions could be linked to alternate land uses, such as horticulture, in the future.

Solution Set 9 Point source WWTP management
This solution set refers to upgrading the wastewater treatment plants in five regions from secondary to tertiary treatment. This builds on recent work undertaken by the Queensland Water Directorate.

Solution Set 10 Land use change
This solution set refers to transitioning land from sugarcane to open grazing or conservation; or from open grazing to conservation. The efficacy was determined by comparing the average pollutant loading rates for each of the 46 basins for the current and future land use type. While other land use change actions were considered, there was inconsistency in the likely efficacy and was therefore not considered appropriate for inclusion.

4.2 Water quality baseline and targets

Water quality data from the Paddock to Reef (P2R) modelling for the 2016 Report Cards has been provided by the P2R team for use in this project. The data provides the modelled annual baseline load for dissolved inorganic nitrogen (DIN), fine sediment, and pesticides (5 PSII herbicides), attributed to a specific land use type and pollution source for each of the 5,583 modelled sub-catchments.

The most recent and applicable water quality targets (Centre for Tropical Water & Aquatic Ecosystem Research 2017) report baseline total and anthropogenic loads which are used to generate 2025 target load reductions based on 2012-2013 model outputs. These have been adopted as Ecologically Relevant Targets within the Reef 2050 Plan and the updated WQIPs in relevant NRM regions. For this project, we have used the baseline loads from the 2016 Report Card model outputs, which reflect the most current modelling and science available to the project team. There are only minor differences between the model outputs for the 2025 target loads and the ones used for this study and they have been accounted for in the use of the target loads adopted in this study. We note that there is some debate as to whether the numerical loads (in tonnes) or the % reductions (e.g. 70% DIN reduction) are the actual targets and we have received advice supporting both positions. We have used the % reductions to calculate updated numerical loads.

The Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (P2R program) uses a baseline scenario which represents 2013 land management practices. As modelling practices have been further developed and applied to the P2R models, the baseline loads for each region have been found to increase or decrease as a result of these changes. While there are arguments for maintaining a consistent baseline by which to measure progress, reported progress in the annual report card is measured against the most up to date revision of the baseline.

The P2R data provided has been assessed to compare the 2016 baseline total and anthropogenic loads with the 2012-2013 loads reported in the basin specific water quality targets (Centre for Tropical Water & Aquatic Ecosystem Research 2017). We note that there are some minor differences at the catchment and region level between that originally used for determining the target mass loads and the 2016 data, however for this study, 2016 data and the % reduction ERTs have been used to determine the baseline load and the mass load reductions required in each of the 46 basins. We also note that the targets provided were for DIN and Fine Sediment with further work on pesticide targets to be completed after the finalisation of this study.

A summary of the baseline loads and the percentage and mass load reduction targets for each of the 46 basins is summarised in Attachment C.

4.3 Uncertainty and non-cost risks

In this current set of deliverables, only the variability in costs are incorporated, and a range of costs have been established using Monte-Carlo simulations. In all cases a range of values for the different costs were modelled to establish the most likely, 5th percentile and 95th percentile using a Monte-Carlo analysis with 20,000 iterations. The Monte Carlo analysis provides two key insights, the variability of costs and the drivers of variability in the life cycle costs for each action type.

In addition to the variability in costs, there are some key non-cost factors that can affect the cost-effectiveness of intervention actions to reduce sediment, nutrient and pesticide loads delivered to the Great Barrier Reef. For example, some solutions are more likely to be reversed than others while for some solutions there are significant uncertainties about the achievable efficacies. These efficacy-related uncertainties can arise from limited science, poor design and construction, and risk of failure (includes failure due to lack of maintenance and/or as a result of unavoidable significant climate events). A practice reversal or poorly constructed intervention means that the estimated load reductions would not be achieved. These risks should be properly analysed and incorporated into the assessment to understand the relative risk/return trade-offs of alternative investment pathways, but also to provide insight to longer term investment yield (i.e. making choices between individual investments and the likely success of the overall investment).

In order to capture the impact of these non-cost risks on the cost-effectiveness analysis, an assessment of each of the final solution sets were made against the non-cost risks. The identified non-cost risks were categorised into two broad categories: adoption and efficacy risks. Table 9 and Table 11 provides lists of adoption and efficacy related non-cost risks as well as description of the listed non-cost risks.

Table 9. Adoption related non-cost risks

Non cost risk	Description	Note on modelling impact
Participation	Participation in agricultural programs is driven by the farmer awareness, practice change observability and availability of information. Information on the benefits of the program helps to drive the level and rapidness of adoption (Kuehne et al., 2017). This risk can be minimised through robust program design. Adoption rates can be boosted by farmer involvement in farmer networks (De Souza Filho et al., 1999; Llewellyn, 2007). This is a population related non-cost risk factor.	Risk of lower participation in the relevant NRM region may lead to reduced area for solution implementation.
Implementation	Some practice changes are complex and more challenging to implement and thus require human and technical capacity for the estimated load reductions to be achieved. For example, are there people with the required skills to implement and maintain the solution. Simple solutions that are easy to trial and are easily observable are likely to have lower implementation risks. This is a capacity related non-cost risk factor.	Complex and difficult to implement risk may lead to reduced area for solution implementation
Affordability	Some solutions are costly to implement, and this can be a deterrent to initial adoption of effective programs. Both upfront and on-going maintenance costs can result in lower adoption levels and/or reduced adoption rates (Kuehne et al., 2017). However, in some instances, programs can have tangible financial incentives for those who adopt. For example, recent case studies in the Burdekin have shown that three farmers who installed automated irrigation systems have reported a cost-savings (SRA, 2018). This is a financial or economic related non-cost risk factor. In the case of external investment in an action as would be the case if GBRF provided the required funding to implement the action, affordability may no longer be a significant risk factor, or at least its importance may be reduced. It may still influence future adoption of the practice beyond the initial investment.	Expensive solutions may lead to initially low and/or slow uptake of solutions thereby either reducing implementation area or increasing the time taken to achieve full efficacy. Where external funding of the action is provided (i.e. not borne by the landholder), then this risk factor may reduce or be eliminated, though it may indicate operational and maintenance costs may also be higher.
Dis-adoption	Risk of dis-adoption is a key concern for those implementing the program. Dis-adoption means that the forecasted load reductions may not be achieved should a proportion of adopters be able to reverse practice change. On the contrary, the ability to reverse an action may be appealing to farmers because they know that if they change their minds they can revert to old practice. This is a solution reversibility non-cost risk factor.	Ease of dis-adoption may lead to reduced nutrient load reductions from a solution over time and cause contraction of the implementation area.

In terms of adoption, Greiner et al (2009) surveyed a number of grazing land holders in the Burdekin region to consider the relationship of different motivational factors influencing the level of adoption. As part of this, the survey also asked the level of adoption of different management practices available at that time as shown in the figure below.

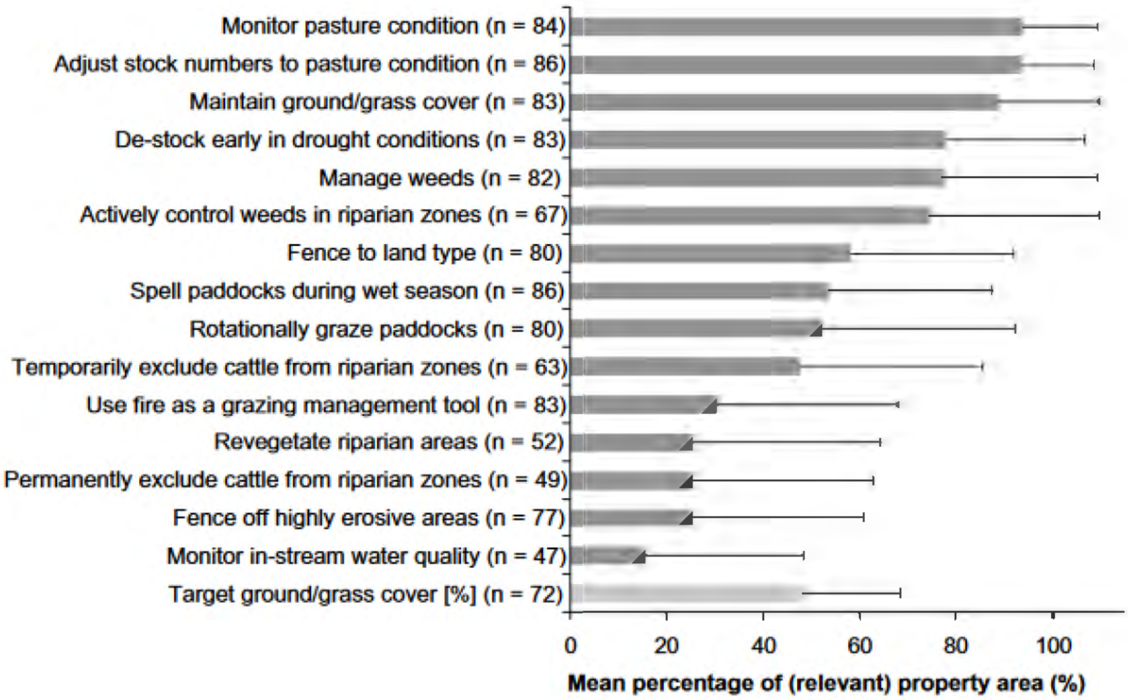


Figure 9. *Grazing landholder practice adoption (as a proportion of area)*

This indicates that adoption rates are likely to significantly vary with each practice element and are unlikely to achieve greater than 90% adoption, with an average of less than 50%. From this, it would be reasonable to assume that even with external funding, it is likely that adoption rates of less than 50% would be generally possible, but particular elements may have higher potential. This is also supported by van Grieken et al (2013) which identified that targeting of specific actions was far more effective than widespread implementation approaches.

Kuehne et al (2017) provided a table of peak adoption levels using the ADOPT framework and showed relatively high adoption levels for particular practices as shown below.

Table 10. Practice adoption levels (Kuehne et al 2017)

Comparison of ADOPT's predictions and actual adoption estimations.

Practice	Peak adoption level (%)		*Time to peak adoption* (yrs.)	
	Predicted	Actual	Predicted	Actual
Autosteer	83	83	15	20
Bt cotton	98	90	9	9
Lupins (WA)	72	75	14	10
Mace wheat (WA)	71	67	4	6
No-till (SA)	79	83	20	22
Saltbush (SA)	9	5	23	22

What is interesting in the above table is the time taken to peak adoption. Given the period over which the GBRF funding is to apply (5 years), the results above would suggest that adoption levels over a 5 year period would not achieve peak adoption. As such, even though the final peak adoption levels are high, given the time to peak adoption, the assumed level of adoption after 5 years is likely to be considerably lower.

Robertson et al (2012) examined the adoption of variable fertiliser rate application in the Australian grain industry which showed that on average, improved fertiliser practices were only adopted by 20% of farmers after incentivisation with a range of (11 – 35%).

Marshall et al (2011) provided an examination of improved climate data availability for farm management in the Burdekin catchment. In that, they noted " *Despite the potential benefits that seasonal climate forecasts offer in some regions and the relatively high awareness of them (as high as 75% of broad-acre farmers in Australia), only between 30–50% of land-holders are actively using them (Stafford Smith et al. 2000; Hayman et al. 2007; Meinke et al. 2007; Cobon et al. 2008)*."

The above information suggests that with the range of non-cost risks and other implementation factors, the maximum level of adoption likely to be possible is less than 50% where it relates to improved practice change. In other solution sets, such as gully treatment, streambank improvement and treatment systems, the level of adoption will be more related to the level of funding available and capacity constraints, rather than directly influenced by farmer behaviour (though this will still be important).

Table 11. Efficacy related non-cost risks

Non cost risk	Description	Note on modelling impact
Science and Technology	Significant scientific or technical uncertainty on the efficacy of solutions can lead to incorrect assumed efficacies. This can be because the technical knowledge needed to confidently design interventions is not yet fully developed through trial and testing of those interventions.	This would increase the variability in the likelihood that the practice will achieve the efficacy outlined in the design
Design and location	Design of interventions is key to achieving the stated efficacies. A poorly designed intervention system (e.g. wetland system) may fail to deliver the envisaged load reductions or may become a pollutant source. If the location of the pollutant source is not correctly identified (e.g. targeting high priority gullies) then the treatment practice may not deliver the required efficacy. Placement in the right location within the landscape (as a complex system) is important to maximize the likelihood that the intervention will correct, or at least beneficially adjust, the harmful process (landscape function) being targeted.	The model assumes that the design would be correctly completed, and the intervention correctly located within the landscape (catchment) to achieve the stated efficacy. This would be a one-tailed risk (i.e. this risk, if present, would lead to a reduction in efficacy, not any improvement in efficacy).
Application	To achieve the optimum nutrient and/or sediment load reductions, it is important that the construction of the asset is completed in certain time periods (e.g. dry weather) or that site impacts (e.g. erosion and sediment controls) are properly implemented.	The model assumes that construction methods for specific treatments (gully treatment, streambank remediation) is constructed according to design. Some discounting of efficacy may need to occur to account for more complex systems (e.g. Type 3 gully remediation).
Operational	Continued load reduction over time is reliant on appropriate operation and maintenance of the intervention asset. This is to avoid a risk of failure and support optimal load reduction.	Efficacy deteriorates over time from maximum, so would also be a one-tailed risk distribution.

Currently, the assessment of non-cost risks is made on the project team's understanding of those risks, based on the information made available to us throughout the project. Further refinement of these risks may be undertaken prior to implementation.

In addition to these, from the previous 2016 work (Alluvium 2016), a number of other issues were identified that are worthy of consideration when developing an implementation program, including:

- **Implications of variability.** The variability in costs identified in this project indicated price-discriminative market approaches should be used as part of the targeting and scheduling of actions, even for the *same* specific action (e.g. nutrient management) *within* the same catchment (e.g. Lower Burdekin). This enables the most cost-effective projects to be prioritised.
- **Unrealistic timelines increase costs.** Some of the policy solution sets used in the project (for practice change) included very bold assumptions relating to the likely pace of change in practice. This pace of change is significantly faster than has been achieved with similar policy approaches, and forcing the pace of change is likely to increase costs across the board. Within the current project, understanding the likely timeframes that are achievable for a given expenditure will be necessary to provide indications of when the investments are able to achieve the desired results.
- **Lack of continuity increases costs.** Program design and implementation has historically been sporadic resulting in multiple cycles of establishing capacity for specific programs and losing the capacity when short-term programs finish. This increases program design, implementation and evaluation costs. The new tranche of investment provides an opportunity to establish continuity in GBR program delivery and enhance cost-effectiveness of expenditure.
- **Sequencing and packaging of interventions.** The relative costs of different abatement actions from the same landholders indicate a need to sequence actions (most cost-effective suite of actions first) and potentially package interventions where there are synergistic effects (e.g. extension with financial assistance for capital equipment).
- **Timing of interventions.** The timing of on-ground actions should be cognisant of exogenous factors that may reduce efficacy (e.g. vegetation planting when an El Nino event is commencing), or unnecessarily increase costs (e.g. where constraints on inputs are forcing up input costs).
- **Duplication in effort increases costs.** Where possible, duplication of administration should be avoided to reduce the overheads of GBR management.
- **Capacity constraints on actions.** The whole GBR management system ranging from high level modelling through to human resources to implement on-ground actions is insufficient to implement the scale of investments required to meet the GBR targets. These capacity constraints will need to be accounted for in any prioritisation of investment.
- **Flexibility in policy choice.** There are multiple impediments to change (financial, risk, social, knowledge etc.) and therefore multiple policy tools may need to be considered to reduce the likelihood of poorly targeted or inefficient investment.

Whilst some of these are addressed in the non-cost risks identified above, others are related to program design and are worthy of consideration in moving through program design and implementation once the investment strategy is completed.

Notwithstanding the variability in costs and in adoption levels across different catchments, we have high confidence that the major solutions for each pollutant in each catchment are robust and would figure in any well-designed and selected suite of measures. Conversely the *possible* solution sets that are NOT selected for implementation are likely to be rationally excluded, i.e. despite some imprecision, those that consistently have very poor cost effectiveness are unlikely to warrant implementation except in rare and small-scale conditions, or where it can be demonstrated that the cost-effectiveness is similar to other solutions already selected for investment.

5 The scenario development and data visualisation tool

This section briefly outlines the design and functionality of the scenario development and data visualisation tool – data visualisation tool. The objective of the data visualisation tool is to take the outputs of the very detailed modelling (outlined in the solution sets) and provide a user-friendly approach to establish user-defined investment scenarios. This allows a user to quickly develop and run and compare alternative scenarios of investments.

5.1 User requirements

A series of meetings and workshops were held to establish and confirm the use cases to which the tool would be applied. The outcomes of this use case definition can then be transformed into a representation of the functionality requirement. This functionality requirement forms the basis of user acceptance criteria. The functionality requirement and use cases inform both the interface design and the computational process.

Key principles for Reporting:

- Reporting should apply at three spatial scales
  - Whole of Great Barrier Reef
  - NRM Region (6)
  - Basin (46)
- Reporting needs to apply across three constituents;
  - Dissolved Organic Nitrogen (DIN)
  - Fine Sediment (FS)
  - Pesticides
- Reporting should include performance against targets
- Reporting should include total load reduction (t)
- Reporting should include percentage reduction in load
- Reporting should include an overall cost per kg for the scenario for each constituent
- Reporting should include cost effectiveness curves
- Summary data should be available for download
- Full scenario output should be available for download.

Key principles for scenario setting

- There should be three alternative operational modes:
  - Budget based (actions applied until budget is met)
  - Full implementation (selected actions applied for selected regions irrespective of budget or load target)
  - Load target (Selected actions are applied for selected regions up until load targets are achieved).

Budget Allocation:

- Budget should be allocated based on target constituent
- Budget per constituent should be able to be set per region
- Budget per constituent should be able to be set per basin.

Actions:

- Actions should be selectable at the global (scenario) level
- Actions should be able to be selected at a basin level
- The level of implementation (% of available area) should be adjustable at the basin level
- The default order of actions is defined by the $/kg for each action for each basin
- The order of actions should be able to be manually adjusted.

Other

- Scenario settings should be able to be downloaded and uploaded.

5.2 Computational processes

The computational process has been developed based on the defined user requirements coupled with an understanding of the data available to drive the computational process. The computational process has been developed as a python package (flipper.py), which in turn is controlled by the user interface via the selection of scenario settings and relies on a Master Data file and Reporting limits file (see Figure 10 below).

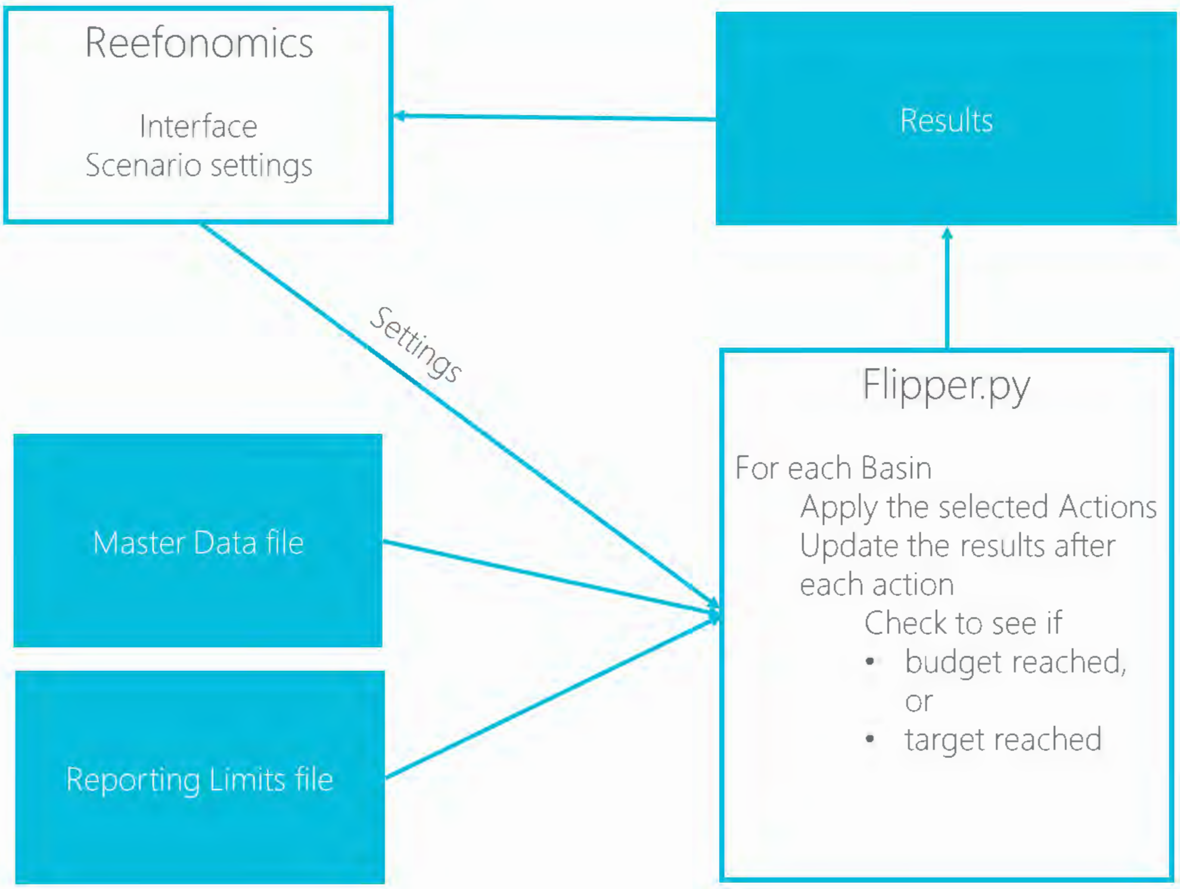


Figure 10. *Basic elements of the visualisation tool*

The basic workflow of the computational methods (see Figure 11 below) are to apply the actions for each constituent, for each basin. The process of applying the actions is to ensure both the order of Actions is respected as well as the concept of capturing sequential practice change improvement. The basic order of actions is based on the marginal abatement cost approach whereby the most cost effective Action is implemented at each step.

This may give rise to Actions of practice change improvement being conducted 'out of order'. That is, it may be more effective to convert cane practice change B to practice change A, than it is to apply practice change C to practice change B. In this case, the tool will apply the practice change according to the order specified by the marginal cost abatement method, however if more land has become available due to an Action (e.g. more practice B land is available), then all preceding Actions that have been applied are reconsidered, and reapplied.

Example input:

- Action 1- Cane B to A – area 1
- Action 2 - Cane C to B – area 2

- Action 3 - Cane D to C – area 3

Computation steps:

- Round 1 – apply Cane B to A Action (area 1)
    - Check budget / target
- Round 2 – apply Cane C to B Action (area 2)
    - Check budget / target
- Round 3 – apply Cane B to A Action (area 2)
    - Check budget / target
- Round 4 - apply Cane D to C Action (area 3)
    - Check budget / target
- Round 5 - apply Cane C to B Action (area 3)
    - Check budget / target
- Round 6 - apply Cane B to A Action (area 3)

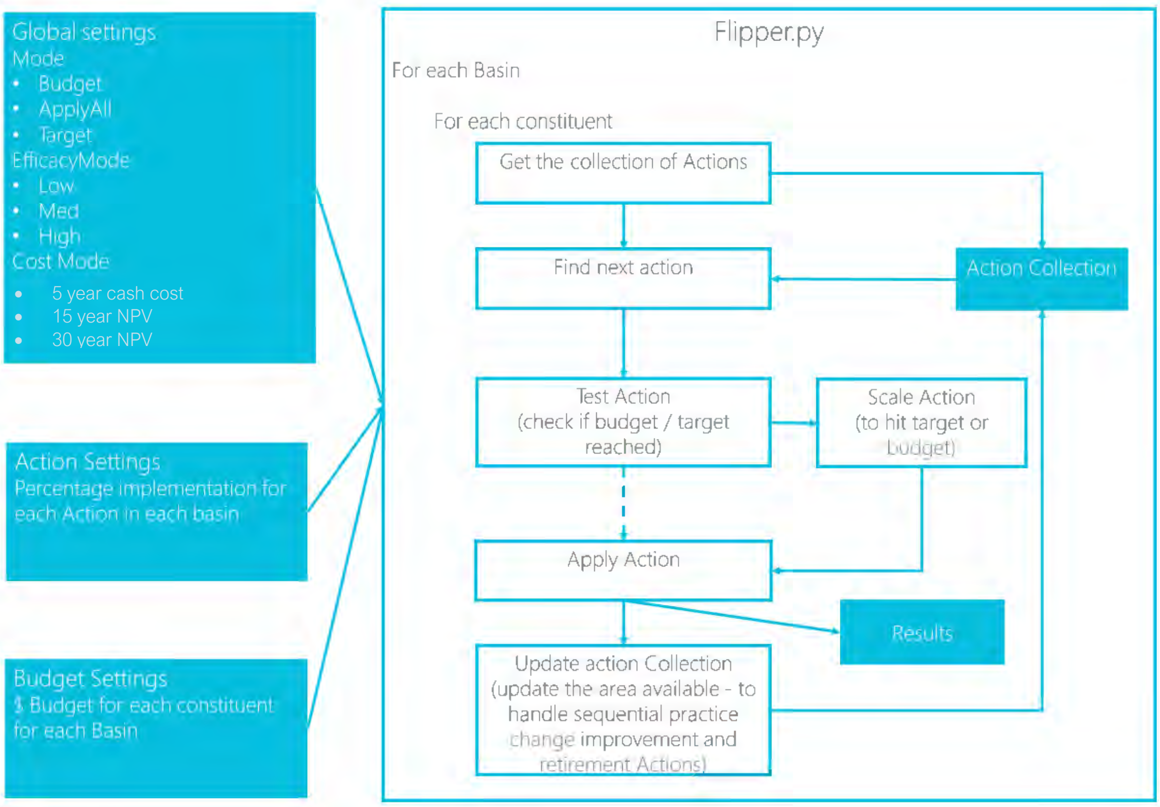


Figure 11. *Basic computational steps (inputs/tables as infilled boxes)*

The computational process is being developed based on the defined user requirements coupled with an understanding of the data available to drive the computational process. At the time of writing, the architecture of the computational process has been completed as a spreadsheet representation of the most straightforward case for use in algorithm testing. The definition of the input data structure has been agreed.

Subsequent steps are the full coding of the computational process. This will be followed by testing, firstly with mock data prepared in the correct input structure and subsequently with real data once available.

5.3 Interface design

Based on the agreed user requirements, mock ups which represent the tool interface have been prepared, revised by the project team and further discussed with GBRF. The agreed interface design is a single page application with a side settings panel, as shown in Figure 12 and Figure 13. Now that this design has been agreed it is not anticipated that many further modifications will be made during the current phase of this project. Following further consultation with the Project Working Group and the Peer Review Panel, a short User Manual for the tool has been produced based on the final version of the tool.

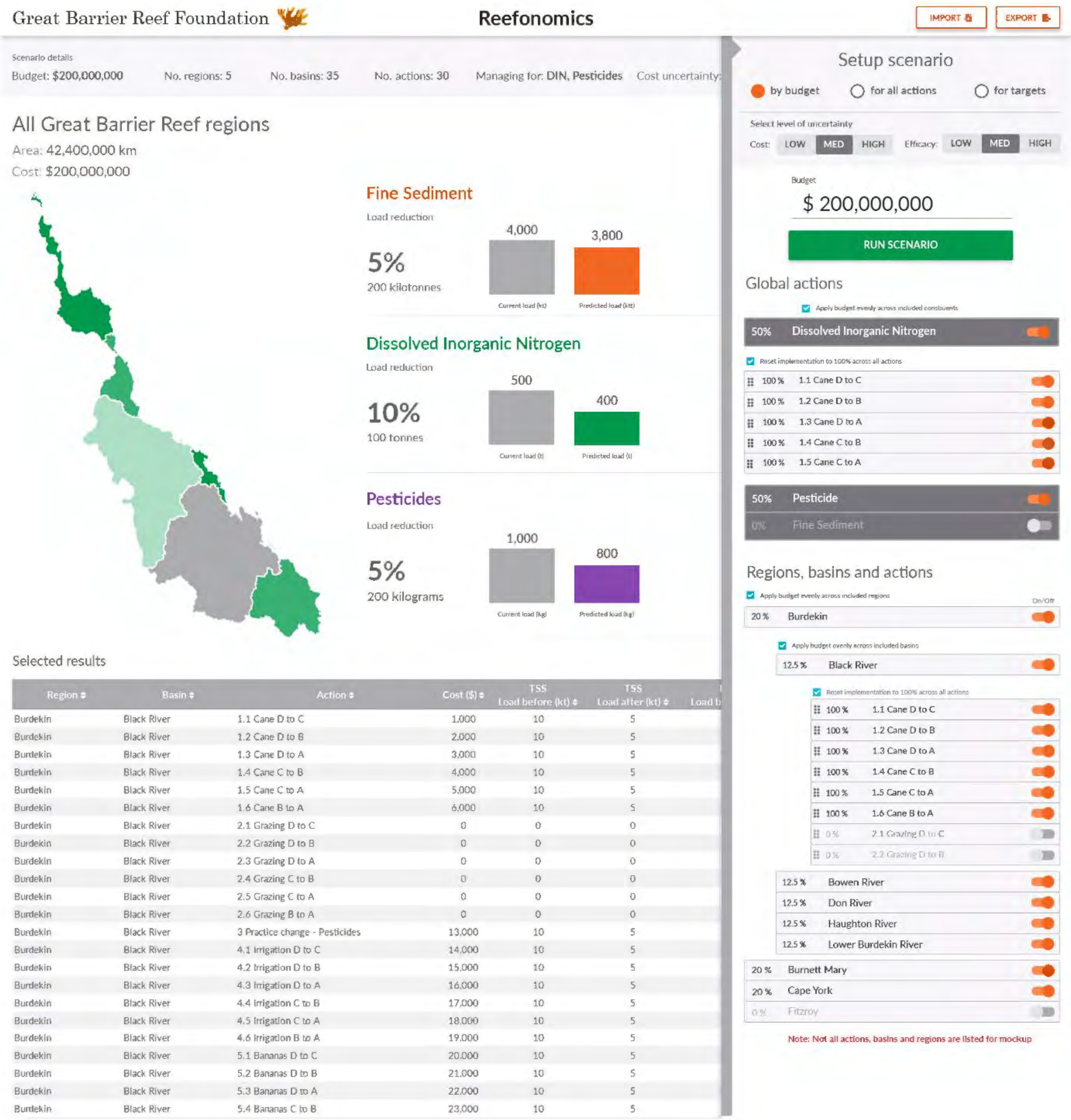
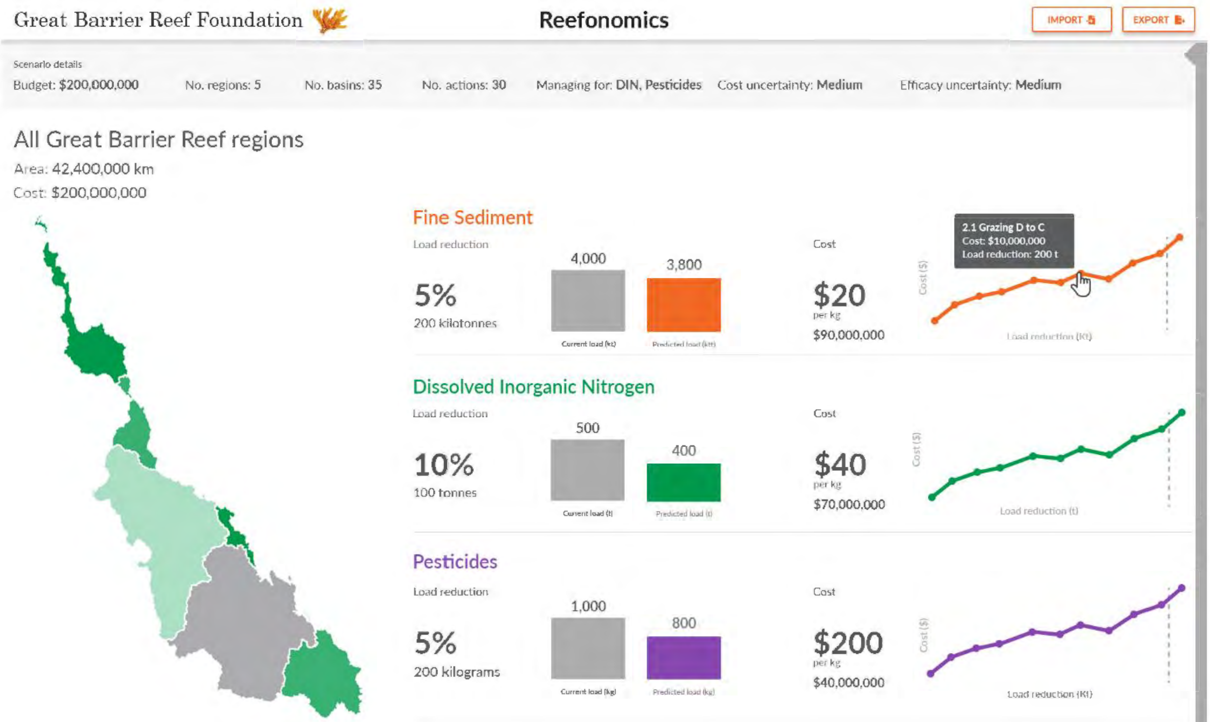


Figure 12. *Mock-up showing the side settings panel expanded*



Selected results

Download table

Region	Basin	Action	Cost ($)	TSS Load before (kt)	TSS Load after (kt)	DIN Load before (t)	DIN Load after (t)	Pesticide Load before (kg)	Pesticide Load after (kg)
Burdekin	Black River	1.1 Cane D to C	1,000	10	5	100	50	10	5
Burdekin	Black River	1.2 Cane D to B	2,000	10	5	100	50	10	5
Burdekin	Black River	1.3 Cane D to A	3,000	10	5	100	50	10	5
Burdekin	Black River	1.4 Cane C to B	4,000	10	5	100	50	10	5
Burdekin	Black River	1.5 Cane C to A	5,000	10	5	100	50	10	5
Burdekin	Black River	1.6 Cane B to A	6,000	10	5	100	50	10	5
Burdekin	Black River	2.1 Grazing D to C	0	0	0	0	0	0	0
Burdekin	Black River	2.2 Grazing D to B	0	0	0	0	0	0	0
Burdekin	Black River	2.3 Grazing D to A	0	0	0	0	0	0	0
Burdekin	Black River	2.4 Grazing C to B	0	0	0	0	0	0	0
Burdekin	Black River	2.5 Grazing C to A	0	0	0	0	0	0	0
Burdekin	Black River	2.6 Grazing B to A	0	0	0	0	0	0	0
Burdekin	Black River	3 Practice change - Pesticides	13,000	10	5	100	50	10	5
Burdekin	Black River	4.1 Irrigation D to C	14,000	10	5	100	50	10	5
Burdekin	Black River	4.2 Irrigation D to B	15,000	10	5	100	50	10	5
Burdekin	Black River	4.3 Irrigation D to A	16,000	10	5	100	50	10	5
Burdekin	Black River	4.4 Irrigation C to B	17,000	10	5	100	50	10	5
Burdekin	Black River	4.5 Irrigation C to A	18,000	10	5	100	50	10	5
Burdekin	Black River	4.6 Irrigation B to A	19,000	10	5	100	50	10	5
Burdekin	Black River	5.1 Bananas D to C	20,000	10	5	100	50	10	5
Burdekin	Black River	5.2 Bananas D to B	21,000	10	5	100	50	10	5
Burdekin	Black River	5.3 Bananas D to A	22,000	10	5	100	50	10	5
Burdekin	Black River	5.4 Bananas C to B	23,000	10	5	100	50	10	5

Figure 13. *Mock-up showing the settings panel closed.*

6 Discussion of cost-effectiveness results

Phase 4 of this project used the results of the outputs of Phases 2 and 3 to assess several scenarios, each of which consist of a suite of management actions across different basins. This process gave a detailed analysis of the results by providing an indication of the total impact and cost of a given action, as well as reviewing the risks around uncertainty in the estimates of efficacy and/or cost of given actions across the GBR.

This section provides a discussion of results, identifying key trends in cost-effectiveness of given management actions relative to other actions, and regional variations. The analysis is based on the most likely efficacy and most likely costs for each action and doesn't take into account the available load to be reduced by a given action in a given basin, or the reduction relative to the targets. More detailed and accurate results were derived through the scenario development process.

6.1 Nitrogen

The baseline and target loads for each basin for dissolved inorganic nitrogen (DIN) are shown in Figure 14. These are based on the results shown in Table 6 as provided by the Paddock to Reef modelling team from their 2016 Report Card work (see also Waters et al 2013). The solution sets with actions applicable to achieving a reduction in DIN loads include practice change for sugarcane (fertiliser and irrigation management) and bananas, treatment systems, point source load reduction and land use change.

An analysis of cost-effectiveness results using the most likely cost ($/ha) and most likely efficacy (percentage load reduction) indicates that the greatest opportunity for DIN load reduction is in the Wet Tropics, primarily through sugarcane practice change and land use change, with other opportunities in the Lower Burdekin (including the Haughton, BRIA and Delta sugarcane regions). Treatment systems were generally found to be much less cost-effective than practice change and, when included in the actions to achieve targets, significantly increased the overall costs.

Bananas were found to be within the least cost-effective set of actions available for reducing DIN, due to higher cost and lower efficacy compared with other actions.

In the Burdekin, land use change was determined to be similarly cost-effective to practice change.

In most regions, upgrades to sewage treatment plants (STPs) were found to be similarly cost-effective to other options involving engineered treatment systems, though the total load discharged from the STPs identified for upgrade was found to be relatively low compared with the total load from sugarcane. Furthermore, the data limitations for STP upgrades means that those results should be treated with extreme caution (see solution set for details).

In nearly all cases, based on the data available to date, treatment systems such as wetlands and bioreactors were found to be far less cost-effective than nearly all other actions.

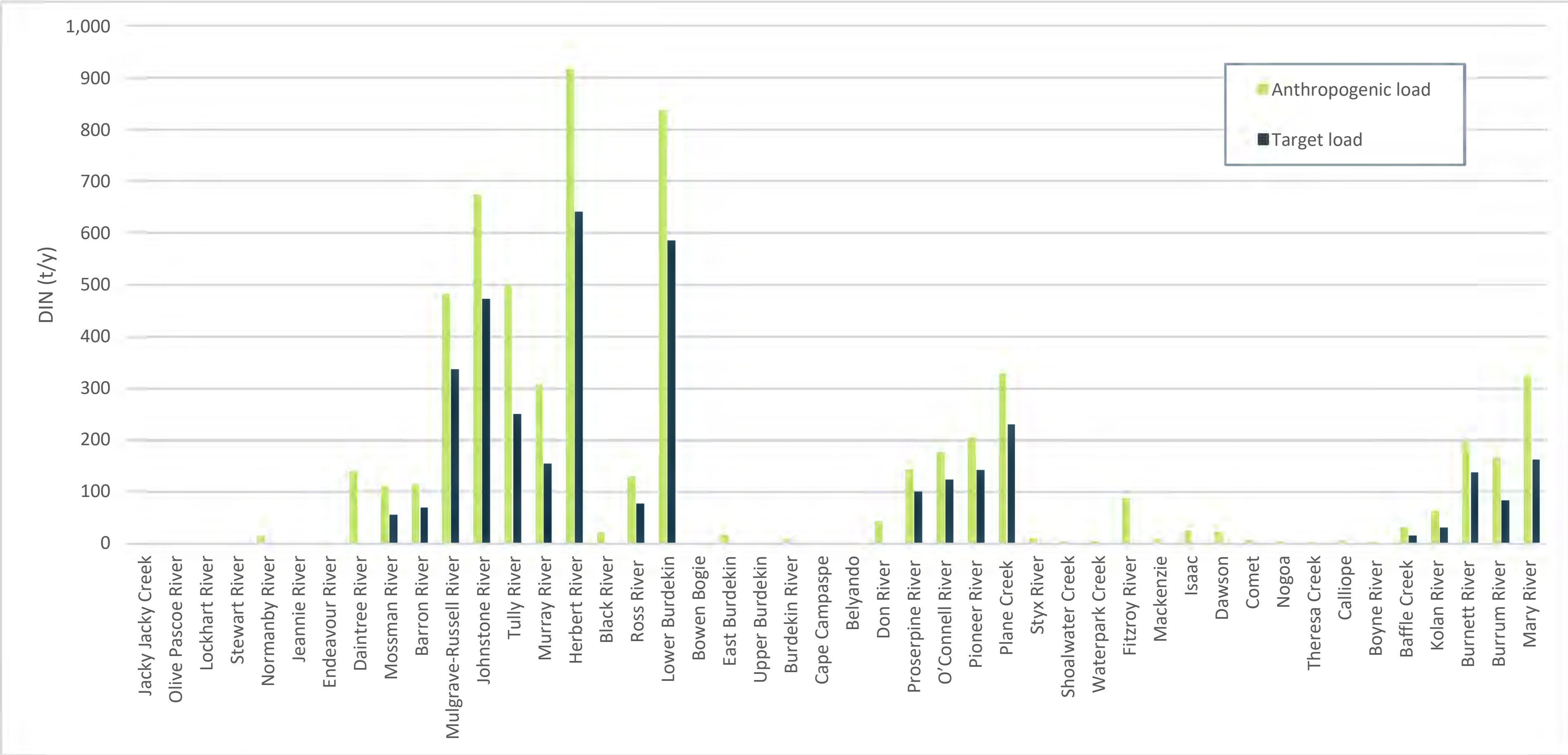


Figure 14. *Dissolved inorganic nitrogen (DIN) baseline anthropogenic loads (as per 2016 Report Card) and targets (according to percentage reduction targets from WQIP) by basin (see also* **Table 6***)*

6.2 Sediment

The baseline and target loads for each basin for fine sediment are shown in Figure 15. The solution sets with actions applicable to achieving a reduction in fine sediment loads include practice change for grazing, land use change, gully repair and streambank remediation.

An analysis of cost-effectiveness results using the most likely cost ($/ha) and most likely efficacy (percentage load reduction) indicates that the greatest opportunity for fine sediment load reduction is through grazing practice change (particularly from D to C practice), gully remediation, as well as streambank repair. The largest components of that are within the Burdekin NRM region, but also to a lesser extent the Herbert basin, Fitzroy NRM region and the Mary basin. Generally, lower intensity gully remediation (e.g. fencing, porous check dams) is similarly cost-effective to practice change.

While not specifically examined in this study, there is a growing body of literature examining the export of particulate nitrogen in the reef and how this may be converted to DIN in estuarine and marine environments. Efforts to reduce sediment loads may also be correlated with particulate N loads in that there will be co-benefits obtained if overall sediment loads are reduced, because some practices (such as streambank remediation, cover improvement) may also lead to reductions in particulate N. The extent to which this occurs was not examined by this study but is one for further consideration. We note that current work is being undertaken in this area through state agencies and research partners and could inform future iterations.

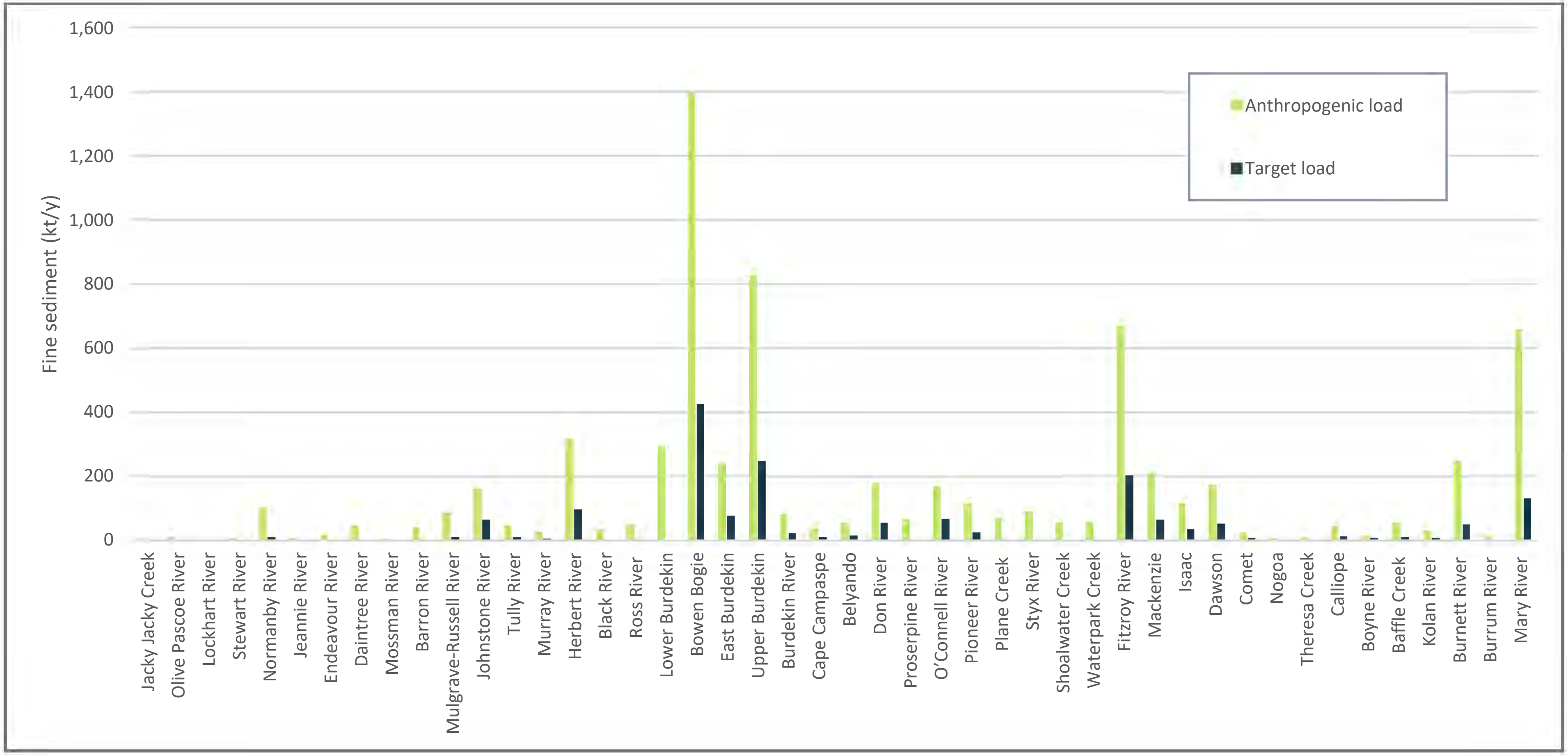


Figure 15. *Fine sediment baseline anthropogenic loads (as per 2016 Report Card) and targets (according to percentage reduction targets from WQIP) by basin*

6.3 Pesticides

The baseline and target loads for each basin for pesticides are shown in Figure 16. We note that the overwhelming majority of pesticide generation is in sugarcane regions. The solution sets with actions applicable to achieving a reduction in pesticide loads include practice change for pesticide use in sugarcane, and land use change from sugarcane. It is also highly likely that actions to reduce DIN may also assist in reducing pesticides, or there may be opportunities for co-benefits in combining nutrient and pesticide management actions, though in this analysis they have been considered mutually exclusive as there is insufficient information to account for these.

An analysis of cost-effectiveness results using the most likely cost ($/ha) and most likely efficacy (percentage load reduction) indicates that the cost-effectiveness for land use change is similar to sugarcane pesticide practice change from C to B practice. In the Wet Tropics, land use change was determined to be more cost-effective than practice change. When initial results were presented, concern was raised over the high cost-effectiveness values identified. Further discussion suggested this was related to a key capital expenditure component (high clearance tractor) as identified in the Water Quality Risk Framework. Our approach throughout the project has been to evaluate the costs and effectiveness of the major steps in transitioning from high to low risk in the framework and hence these costs were relevant. Subsequently, on the basis of stakeholder consultation, GBRF directed that the lower (ex-tractor) costs be used on the basis of advice of agronomy service providers that it is realistic to achieve substantial improvements in pesticide through practice change and with limited capital investment, as well as expectations that many landholders will already have high-clearance vehicles and/or that GBRF would not fund such purchases in any case.

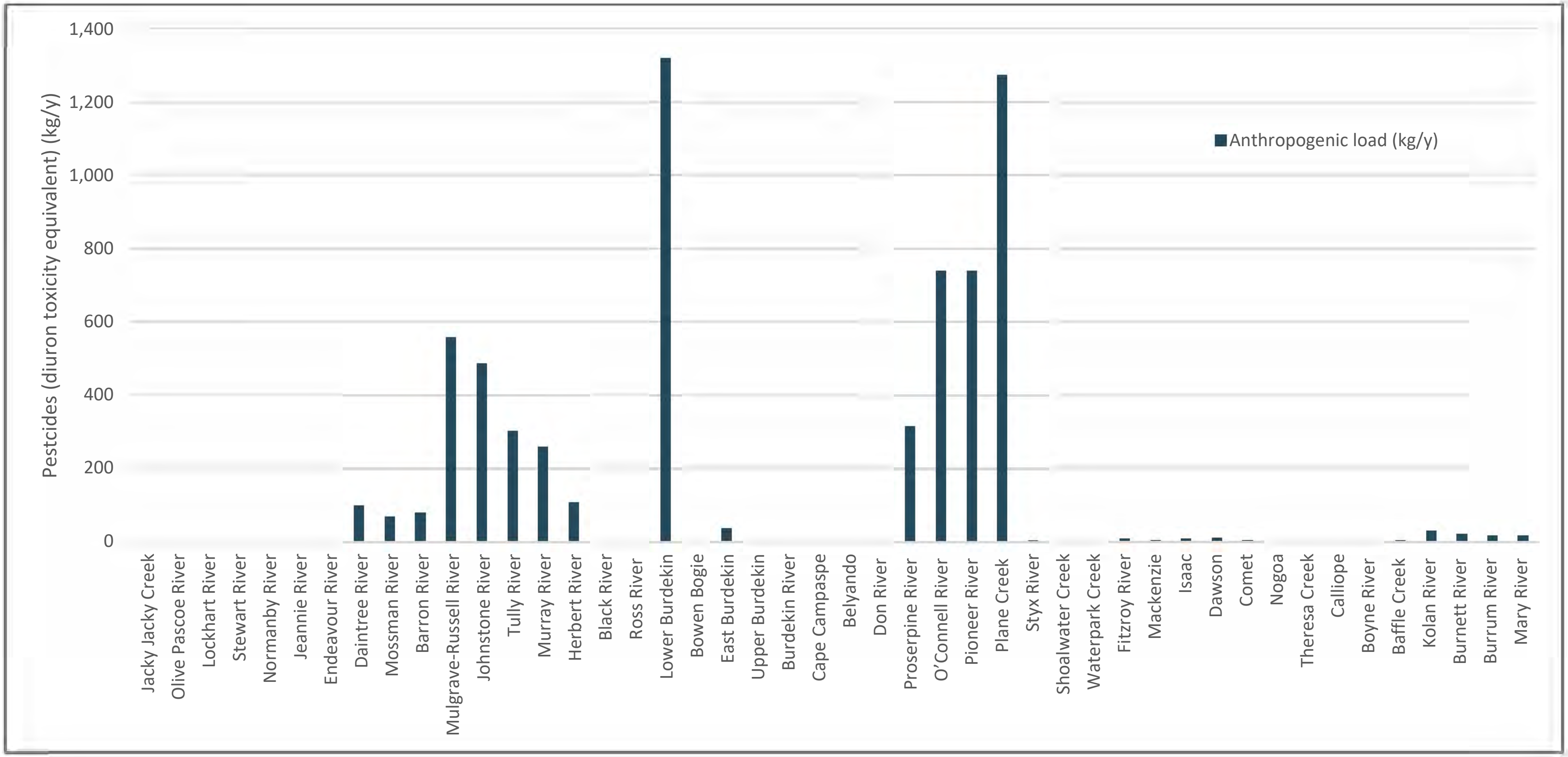


Figure 16. *Pesticides (diuron toxicity equivalent) baseline anthropogenic loads (as per 2016 Report Card) by basin*

7 Scenario development and assessment

The primary outcome of this project is to provide the necessary information to undertake assessments of different investment scenarios. Ultimately, this information needs to provide a clear line of sight between the underlying data, modelling and documentation and the final investment pathway chosen. To assist in this process, we have worked collaboratively with GBRF to develop and assess a range of scenarios quantitatively, but these also were examined through a values assessment in work commissioned by GBRF (Aurecon 2019). A summary of this process is shown below.

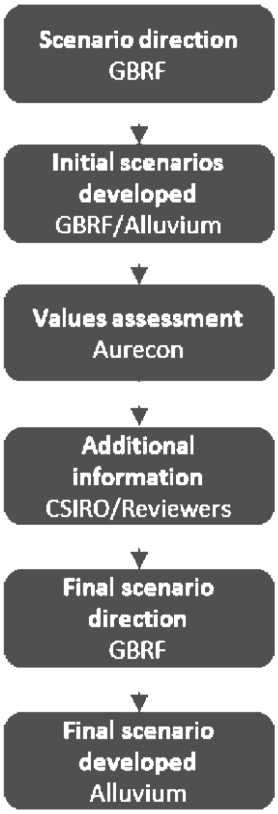


Figure 17. *Scenario process*

Initial direction on scenarios was provided by GBRF to be used as a basis to develop 12 separate scenarios. Each of these scenarios were then developed to prepare a list of actions using the information on cost-effectiveness, cost of the action selected, load reduction provided by the action and the amount of the target that was satisfied by the investment in the action. This resulted in lists of actions (in order from most cost-effective to least cost-effective) that would satisfy the scenario.

7.1 Scenario direction

The intent of the twelve scenarios was to capture a broad range of potential interventions, to assess the water quality benefits of different investment approaches, and to assess how those approaches align with a set of eight water quality investment “value drivers” that had developed through the Aurecon (Aurecon 2019)work.

The scenarios were constructed based on different approaches to allocating funding:

- between basins (e.g. based on priority level, NRM region)
- between target pollutants (e.g. giving greater or lesser priority to DIN vs. FS)
- between intervention types (generally the most cost-effective option was adopted, but in some instances, for example, practice change might be prioritised over other interventions, or vice versa).

Identifying options for scenarios involved balancing between (i) options that seemed 'most' likely and/or feasible with (ii) options that tested the boundaries of what might be considered acceptable.

Budget adopted for the scenarios

The Reef Trust Partnership (RTP) funding includes approximately $201M for water quality improvement activities. While the final allocations of funding had not been made at the time of this report, it was likely that a final investment amount of approximately $141M in regionally-focussed interventions would be available after other funding commitments had been satisfied. This was used as the upper bound for the scenario investment totals. In addition, a further $250M scenario was also considered to evaluate the effect of additional funding being made available (through government and non-government sources) and whether this would alter the likely investment pathway. It also should be noted that given that the modelling used in this report may not include all investments to date, the investments planned through the RTP may be in addition to that already being expended in some reporting basins. As such, coordination of different funding sources and deliverables will be essential.

7.2 Initial scenario development

The collation of information from the previous tasks was compiled into a single spreadsheet that considered the following components:

- NRM Region
- Reporting basin
- Area where the investment would be applied
- Untreated load
- Costs per ha of applied area
- Efficacy
- Cost-effectiveness

In constructing scenarios, and within the broader scenario constraints (e.g. budget available to a particular basin), interventions were selected based on cost effectiveness. That is, the most cost-effective intervention is adopted until the availability of that option is exhausted (e.g. based on the area of land available for gully remediation or a type of practice change).

The most cost-effective option is selected based on the 30-year net present value (NPV) for the intervention. This is to ensure that the most cost-effective option, over the long-term, is used. However, for the purposes of the costs included in the scenario, the 5-year actual costs are used, as these reflect the cost to GBRF of the investment. The following decision rules were used to select the actions:

- Choose action in the order of most cost-effective to least cost-effective
- If the action is not mutually exclusive (e.g. D to C or D to B practice change) then if first action doesn't satisfy scenario requirement, discard and use the next most cost-effective action (e.g. if D to C didn't achieve the requirement then it was discarded and D to B practice change used).
- The scenarios allow for no more than 40% of available practice change in a basin to be adopted in any scenario (i.e. 40% of the available area of the particular C or D class of practice). This is on the basis that it is not considered feasible to achieve more than that level of change over a 5-year period. Further discussion of this is presented in the non-cost risk analysis.
- Generally, the scenarios do not allow for practice change to 'A' practice, on the basis that this involves unproven approaches. However, for the purposes of the 'DIN only' and 'FS only' scenarios (scenarios 5 and 6), practice change to A was included. (However, in this case it is assumed that a landholder will move no more than 2 'steps' during the investment period. That is, a landholder might move from D to B, or C to A, but not from D to A).

- Scenarios do not allow for more than 40% of Type 3 gully work and 20% of the Type 1 Gully work to be included (i.e. 40% or 20% of the area of gully available for remediation), based on the feasibility of undertaking this extent of repair work, including the actual availability of suitable sites.
- Irrigation practice change (C to B) is generally a highly cost-effective action when the 30-year NPV is considered: it typically has a positive NPV over 30 years. However, this intervention has a relatively high 5-year (upfront) cost. Where this intervention applies, the scenarios assume that GBRF would only fund 10% of the 5-year cost, on the basis that there should be long-term benefits to landholders, with landholders thus to meet the rest of the up-front costs. Funding for this sort of intervention is likely to be in the form of financial incentives or loans.
- No more than 1% of the available land use change is adopted for any basin. This is to reflect the political challenges of potentially moving land out of productive use.

Approach to Pesticides
Due to uncertainty with the pesticide costs and targets identified in the previous tasks, the scenarios have reduced the funding allocated to this constituent, with an assumption that this would be held back until after a pesticide-focussed project that is being funded through the early investments grant round is completed and better information is available on efficacy and cost. Where funding for work on pesticides has been included in a scenario, the funding has been capped at $15m. This is generally split evenly between the 3 basins (1x VHP and 2xHP) where pesticides are identified as a priority in the WQIP.

Due to the modelling uncertainties, the tables for the scenarios that were originally assessed did not include estimates of the level of reduction in pesticide load. For the final scenario, these have now been included.

Approach to Reef Regulations
The modelling used in constructing the investment scenarios has assumed that in the case of cane and irrigation practice change, where an intervention will involve a landholder moving from 'D' practice to 'C' practice, then (i) the cost of moving from D to C is to be met by the landholder (i.e. not paid for by GBRF), on the basis that this is a regulatory requirement and (ii) the pollutant reduction is captured by the modelling, as part of showing progress towards target. In the final scenario, the amount of load reduction attributed to regulation compliance is shown.

Other issues
We recognise that there will be co-benefits from certain approaches. For example, reductions in FS will likely also reduce particulate nitrogen, with associated benefits for the Reef. These benefits are not captured in the modelling due to the difficulty of quantifying these benefits, but were considered (where appropriate) as part of assessing scenarios against the value drivers.

The relative cost-effectiveness of different interventions means that while the modelling incorporates 10 intervention types, some of these do not figure at all in the scenarios (e.g. sewerage treatment plants), and others only to a limited extent (e.g. treatment systems, land use change).

Scenario configuration
The table below shows a summary of the final scenario configurations trialled. Prioritisation (Very High, High, Medium etc) was adopted from the Ecologically Relevant Target prioritisation, in the assumption that this provides indications of where efforts should be focussed. The approach used as indicated above was to provide different approaches to investment pathways that could be considered, and it does not suggest that any or all of these would necessarily be achievable in their own right. The results of these were then used to consider the assessment of how these would address the value objectives determined in the Aurecon (Aurecon 2019) work.

Table 12. Scenario configurations

No	Name	Description	Notes
1	VHP Locations Only	- VHP basins only - $15m pesticides - Roughly even split between FS and DIN - Based on most cost-effective interventions available in VHP basins	- Gives utmost importance to the VHP regions identified in the WQIP. However, allows no progress towards the targets in HP (and lower priority) basins. - Allows for significant progress towards targets than more dispersed investment options. - Results in some interventions with a low cost-effectiveness. For example, this is one of only two scenarios that include treatment systems (dry weather recycle pits – cost effectiveness 2,065), which are significantly less cost-effective than many other options available in lower priority basins. Also includes some land use change (cane to conservation) which is significantly less cost-effective that practice change. - Provides for interventions that achieve more than 100% of the FS target for the Bowen Bogie, given the significant amount of highly cost-effective of actions available in that basin. This approach is included on basis that the target is only a sub-target of the overall Burdekin target, and it is assumed this reduction (beyond the local target) would provide equivalent reef benefits to achieving a similar reduction from other (less cost-effective) basins within the Burdekin.
2	VHP and HP, balanced portfolio (with pesticides)	- VHP and HP basins only - Roughly even split between basins (greater $ to VHP basins) - Roughly even split between FS and FIN - $15m pesticides	- Gives utmost importance to the VHP and HP regions identified in the WQIP. However, allows no progress towards the targets in lower priority basins. - Greater funding allocated to VHP basins compared to the HP basins. - While intention of scenario was to have relatively even split as between VHP basins, and as between HP basins, some pragmatic adjustments were made where allocating identical amounts to basins would require a much less cost-effective option to be adopted: in that case a higher allocation was made to the basin with the more cost-effective option. - Generally, allows for progress of 20-30% towards targets in the 13 basins where interventions are proposed. (Higher in Herbert and Bowen Bogie).
3	VHP and HP, balanced portfolio (no pesticides)	- As above, without pesticides	- As above, but without pesticides, resulting in greater progress on DIN and FS targets. - Compared with scenario 2, the additional funding (due to removal of pesticides) goes primarily to (i) DIN reduction in the Herbert (through land use change: cane to conservation,) and (ii) an additional $10m on Type 3 Gullies in the Bowen Bogie.
4	All NRM regions	- Split by NRM region, with regard to priorities - Wet Tropics and Burdekin $35m each - MW, Fitzroy, BM $20m each - Cape York $5m - Funding in each based on priority locations and cost effectiveness	- Provides for funding based on NRM region, as a basis for (potentially) greater regional 'fairness'. - Within those regions, funding is then allocated based on the WQIP priorities. - This is the only scenario where there is substantial funding made available to Cape York. - Results in higher DIN reductions than many of the scenarios focussed solely on VHP and HP basins, but a lower FS reduction.
5	DIN Only	- VHP, HP and MP basins only - DIN only	- Tests the impact of focussing on a single pollutant

No	Name	Description	Notes
		- Includes practice change to A. However, assumes a landholder moves no more than 2 steps in practice change (i.e. D-B, or C-A, but no D-A)	- Results in the adoption of a number of interventions with a low cost-effectiveness, e.g. a significant number of basins where land use change (cane to conservation) is allocated funding. - Compared with (for example) scenario 4, the DIN only scenario involves more than twice the budget for DIN activities, but achieves only 50% more reduction in DIN.
6	FS Only	- As above, but FS instead of DIN	- Similar to scenario 5 above
7	VHP for FS; balance for DIN and pesticides	- VHP basins only for FS, $40m - HP, VHP basins for DIN, $85m - HP, VHP basins only for pesticides, $15m	- Provides for greater investment in DIN, with FS limited to VHP basins and half the funding for DIN
8	VHP only for DIN, balance for FS and pesticides	- VHP basins only for DIN, $40m - HP, VHP basins only for FS, $85m - HP, VHP pesticides, $15m	- Compared with scenario 7, this approach results in substantially more funding for Burnett Mary and Fitzroy (compared with none in those regions under scenario 7) - Compared with scenario 7, this approach involves significantly less practice change
9	Limited practice change	- VHP and HP basins only - $30m for practice change, balance for other intervention types - No pesticides	- Investment skewed towards actions that are not as reliant on practice change - Recognises that practice change adoption is a slow process and there is significant anecdotal evidence of dis-adoption. - The scenario recognises that the modelled load reductions will be lower than some other options, but that this is offset by a lower investment risk profile and a lower delivery failure risk. - Pesticides could readily be incorporated into the scenario, noting that all the interventions related to pesticides involve practice change
10	Majority practice change	- VHP and HP basins only - $110m for practice change, balance for other intervention types - No pesticides	- Recognises that practice change is generally a cost-effective intervention - Would allow for a concerted effort at practice change, including potentially options for better coordination and generally improving the efficiency of extension works - Pesticides could readily be incorporated into the scenario
11	Most cost effective options in HP and VHP basins	- VHP and HP basins only - Even split between FS and FIN - $15m pesticides - Interventions based on most cost effective intervention	- Results in $84m in VHP basins, which is significantly more than in scenario 2 ($56m in VHP basins). Much of this additional investment is in the Bowen Bogie, with a much lower investment in the Fitzroy compared with scenario 2. The scenario 2 and 11 investments are otherwise similar. - Results in higher DIN and FS reduction that scenario 2.
12	Most cost effective option any location	- Any location - Even split between FS and FIN - $15m pesticides - Interventions based on most cost effective	- Achieves highest DIN and FS reductions, save for the FS only and DIN only scenarios - Results in a much larger number of interventions across a larger number of basins (around 26) - Results in a significant number of relatively small value interventions (<$100,000) - Gives no priority to areas identified as higher priority by the WQIP

7.3 Values assessment

As noted in the introduction, supporting work around a structured decision-making process was commissioned by the GBRF to examine the range of values associated with implementing the scale of investment planned within the GBR regions. The association of this work with the results presented here is shown in the figure below (repeated from Figure 1).

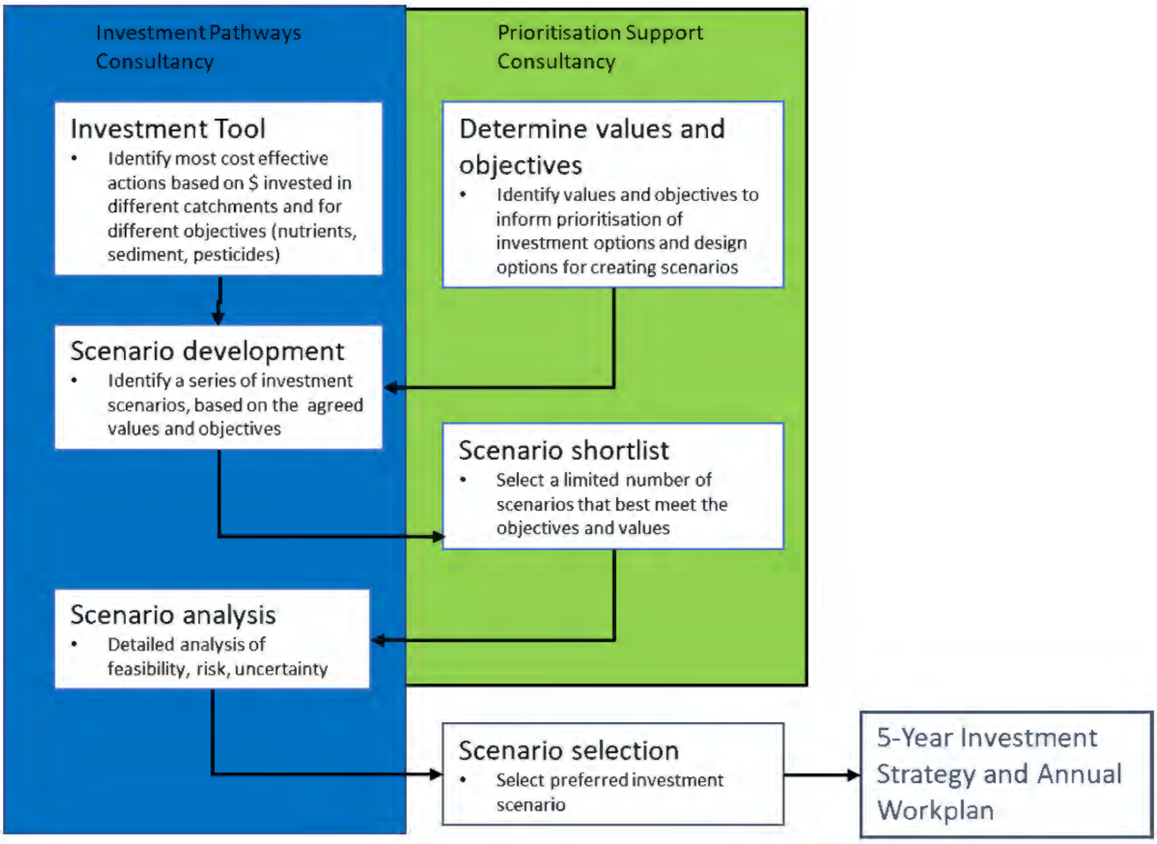


Figure 18. *Relationship of Investment Pathways Project and Prioritisation Support Consultancy and the GBRF Investment Strategy*

The results of the 12 scenarios were analysed through a consultative process to examine how they aligned with the values and objectives defined in the Aurecon work. The key messages that emerged from the analysis of the results, as well as the consultation were:

- The results strongly supported the inclusion of pesticides in the preferred scenario
- The results strongly supported significant investment in practice change
- Cost effectiveness of interventions was highly favoured
- WQ outcomes should be favoured above all other considerations, and for this regard must be had to the WQIP priorities
- Linked to this last point, there were some scenarios that arguably would not satisfy the requirements of the grant agreement around investing in priority areas. It was noted that while the overall intention was to present a set of scenarios, all of which satisfied the grant requirements, it was also necessary to include scenarios that tested the boundaries of what might be acceptable to see the consequence of that sort of approach.

In addition, considerable sensitivity analysis was also undertaken, looking at the full range of responses from different individuals. While this produced a range of outcomes, there were some consistent themes. Six of the scenarios were always in the bottom half of the scenarios, regardless of how the data was analysed. Similarly, three scenarios (2, 11 and 12) were consistently ranked at or close to the top of all groups of scenarios evaluated. These scenarios were:

- Scenario 2 - VHP and HP basins, with a fixed $ in each basin, more in VHP than HP. Those funds then used on the most cost-effective option in the relevant basin. E.g. this allocated $15m to sediment in the HP sediment basins (e.g. Fitzroy, Mary), which was then allocated for the most cost-effective options available.
- Scenario 11 - VHP and HP basins, with interventions based on the most cost effective option, where ever they are available (no priority to VHP over HP).
- Scenario 12 - most cost-effective action anywhere.

These three scenarios were the top three both for the average (not weighted) and average (weighted) scores. There was some variance associated with the sensitivity analysis, but they always remained in the top few options.

On that basis, GBRF determined that the final scenario should be based on a combination of the top ranking scenarios. This was primarily based on scenarios 2 and 11. It was assumed that scenario 12 did not meet the principles in the grant agreement that investments seek to address highest priority threats in the highest priority locations.

Overall, there wasn't a major difference between scenarios 2, 11 and 12 in terms of actual interventions. This is the case across all of the scenarios to a degree - the same interventions, representing the majority of the spend, were included in nearly all scenarios, due to their cost-effectiveness and their presence in high priority basins. (e.g. sediment work in the BBB).

This provided sufficient direction to consider the preparation of the final investment pathway scenario.

7.4 Additional information

Throughout the scenario development process, further information on the costs and efficacies of gully remediation were provided through Wilkinson et al 2019 and discussed with the technical review panel. This resulted in a significant adjustment in gully costs associated with assumptions made around gully density (length of gully per ha). Previous assessments that were completed in 2016 were originally used to develop gully costs. These assumed lower gully densities (length of gully per hectare of gully area) than that completed as part of the modelling associated with this project. This led to a mismatch between the costs and efficacies assumed which was rectified through subsequent re-analysis. There is still some uncertainty around the loading rates outlined in the Solution Statement for gullies, however this loading rate is provided for information purposes only and not used in the final modelling.

The change in cost-effectiveness was determined after the initial scenario runs were completed but only resulted in very minor changes in the ranking of cost-effectiveness. The only real impact was that the amount of sediment reduction achieved was reduced by approximately 10% as the lower intensity gully remediation was now less cost-effective than previously assumed (i.e. the investment assumed would not achieve as many tonnes of reduction).

Further information and consultation regarding pesticide costs were also considered during the peer review process. Based on directions from GBRF, the lower range costs were used on the basis of advice given to them by agronomy service providers that it is realistic to achieve substantial improvements in pesticide through practice change and with limited capital investment. There are also expectations that many landholders will already have high-clearance vehicles recommended in the Water Quality Risk Framework and/or that GBRF would not fund such purchases as part of their investments. The spreadsheet was then updated to provide cost results for pesticides such that the likely reductions achieved for a given investment could now be quantified.

Additional information on costs for fertiliser reductions through implementation of improved practice in the Lower Burdekin were provided by the Queensland State Government. These results indicated lower values for

$ per kg for reductions in Nitrogen applied as fertiliser through the application of the 6 Easy Steps framework (Connellan et al 2017). This information showed values in the range of $4.64-$9.09 per kg of fertiliser not applied to land, compared to our predictions of cost-effectiveness in the ranges of $100 - $3200 per kg of DIN not exported from the catchment. There are some fundamental differences in method between the Connellan et al 2017 work and this project, in that we focussed on the costs of whole steps in the water quality risk framework outlined in the Reef 2050 WQIP, whereas our understanding is that the 6 Easy Steps are one component of a step. We also were examining the impacts of DIN loads exported to the reef being reduced, not just in terms of reductions in kg of nitrogen applied to farm. There are a range of factors such as soil adsorption, crop uptake, and water retention that can alter the amount of DIN released per kg of N applied as fertiliser. Our understanding is that this is incorporated into the APSIM modelling provided by the Queensland State Government as part of this project. The results obtained from this work showed reductions in the order of 30-40% for DIN loads through transitioning from D to C practice, however exactly which step the 6 Easy Steps related to, and the challenge of converting from reductions in kg of Nitrogen applied compared to the quantities of Dissolved Inorganic Nitrogen delivered to the reef further complicates the direct use of the Connellan et al 2017 data.

7.5 Final revised scenarios

Based on the above process steps, a final scenario was developed for the investment pathway. This was the result of internal decisions within GBRF and advice from the WQ working group and was based on the outcomes of the structured-decision making process (SDM process).

The final scenario directions were:

- Total scenario investment value of $140m
- Funding allocation
  - $15m for pesticides – on basis that the SDM process identified value in investing in pesticides, but that there is greater uncertainty with respect to pesticide interventions, cost, and efficacy, and due to the relative loads across the three priority pollutants
  - $62.5m for each of FS and DIN - on basis that the SDM process identified each as of relatively equal importance
- Only VHP and HP locations under the WQIP (for the relevant pollutant)
- For pesticides:
  - $11m in Mackay Whitsunday - Plane Ck ($7m, VHP) and Pioneer ($4m, HP)
  - $4m in Lower Burdekin (HP)
- For DIN
  - Available funding allocated within VHP and HP basins on basis of most cost-effective intervention available
  - Practice change capped at 40% of available, on assumption that it is not feasible to shift more that this % over the 5-year window.
  - For irrigation practice change, program to fund max of 10% of up-front costs.
  - Land use change capped at 1%, to minimise impacts on productivity and viability of cane industry
  - No practice change beyond B to be included
- For FS: starting point of scenario 11
  - Cap at 20% for Type 1 and 40% for Type 2. These values to be adjusted on catchment-by-catchment basis recognising capacity constraints.
  - Wherever possible, gully restoration and grazing practice change to be linked together – i.e. both interventions to be adopted in same catchment. Average cost-effectiveness across the 2 intervention types to be considered.
  - Cap total expenditure on FS in the Burdekin at approx. $30m, having regard to capacity to deliver. Further adjusted where required to provide for appropriate load reductions and linkage to grazing practice change.
  - If apportioning between basins with same priority and interventions with similar cost-effectiveness, then look to apportion with consideration for (i) delivery capacity in each basin and (ii) the total load reduction targets for the basins, i.e. with greater funding to basins with a greater load reduction target.

- Identify for DIN and FS what and where the next most cost-effective interventions would have been, i.e. where the final decision points are as we approach the limit of the available funding.
- When selecting the most cost-effective action, these are to be based on 30-year NPV
- Consider exclusion of interventions if the size of the intervention available is sufficiently small that the cost-effectiveness will be significantly reduced due to (fixed) program costs. As part of this consider if the intervention can be linked with other interventions.
- For Regulations:
    - For Cane - assume that 40% of D has moved to C at no cost to GBRF and is available for practice change from C-B. Load associated with D to C to be included in overall progress towards targets, but accounted for separately
    - For Grazing – allow for program to fund D to C .

From the above, a final scenario was then constructed using all information obtained to date.

Table 13. Final Scenario - DIN

Region	Basin	Priority	Pollutant	$	Intervention	Cost effectiveness (5yr) ($/kg)	DIN Reduction (t)	DIN Target (t)	% to DIN target	Reduction due to regulation (D to C) (t)
Wet Tropics	Herbert River	VHP	DIN	$1,890,000	Cane C to B (40%)	$70.58	26.8	641.0	4%	
Wet Tropics	Herbert River	VHP	DIN	$8,080,000	Cane D to B (40%)	$168.40	159.8	641.0	25%	52.1
Wet Tropics	Herbert River	VHP	DIN	$6,260,000	Cane to conservation (1%)	$690.98	9.1	641.0	1%	
Wet Tropics	***Herbert River***			***$16,200,000***			***195.7***	***641.0***	***31%***	
Wet Tropics	Johnstone River	HP	DIN	$2,090,000	Cane C to B (40%)	$48.36	43.2	471.4	9%	
Wet Tropics	Johnstone River	HP	DIN	$2,530,000	Cane D to B (40%)	$105.67	79.6	471.4	17%	26.0
Wet Tropics	Johnstone River	HP	DIN	$2,300,000	Cane to conservation (1%)	$428.95	5.4	471.4	1%	
Wet Tropics	***Johnstone River***			***$6,920,000***			***128.2***	***471.4***	***27%***	
Wet Tropics	Mulgrave-Russell River	HP	DIN	$1,050,000	Cane C to B (40%)	$55.19	19.0	336.7	6%	
Wet Tropics	Mulgrave-Russell River	HP	DIN	$3,100,000	Cane D to B (40%)	$136.10	75.7	336.7	22%	24.7
Wet Tropics	Mulgrave-Russell River	HP	DIN	$2,060,000	Cane to conservation (1%)	$500.77	4.1	336.7	1%	
Wet Tropics	***Mulgrave-Russell River***			***$6,200,000***			***98.8***	***336.7***	***29%***	
Wet Tropics	Tully River	HP	DIN	$1,000,000	Cane C to B (40%)	$43.80	22.8	249.7	9%	
Wet Tropics	Tully River	HP	DIN	$2,130,000	Cane D to B (40%)	$108.14	65.5	249.7	26%	21.3
Wet Tropics	Tully River	HP	DIN	$1,570,000	Cane to conservation (1%)	$401.86	3.9	249.7	2%	
Wet Tropics	***Tully River***			***$4,690,000***			***92.2***	***249.7***	***37%***	
Burdekin	Lower Burdekin	VHP	DIN	$9,310,000	Cane D to B (15%)	$673.93	26.7	585.3	5%	26.1
Burdekin	Lower Burdekin	VHP	DIN	$7,100,000	Irrigation C to B Level 2 (40%)	$1,493.73	47.5	585.3	8%	
Burdekin	***Lower Burdekin***			***$16,400,000***			***74.3***	***585.3***	***13%***	
Mackay/Whitsundays	Plane Creek	HP	DIN	$8,710,000	Cane D to B (40%)	$376.39	65.2	230.5	28%	38.6
Mackay/Whitsundays	Plane Creek	HP	DIN	$2,940,000	Cane C to B (40%)	$441.06	6.7	230.5	3%	
Mackay/Whitsundays	***Plane Creek***			***$11,700,000***			***65.2***	***230.5***	***28%***	

Table 14. Final Scenario – Fine Sediment (FS)

Region	Basin	Priority	Pollutant	$	Intervention	Cost effectiveness (5yr) ($/kg)	FS Reduction (kt)	FS Target (kt)	% to FS target
Burdekin	Bowen Bogie	VHP	FS	$6,130,000	Grazing D to C (40%)	$0.03	196.8	426	
Burdekin	Bowen Bogie	VHP	FS	$1,960,000	Gully Type 1 Treatment (10%)	$0.04	44.9	426	
Burdekin	Bowen Bogie	VHP	FS	$19,300,000	Gully Type 3 Treatment (10%)	$0.21	89.9	426	
Burdekin	***Bowen Bogie***			***$27,300,000***			***331.6***	***426***	***78%***
Burdekin	East Burdekin	VHP	FS	$1,040,000	Grazing D to C (40%)	$0.07	15.5	75	
Burdekin	East Burdekin	VHP	FS	$489,000	Gully Type 1 Treatment (10%)	$0.09	5.4	75	
Burdekin	***East Burdekin***			***$1,530,000***			***20.9***	***75***	***28%***
Fitzroy	Fitzroy River	HP	FS	$5,970,000	Grazing D to C (40%)	$0.34	17.4	201	
Fitzroy	Fitzroy River	HP	FS	$9,990,000	Streambank repair (10%)	$0.37	27.3	201	
Fitzroy	***Fitzroy River***			***$16,000,000***			***44.7***	***201***	***22%***
Wet Tropics	Herbert River	HP	FS	$1,040,000	Grazing D to C (40%)	$0.17	6.0	95	
Wet Tropics	Herbert River	HP	FS	$2,410,000	Streambank repair (5%)	$0.37	6.5	95	
Wet Tropics	***Herbert River***			***$3,450,000***			***12.5***	***95.***	***13%***
Fitzroy	Mackenzie	HP	FS	$3,610,000	Grazing D to C (20%)	$0.59	6.1	63	
Fitzroy	***Mackenzie***			***$3,610,000***			***6.1***	***63***	***10%***
Burnett Mary	Mary River	HP	FS	$9,400,000	Streambank repair (12.5%)	$0.33	28.3	132	
Burnett Mary	***Mary River***			***$9,400,000***			***28.3***	***132***	***22%***
Burdekin	Upper Burdekin	VHP	FS	$2,560,000	Grazing D to C (40%)	$0.11	22.7	245	
Burdekin	***Upper Burdekin***			***$2,560,000***			***22.7***	***245***	***9%***

Table 15. Final Scenario – PSII Pesticides

Region	Basin	Priority	Pollutant	$	Intervention	Cost effectiveness (5yr) ($/kg)	Pest reduction (kg)	Pest anthropogenic load (kg)	% of anthropogenic load
Mackay Whitsunday	Plane Creek	VHP	Pesticides	$7,000,000	Pesticides C-B (16%)	$52,312	133.8	1271.4	11%
Mackay Whitsunday	Pioneer	HP	Pesticides	$4,000,000	Pesticides C-B (18%)	$46,307	86.4	737.7	12%
Burdekin	Lower Burdekin	VHP	Pesticides	$4,000,000	Pesticides C-B (4%)	$109,723	36.5	1318.7	3%

Table 16. Final Scenario – NRM Region Summary

	DIN	Pesticides	Fine Sediment	Total
Wet Tropics	$34,000,000		$3,450,000	$37,500,000
Burdekin	$16,400,000	$4,000,000	$31,400,000	$51,800,000
Mackay Whitsunday	$11,700,000	$11,000,000		$22,700,000
Fitzroy			$19,600,000	$19,600,000
Burnett Mary			$9,400,000	$9,400,000
	$62,100,000	$15,000,000	$63,900,000	$141,000,000

8 Non-cost risk assessment

When considering the initial project, a component that we wanted to focus on was the evaluation of implementation factors or non-cost risks which may influence the costs and efficacy of a particular action. As the project progressed, it was the intention that this may inform GBRF and relevant stakeholders as to whether there were clear investment choices and that this would form part of investment decision process. Ultimately, the decision process used the values and objectives process as one of the methods to evaluate more anecdotal and non-numerical considerations, which obtained inputs from a range of experienced practitioners. Even so, the issues surrounding implementation still exist, however there is a significant lack of information on which to make a more quantitative assessment of these risks and it was therefore difficult to evaluate these in a quantitative fashion.

Ultimately, the non-cost risks will influence the ability to achieve the required outcomes for the level of investment planned. We believe that there is still value by documenting these factors, and describing how they may influence the ability to implement an action and/or whether that action is able to achieve the efficacy suggested by the modelling. As such, we have qualitatively assessed the action types identified in the final scenario such that these can be more fully explored prior to a proper implementation process being formulated. These are set out in the tables below.

Further discussion on the risk factors is provided in Section 4.3. The information provided in the tables below is indicative only and would benefit from considerable further consultation with key practitioners in the reef space.

Table 17. Non-cost risks - DIN

Action	Non cost risk component								
	Adoption				*Efficacy*				**Assumed level of overall adoption**
	Participation	**Implementation**	**Affordability***	**Disadoption**	**Scientific & technical uncertainty**	**Design and location**	**Application**	**Operational**	
Cane Practice Change (C to B)	May be more challenging to demonstrate that the additional complexity of moving from C to B is consistent with the effort required.	Higher complexity may limit widespread adoption as would require more dedicated effort for implementation	More costly to implement per unit area, but where farm profit improvement can be demonstrated, then adoption would not be greatly affected	Without ongoing support and demonstration that effort is worth, may be challenging to retain adoption.	While modelling is advanced, there are still some uncertainties that may affect efficacy	Design components well understood so efficacy mainly influenced by location	Possibility of inconsistent application within and across regions without considerable coordination effort	Likely to become part of day to day farm practice, therefore unlikely to significantly alter efficacy.	*Maximum uptake less than half - assume 40% (as per Section 4.3)*
Cane Practice Change (D to B)	Likely to be high given regulatory drivers	Likely to be high given regulatory drivers	Regulatory requirement and low cost so unlikely to influence adoption	Regulatory requirement so likely to retain practice improvement for D to C component, but C to B risk as per above	While modelling is advanced, there are still some uncertainties that may affect efficacy	Design components well understood so efficacy mainly influenced by location	Possibility of inconsistent application within and across regions without considerable coordination effort	Likely to become part of day to day farm practice, therefore unlikely to significantly alter efficacy.	*Maximum uptake greater for D to C component, but C to B step will be limiting factor, so assume 40% as per C to B*
Cane to conservation	Possibly highly contentious in some locations but intent was that would allow for transition out of marginal land	Relatively simple to implement from landholder perspective	Low cost-to implement per unit area but would need to be compensated for loss of land	Unlikely to be significant once land use change is complete	Considerable uncertainty in the modelling but intuitively correct.	Design component relatively simple so efficacy mainly influenced by location	Action is mostly associated with lower level tasks which are well understood (fencing and reveg)	Some uncertainty as to who will have responsibility for upkeep so may deteriorate over time.	*Uncertain as to overall social impact which needs further consideration. Suggest limit to pilot scale initially*
Irrigation C to B Level 2	Profitable if implemented so should encourage wider participation if net benefit to landholder	Infrastructure requirements well supported and understood, so unlikely to limit adoption	Higher up front costs balanced by improvement in farm profit	Unlikely to be significant risk given net benefit	While modelling is advanced, there are still some uncertainties that may affect efficacy	Considerable uncertainty in the modelling but intuitively correct.	Action is well understood in irrigation industry so unlikely to affect efficacy	More complex infrastructure so without ongoing funding for operation, may reduce performance	*Given net profitability, unlikely to want to fully fund actions where net benefit only comes back to landholder*

* Affordability may not be a significant factor given funding is being provided – however may influence ongoing implementation beyond funding.

Table 18. Non-cost risks – Fine Sediment

Action	Non cost risk component								
	Adoption				*Efficacy*				Assumed level of overall adoption
	Participation	Implementation	Affordability*	Disadoption	Scientific & technical uncertainty	Design & location	Application	Operational	
Grazing D to C	Existing evidence suggests difficulty in achieving widespread engagement. If part of regulatory compliance then less impact on adoption	Relatively simple to implement, unlikely to influence adoption	Some concerns over impacts to farm profitability, need to ensure appropriate information available	May be some disadoption if not a regulatory requirement.	Not confirmed by modelling but intuitively correct i.e. improving cover will reduce sediment generation	Very straight forward design so efficacy mainly influenced by location	Very straight forward so unlikely to influence efficacy	Will become part of farm practice	Limited by extension effort. Existing evidence suggests upper limit is less than half of all landholders – suggest 40% *(as per Section 4.3)*
Gully Type 1 Treatment	Will be largely non-landholder led to identify sites, but needs to be coordinated with the landholder and also integrated with practice change	Some resistance to porous check dams which may limit implementation	Low cost measures	Once implemented, needs ongoing inspection and maintenance to ensure it doesn't fall into disrepair	Not confirmed by modelling (results are based on field assessments with high variability) but intuitively correct i.e. slowing down flows and restricting stock access will lead to improvement	Simple measures that are easy to design consistently, with location addressed by site selection (see Participation)	Simple application with tasks well understood	Will require ongoing inspection and maintenance to ensure it maintains full efficacy	Only limited by funding and site identification
Gully Type 3 Treatment	Will be largely non-landholder led	May not be possible in all areas. Existing works show that targeted implementation most beneficial	Considerable expense	Once implemented, needs ongoing inspection and maintenance to ensure it doesn't fall into disrepair	Not confirmed by modelling but intuitively correct i.e. complete rehabilitation of erosion source	Highly site specific and complex, so may provide significant challenges to effective design in some locations	Highly site specific and complex, so may provide significant challenges to construction in some places	Will require ongoing inspection and maintenance to ensure it maintains full efficacy	Only limited by funding and site identification

Action	Non cost risk component								
Streambank repair	Will be largely non-landholder led	Complex to implement so may not be able to complete in all areas (susceptible to site factors)	Considerable expense	Once implemented, needs ongoing inspection and maintenance to ensure it doesn't fall into disrepair	Not confirmed by modelling (results based on field observations only) but intuitively correct i.e. complete rehabilitation of erosion source.	Highly site specific and complex	Highly site specific and complex	Will require ongoing inspection and maintenance to ensure it maintains full efficacy	Only limited by funding and site identification

* Affordability may not be a significant factor given funding is being provided – however may influence ongoing implementation beyond funding

9 Conclusions

This project has developed and used a marginal abatement cost curve approach to estimate the relative costs effectiveness of management interventions for future investment targeted at improving water quality entering the Great Barrier Reef Lagoon, including the Great Barrier Reef Foundation's investment in water quality as part of the Reef Partnership. To do this the project:

Used scientific modelling at the point of pollutant abatement for three key constituents (Dissolved Inorganic Nitrogen, fine sediment and pesticides) to assess the efficacy of individual types of interventions (including regionally-specific paramaters),

- Source modelling was then used to determine the resultant changes in pollutant loads at the end of catchment as a result for each of the management interventions.
- The economic modelling considered life cycle costs at the point of abatement which were adjusted using the project's modelling outputs to provide lifecycle costs of abatement at the end of catchment. Furthermore, the investment costs to the GBRF for the next five years were also estimated.
- Where data permitted, significant sensitivity analysis was also undertaken to better understand the potential variability in overall costs effectiveness of alternative actions.
- The development of the user friendly front-end of the model enables end-users to run highly complex investment scenarios instantaneously, including within the mapped constraints of possibilities for change (e.g. areas available for investment).

In combination, these components of the project have resulted in an approach and tool that is arguably the most comprehensive (pollutants, regions, investment options and the sophistication of scenario development) and practical ever developed.

In addition, the project used a consultative process to elicit appropriate data, establish the investment framework, and develop the investment scenarios for consideration. This included additional work in a parallel project by Aurecon (Aurecon 2019), to select a final preferred investment scenario.

Outputs from this project will ultimately allow investors to assess and compare alternative portfolios of management interventions for the three constituents investigated, across the 46 sub-catchment basins that flow into the GBRF lagoon.

Key project findings

This project developed a total of 12 scenarios that were considered against a range of quantitative and qualitative criteria. Using the work from both these pieces of work, as well as a significant expert opinion/peer review process, a final scenario was agreed to guide the next phase of the GBRF's investment in water quality management actions.

The work from this project was utilised as an input into finalising GBRF's Five Year Investment Strategy (and Annual Workplan) for the Water Quality Component of the Reef Trust Partnership.

Importantly, investment in this scenario results in significant progress towards the updated regional water quality targets for the GBR in priority locations, in accordance with the objectives stated in the Reef Trust Partnership Grant Agreement. The proposed Reef Partnership investment does not however reach the targets across the 46 basins, reflecting both the nature and scale of issues that need management intervention, and therefore the magnitude of investment required to address them.

It is important to note that whilst every effort has been made to incorporate the best available science and information from relevant stakeholders to guide this work and therefore future investment, there remain opportunities to further improve the data utilised in any future versions of this work. In terms of the biophysical data, this includes better understanding of the efficacy of specific management interventions. Similarly, there are opportunities to improve the extent and quality of the economic data available across the suite of management interventions, which is why this project used a sensitivity analysis approach to ensure the findings derived from the available data were as robust as possible. Furthermore, robust information regarding long-term levels of disadoption is patchy at best. This creates a significant compliance risk for investors and emphasises the need for a robust long-term monitoring and evaluation framework.

Potential next steps

While this project makes a significant step forward in the efficient investment in load abatement in the GBR, it is just part of a cohesive, effective and efficient approach to investment. A range of potential next steps have been identified that would be beneficial to GBRF and other investors to ensure outcomes being achieved are both realistic and efficient. These are as follows:

- **Consistency in high-level investment decisions.** That wherever possible this work is utilised to help inform future investment in water quality-related initiatives linked to the GBR. This should include investment by the State and other investors. This will ensure that duplication of effort is avoided, investments strategies are cohesive across multiple investors, and that higher-level investment decisions are being made in a relatively consistent way.
- **Establish enduring and effective delivery partnerships.** The GBRF will need to further establish robust and enduring partnerships with key delivery agencies that provide the conduit between investment funds and on-ground change. This will require a degree of consistency in the on-ground delivery approaches used, while still enabling sufficient regional variability to reflect local circumstances and needs.
- **Design effective and efficient on-ground incentive approaches.** Further consideration needs to be given to regional variations in on-farm activities linked to the implementation of the preferred management interventions, including their private costs and benefits. This is important for the future design of any incentive mechanisms that may be developed to assist investment processes. This would infer that investments should be made using 'price-discriminatory' approaches (or similar) wherever possible to ensure that the GBRF is achieving genuine value for money. Clever design of incentives pays dividends for investors via greater efficiency gains.
- **Recycle financial capital when possible.** Some management interventions such as improved irrigation efficiency (particularly water use efficiency) have identified long-term commercial benefits to landowners. Under these circumstances it may be more appropriate to utilise concessionary lending approaches to fund projects, enabling capital to be recycled as part of the overall investment framework adopted. Again, it is the design and implementation of the on-ground programs that can deliver much of the efficiency gains.
- **Robust monitoring and evaluation that targets investors' needs is required.** There is a need for any investment to have robust monitoring and evaluation processes in place to ensure that the water quality gains (load reductions) being sought are not only achieved, but also enduring. This would provide valuable information that could be used to further improve the modelling (e.g. did the investment achieve the level of abatement expected?) and, as a result, reduce the risks to future investors. This is fundamental to establishing genuine investor confidence, particularly if the GBRF is to 'crowd-in' investment from other sources. Furthermore, the lessons from the monitoring and evaluation should be used to periodically update and enhance the model developed by this current project.

The above-mentioned next steps should ensure transformative gains can be made through the GBRF investment on the Reef.

10 References

Alluvium (2016). Costs of achieving the water quality targets for the Great Barrier Reef by Alluvium Consulting Australia for Department of Environment and Heritage Protection, Brisbane.

Alluvium (2018). Effective and Efficient Pathways for Investment in Improved Water Quality in the Great Barrier Reef Report 1: Methods and Input Report. A report for the Great Barrier Reef Foundation, Brisbane.

Aurecon (2019). Reef Trust Partnership Water Quality Investment Planning v2, reference 505646. A report for the Great Barrier Reef Foundation, 24th May 2019.

Baheerathan R, Ellis R, Fentie B, McCloskey GL, Waters D, (2017), Assessment of the GBR Source Catchments model to estimate fine-sediment streambank erosion and export, 22nd International Congress on Modelling and Simulation, Hobart, Tasmania, December 2017.

Bartley, R., Waters, D., Turner, R., Kroon, F., Wilkinson, S., Garzon-Garcia, A., Kuhnert, P., Lewis, S., Smith, R., Bainbridge, Z., Olley, J., Brooks, A., Burton, J., Brodie, J., Waterhouse, J., 2017. 2017 Scientific Consensus Statement: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 2: Sources of sediment, nutrients, pesticides and other pollutants to the Great Barrier Reef. Published by the State of Queensland, 2017.

Centre for Tropical Water & Aquatic Ecosystem Research (2017). Development of basin-specific ecologically relevant water quality targets for the Great Barrier Reef. TropWATER Report number 17/38. James Cook University, Townsville.

Eberhard, R., Thorburn, P., Rolfe, J., Taylor, B., Ronan, M., Weber, T., Flint, N., Kroon, F., Brodie, J., Waterhouse, J., Silburn, M., Bartley, R., Davis, A., Wilkinson, S., Lewis, S., Star, M., Poggio, M., Windle, J., Marshall, N., Hill, R., Maclean, K., Lyons, P., Robinson, C., Adame, F., Selles, A., Griffiths, M., Gunn, J., McCosker, K., 2017. Scientific Consensus Statement: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 4: Management options and their effectiveness. State of Queensland, 2017.

Greiner, R., Patterson, L. and Miller, O. (2019). Motivations, risk perceptions and adoption of conservation practices by farmers. *Agricultural Systems*, 99(2-3), 86-104.

Kuehne, G., Llewellyn, R., Pannell, D. J., Wilkinson, R., Dolling, P., Ouzman, J., & Ewing, M. (2017). Predicting farmer uptake of new agricultural practices: A tool for research, extension and policy. *Agricultural Systems*, 156, p115-125.

Llewellyn, R. S. (2007). Information quality and effectiveness for more rapid adoption decisions by farmers. *Field Crops Research*, 104(1-3), 148-156.

Reef 2050 Water Quality Improvement Plan, Water Quality Risk Framework, Australian Government and Queensland Government, accesses at www.reefplan.qld.gov.au/measuring-success/paddock-to-reef/management-practices, 14 November 2018.

Robertson, M.J., Llewellyn, R.S., Mandel, R. et al. "Adoption of variable rate fertiliser application in the Australian grains industry: status, issues and prospects", Precision Agric (2012) 13: 181. https://doi.org/10.1007/s11119-011-9236-3

SRA (2018) Automation of furrow irrigation, Sugar Research Australia https://sugarresearch.com.au/wp-content/uploads/2017/02/AFI_General_InfoSheet_2018-F-Web.pdf

State of Queensland (2017) Progress Report 2017 – Queensland Regional Natural Resource Management Investment Program 2013 – 2018. Department of Natural Resources and Mines.

Schaffelke, B., Collier, C., Kroon, F., Lough, J., McKenzie, L., Ronan, M., Uthicke, S., Brodie, J., 2017. 2017 Scientific Consensus Statement: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 1: The condition of coastal and marine ecosystems of the Great Barrier Reef and their responses to water quality and disturbances. State of Queensland, 2017.

Wilkinson S.N., Hairsine P.B., Hawdon A.A., Austin J. (2019) Technical findings and outcomes from the Reef Trust Gully Erosion Control Programme. CSIRO, Australia

Waterhouse, J., Brodie, J., Tracey, D., Smith, R., VanderGragt, M., Collier, C., Petus, C., Baird, M., Kroon, F., Mann, R., Sutcliffe, T., Waters, D., Adame, F., 2017. 2017 Scientific Consensus Statement: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 3: The risk from anthropogenic pollutants to Great Barrier Reef coastal and marine ecosystems. Published by the State of Queensland, 2017.

Waterhouse, J., Schaffelke, B., Bartley, R., Eberhard, R., Brodie, J., Star, M., Thorburn, P., Rolfe, J., Ronan, M., Taylor, B., Kroon, F., 2017. 2017 Scientific Consensus Statement: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 5: Overview of key findings, management implications and knowledge gaps. State of Queensland, 2017.

Waters, D, Carroll, C, Ellis, R, McCloskey, G, Hateley, L, Packett, R, Dougall, C&Fentie, B 2013,'Catchment modelling scenarios to inform GBR water quality targets', in J Piantadosi, RS Anderssen and J Boland (eds),MODSIM2013, 20th International Congress on Modelling and Simulation,Modelling and Simulation Society of Australia and New Zealand, pp.3204–10, ISBN 978-0-9872143-3-1.www.mssanz.org.au/modsim2013/L21/waters.pdf

Attachment A

List of Management Actions

	Solution Set	Management Action	Target consituent	Applicable					
				Cape York	Wet Tropics	Burdekin	Mackay/ Whitsundays	Fitzroy	Burnett Mary
1	Practice change – Cane	Cane D to C Fertiliser Management	DIN	N	Y	Y	Y	N	Y
		Cane C to B Fertiliser Management	DIN	N	Y	Y	Y	N	Y
		Cane B to A Fertiliser Management	DIN	N	Y	Y	Y	N	Y
2	Practice change – Grazing	Grazing D to C	FS	Y	Y	Y	Y	Y	N
		Grazing C to B	FS	Y	Y	Y	Y	Y	Y
		Grazing B to A	FS	Y	Y	Y	Y	Y	Y
3	Practice change – Pesticides	Cane C to B Pesticide Management	Pesticides	N				N	Y
		Cane B to A Pesticide Management	Pesticides	N				N	Y
4	Practice change – Irrigation	Cane Irrigation C to B Level 1	DIN	N	N	Y	N	N	N
		Cane Irrigation C to B Level 2	DIN	N	N	Y	N	N	N
5	Practice change – Horticulture (bananas)	Bananas D to C	DIN	Y	Y	N	N	N	N
		Bananas C to B	DIN	Y	Y	N	N	N	N
6	Catchment remediation – Alluvial and hillslope gullies	Gully Repair Type 1 Treatment	FS	Y	Y	Y	Y	Y	Y
		Gully Repair Type 3 Treatment	FS	Y	Y	Y	Y	Y	Y
7	Catchment remediation – Streambanks	Streambank repair	FS	Y	Y	Y	Y	Y	Y
8	Catchment remediation – Treatment systems	Wet weather recycle pit	DIN	N	N	Y	N	N	N
		Wetland (constructed)	DIN	N	Y	Y	Y	N	Y
		Wetland (landscape)	DIN	N	Y	Y	Y	N	Y
		Bioreactors	DIN	N	Y	Y	Y	N	Y
9	Point source WWTP management	Ayr STP	DIN	N	N	Y	N	N	N
		Home Hill STP	DIN	N	N	Y	N	N	N
		Condon STP	DIN	N	N	Y	N	N	N
		Henry Lawson STP	DIN	N	N	Y	N	N	N
		Bundaberg North STP	DIN	N	N	N	N	N	Y
		East WWTP	DIN	N	N	N	N	N	Y
		Millbank STP	DIN	N	N	N	N	N	Y
		Woodgate STP	DIN	N	N	N	N	N	Y
		Childers STP	DIN	N	N	N	N	N	Y
		North Rockhampton STP	DIN	N	N	N	N	Y	N
		South Rockhampton STP	DIN	N	N	N	N	Y	N
10	Landuse change	Cane to grazing open	DIN	N	Y	Y	Y	N	Y
		Cane to conservation	DIN	N	Y	Y	Y	N	Y
		Grazing open to conservation	FS	Y	Y	Y	Y	Y	Y

Attachment B

Solution Statements

Attachment C

Baseline pollutant loads and targets

Region	Ausgov reporting basin	WQIP ERT catchment/basin	Dissolved Inorganic Nitrogen (t/y)					Fine sediment (kt/y)					Pesticides (diuron toxicity equivalent)
			WQIP ERT		Report Card 2016			WQIP ERT		Report Card 2016			Report Card 2016
			Tonnes	% reduction	Baseline load	Anthropogenic load	Target load reduction	Kilo-Tonnes	% reduction	Baseline load	Anthropogenic load	Target load reduction	Anthropogenic load (kg/y)
Cape York	Jacky Jacky Creek	Jacky Jacky Creek	MCL	MCL	67	0	MCL	MCL	MCL	32	4	MCL	0
	Olive Pascoe River	Olive Pascoe River	MCL	MCL	98	1	MCL	MCL	MCL	62	12	MCL	0
	Lockhart River	Lockhart River	MCL	MCL	49	0	MCL	1	2	74	3	0	0
	Stewart River	Stewart River	MCL	MCL	31	0	MCL	2	6	33	7	0	0
	Normanby River	Normanby River	MCL	MCL	111	16	MCL	15	10	139	103	10	0
	Jeannie River	Jeannie River	MCL	MCL	35	0	MCL	2	6	40	7	0	0
	Endeavour River	Endeavour River	MCL	MCL	41	2	MCL	3	10	60	17	2	0
Wet Tropics	Daintree River	Daintree River	MCL	MCL	482	138	MCL	MCL	MCL	142	47	MCL	100
	Mossman River	Mossman River	52	50	167	111	56	MCL	MCL	18	4	MCL	68
	Barron River	Barron River	52	60	180	115	69	MCL	MCL	63	38	MCL	80
	Mulgrave-Russell River	Mulgrave-Russell River	300	70	992	481	337	16	10	214	87	9	558
	Johnstone River	Johnstone River	350	70	1,233	673	471	100	40	304	161	64	485
	Tully River	Tully River	190	50	892	499	250	17	20	136	47	9	303
	Murray River	Murray River	120	50	489	307	154	8	20	71	26	5	260
	Herbert River	Herbert River	620	70	1,552	916	641	99	30	484	317	95	107
Burdekin	Black River	Black River	ND	ND	94	22	ND	ND	ND	61	33	ND	0
	Ross River	Ross River	74	60	180	129	78	ND	ND	62	49	ND	0
	Lower Burdekin	Haughton River*	640	70	965	836	585	MCL	MCL	337	294	MCL	1,319
	Bowen Bogie	Burdekin River*	100	60	175	0	0	840	30	1,655	1,395	426	0
	East Burdekin				85	16	0			293	240	75	36
	Upper Burdekin				451	0	0			953	828	245	0
	Burdekin River				90	9	0			88	80	23	1
	Cape Campaspe				75	0	0			42	36	11	0
	Belyando				61	1	0			59	54	15	0
	Don River	Don River*	MCL	MCL	106	43	MCL	55	30	212	181	54	2
Mackay/Whitsundays	Proserpine River	Proserpine River	110	70	248	143	100	MCL	MCL	125	67	MCL	315
	O'Connell River	O'Connell River	130	70	265	177	124	96	40	242	167	67	738
	Pioneer River	Pioneer River	140	70	251	203	142	35	20	168	117	23	738
	Plane Creek	Plane Creek	260	70	401	329	230	MCL	MCL	119	71	MCL	1,271
Fitzroy	Styx River	Styx River	MCL	MCL	90	10	MCL	MCL	MCL	99	91	MCL	4
	Shoalwater Creek	Shoalwater Creek	MCL	MCL	99	5	MCL	MCL	MCL	63	56	MCL	2
	Waterpark Creek	Waterpark Creek	MCL	MCL	65	4	MCL	MCL	MCL	64	56	MCL	0
	Fitzroy River	Fitzroy*	MCL	MCL	284	88	MCL	390	30	733	669	201	9
	Mackenzie				61	9	MCL			236	209	63	4
	Isaac				236	24	MCL			135	116	35	9
	Dawson				139	23	MCL			195	173	52	10
	Comet				41	7	MCL			24	23	7	4
	Nogoa				22	4	MCL			7	6	2	2
	Theresa Creek				17	3	MCL			11	11	3	2
	Calliope	Calliope*	MCL	MCL	46	6	MCL	15	30	49	43	13	2
	Boyne River	Boyne River	MCL	MCL	37	2	MCL	6	40	17	15	6	1
Burnett Mary	Baffle Creek	Baffle Creek	16	50	57	31	16	11	20	76	53	11	3
	Kolan River	Kolan River	34	50	73	63	31	6	20	40	30	6	30
	Burnett River	Burnett River	150	70	234	196	137	85	20	341	246	49	21
	Burrum River	Burrum River	93	50	179	166	83	3	20	25	16	3	16
	Mary River	Mary River	180	50	421	324	162	130	20	769	658	132	16

Solution Statement 1: Practice change - Sugarcane fertiliser

1 Scenario description and context

Change in farming behaviours and practices can significantly change the frequency, magnitude and extent of pollutant export in catchments, largely because of the area of agricultural land uses within basins. Unlike engineered treatments, which are typically applied at discrete points in a catchment and therefore improve smaller areas, practice changes, if adopted well, can influence large areas and therefore can result in significant overall improvements in catchment discharges. For each agricultural industry within the Great Barrier Reef catchments there is a suite of specific management systems used to describe the water quality risk relevant to that industry. For sugarcane, farm system processes such as nutrient, soil, pesticide and water management are described in the P2R Water Quality Risk Framework (Shaw pers comm 2018, previously described in Reef Plan (2019)).[1] The framework is used to define and report management practices and the predicted water quality improvements at a paddock scale.

The rate of adoption of better management practices is a key determinant to significant pollutant reductions across the 46 individual river basins which are contained in the six NRM regions that flow into the reef, with substantial variation of this adoption within and across regions. Determining the actual proportions of practice steps (High to low water quality risk) becomes critical then in understanding the investments needed and the magnitude of improvement possible. Combined with the understanding of efficacy of each water quality risk step (e.g. D to C or C to B), this allows the calculation of overall effectiveness of practice change in sugarcane.

This solution statement assesses the specific management practice changes for sugarcane categorised as shifting from high risk to lower risk management. In 2018, a new management practice framework was released that provided the basis of this study. To date there have not been any costing or prioritisation studies that have aligned with the management activities of this framework, therefore this study has relied on multiple data sources to estimate costs for shifting management across the 46 basins. The water quality risk levels range from high through moderate to low risk and there are 4 levels of practice. For simplification purposes, we have adopted the previous ABCD nomenclature to classify each level, where D is typically high or moderate to high risk and A is low to very low water quality risk.

The specific management actions being assessed for inclusion in the Investment Pathways tool are:

- Practice change Cane D-C (High to Moderate Risk)
- Practice change Cane C-B (Moderate to Low Risk)
- Practice change Cane B-A (Low to Extremely Low Risk).

1.1 Costs

1.1.1 Data

Production systems for sugarcane have been reviewed and costed using previous data (e.g. from Alluvium 2016 - updated to AU$2018) and with new costing information where available. The basis for all the costs has been for a producer starting at the high water quality risk level and stepping through each of the management risk levels. The following costs were estimated for sugarcane practice changes: (1) capital – on ground direct costs of purchasing and installing capital equipment; (2) operating and maintenance – costs associated with on farm operations and maintenance after the practice change; and (3) program – these are the costs to cover overhead expenses, extension, monitoring and evaluation to support practice change uptake.

For sugarcane, in a review of the management practices from the 2018 framework, it was identified that the capital expenses previously costed as moderate risk management implements are now considered high risk

[1] The framework used for this analysis is provided in the appendix.

practices. The new framework also has a greater emphasis on understanding the biophysical attributes to manage inputs utilised to grow sugarcane i.e. soil tests.

To assess the cost of changing management practices the 2018 sugarcane management practices were used. There were three key steps in assessing the costs of changing management practices.

1. Understanding what the machinery and technology costs are for shifting through the management framework - specifically for nutrient management.

2. Reviewing past costs and investments, collating new data and adjusting past studies based on these findings including , (Law et al., 2016; Rolfe and Windle, 2016; Van Grieken et al., 2010).

3. Assessing past Reef Rescue projects to ensure that the range of capital and operating costs are accounted for, considering the variance in farm size that exists in the management units.

The key elements relevant to shifting from High risk management to Moderate risk management were considered along with information for the cost of development of a farm management plan and soil testing. To understand what landholders require, a base level of equipment was assumed as described in Table 1 below. The capital and management costs for shifting from High risk to Moderate risk included improved understanding of soil type and nutrient requirements along with GPS to enable variable rate technolgoies. It is acknowledged that this aligned more closely with soil management, however to achieve variable rate applications of nutrient, GPS technology is required. As the level of risk declines from Moderate to Low risk, increased calibration of equipment and zonal application of nutrients is required (Table 1). Finally from Low risk management to Extremly Low risk management phosphorus management has increased emphasis and therefore the leaf testing was required. It must be highlighted that some costs such as agronomic support and soil testing have been costed in both the pesticide and nutrient scenarios however in reality these costs are whole farm system change costs that would not be duplicated.

Table 1. Capital and cost required to implement the Sugarcane (nutrient component only) management

Capital machinery Starting point	High Risk (D) to Moderate (C) risk	Moderate (C) to Moderate-Low (B) Risk	Low (B) Risk to extremely low (A) risk
Billet planter **Offset discs** **Rotary hoe** **Ripper 3 tyne** **S-tyne cultivator** **Sidedress fert box** **Cut away** **Weeder rake** **Hilling boards** **Slasher** **Spray boom 5 row**	Development of farm management plan ($5,000). Soil tests 1 for every 2.5ha ($15 per test). Calibration and nutrient management support ($1,500 per property). GPS (Average taken from past Reef Rescue Investments in the relevant catchment, current prices and past literature). Stool Splitter (average taken from past Reef Rescue Investments in the relevant catchment, current prices and past literature). Variable rate controller (Average taken from past Reef Rescue Investments in the relevant catchment, current prices and past literature).	Annual update of soil nutrients and additional 10 soil tests across the property (2 in addition in existing one across 5 blocks to allow for three zones) to allow accounting for zones prior to planting (Soil tests 1 for every 2.5ha ($15 per test) (Law and Star 2015). Unlock GPS field IQ to allow for varied rates within the block ($10,000), banded mill mud applications by mill contractors where used. Variable rate application of fertiliser used (especially if not in mill mud zone) harvest monitored used ($10,000). Calibration at the start of the season and monitored throughout operations (Agronomist for 1 hour every 10 ha for nutrient management and calibration).	Leaf testing 3 every 2.5ha to derive 3 zones ($56 per test) for N, P and K and Agronomic support for 1hour every 10ha @$85 per hour.

1.1.2 Results

After careful consideration of the required changes, costs were estimated for each practice change and region based on the data available. Table 2 provides a summary of the estimated initial cash costs over a 5-year period. A 2.5% inflation rate was used to adjust the estimated year 1 costs over subsequent years (year 1 to 5). The 5-year cash costs are the estimated funds to support practice change over the initial 5 years. For example, in the Burnett Mary region, it is estimated that the most likely cost of shifting from a D to a C practice requires capital costs of $262, operating and maintenance costs of $105 in year 1 and program costs of $45 in year 1. Regional differences in these costs were directly attributable to the input data used. These differences would also transfer across cost categories as they tend to largely be related to capital costs.

Table 2: Most likely cash costs by practice change and region over a 5-year period (2018 AUD)

Practice Change		Capital	Operating and maintenance					Program				
	Year	***1***	***1***	***2***	***3***	***4***	***5***	***1***	***2***	***3***	***4***	***5***
	Region											
Sugarcane D-C	Burnett Mary	262	105	108	110	113	116	45	46	47	48	49
	Burdekin	381	64	65	67	68	70	65	66	68	70	72
	Mackay Whitsunday	304	39	40	41	42	43	52	53	54	56	57
	Wet Tropics	365	82	84	86	88	90	62	64	65	67	69
Sugarcane C-B	Burnett Mary	183	27	28	29	30	30	31	32	33	34	34
	Burdekin	123	90	92	94	97	99	102	104	107	109	112
	Mackay Whitsunday	160	24	25	25	26	27	27	28	29	29	30
	Wet Tropics	179	27	28	28	29	30	30	31	32	33	34
Sugarcane B-A	Burnett Mary	0	76	78	80	82	84	13	13	14	14	14
	Burdekin	0	76	78	80	82	84	13	13	14	14	14
	Mackay Whitsunday	0	76	78	80	82	84	13	13	14	14	14
	Wet Tropics	0	76	78	80	82	84	13	13	14	14	14

Life cycle costs (2018AUD per ha) over a 30-year appraisal were estimated using a 7% discount rate and are the estimated costs per ha. These costs include all three estimated costs categories i.e. capital, operating and maintenance, and program costs. It should be noted that there is significant variability in the range of input data and assumptions used in the modelling. Thus, data on low (best), most likely and high (worst) costs was included in our modelling to capture this variability.

Table 3 shows the estimated most likely costs (annual $ per ha) and the 90% prediction interval from a Monte Carlo simulation with 20,000 iterations. The best and worst values represent the 5th and 95th percentile for each reported cost estimate. These results indicate that the more likely life cycle costs for a practice change in the Burnet Mary from D – C is $2,270 per ha over 30 years and the 90% prediction interval ranges from $1,405 to $2,683.

It is intuitive to assess how much of an impact each of the different costs have on the bottom-line estimates of lifecycle costs (LCCs). For a sugarcane fertilizer management shift from D-C in the Burnett Mary, our Monte Carlo estimations indicate that operating and maintenance costs have the greatest contribution to variance in the 30-year LCCs at 54%, followed by program costs at 39%, and capital costs have the least effect on percentage contribution variance in the LCCs. This contribution to variance is a result of the variability and/or confidence in the input parameter values.

Table 3: Estimate costs of practice change and the contribution to variance in the life cycle costs

Practice change	NRM Region	30 Year life cycle costs			Contribution to variance		
		Best	More Likely	Worst	Capital	Operating & maintenance	Program
Sugarcane D-C	Burnett Mary	1,407	2,270	2,679	7%	54%	39%
	Burdekin	1,703	2,103	2,991	7%	59%	35%
	Mackay Whitsunday	1,423	1,522	2,695	1%	93%	6%
	Wet Tropics	1,566	2,290	8,930	10%	39%	51%
Sugarcane C-B	Burnett Mary	811	968	1,208	10%	40%	51%
	Burdekin	2,232	2,688	6,047	0%	44%	56%
	Mackay Whitsunday	815	848	1,267	10%	40%	50%
	Wet Tropics	893	949	1,304	10%	40%	51%
Sugarcane B-A	Burnett Mary	1,083	1,188	1,292		97%	3%
	Burdekin	1,083	1,188	1,293		97%	3%
	Mackay Whitsunday	1,082	1,188	1,293		97%	3%
	Wet Tropics	1,082	1,188	1,292		97%	3%

1.2 Efficacy

1.2.1 Data

The Paddock to Reef (P2R) modelling program uses a multiple lines of evidence approach (Carroll *et al.* 2012) to derive an understanding of the influence of practice change actions on pollutant export from agricultural enterprises. As part of this, the Agricultural Production Systems Simulator (APSIM) model (Holzworth *et al.* 2014) is used to predict changes in water balance, production and nutrient export from different crop types using different modules available within the model. This is shown in the figure below.

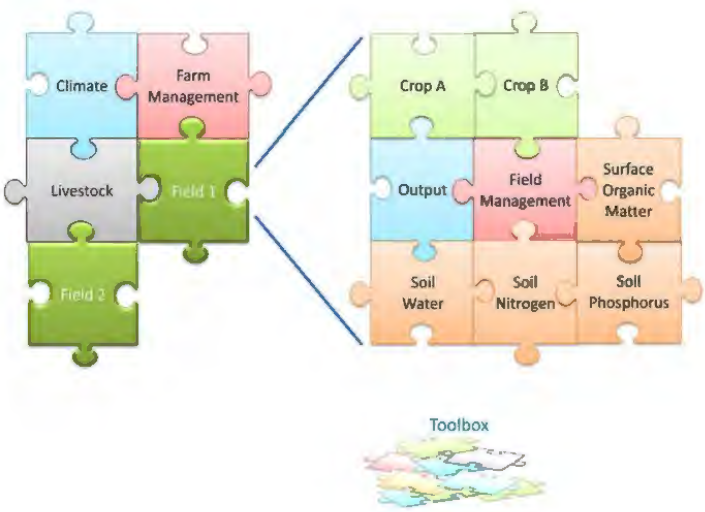


Figure 1. *APSIM model components*

The APSIM model is run for a range of agricultural enterprise configurations in different climates and different management regimes (e.g. fertiliser management, soil management, irrigation methods) to enable the development of data cubes that are then provided to the broader scale Source models to predict overall catchment runoff. This work is based on direct run data provided by DES (Shaw pers comm 2018) but also builds largely on that described in Shaw et al 2013.

In terms of this Solution Set, the different management elements that are part of the water quality risk management framework for sugarcane have provided the model inputs and the project team have received the outputs from the model in terms of each of the practice change steps in the risk framework as outlined in the following table. We have assumed that each step is a full practice change step rather than considering partial steps.

Table 4. Risk management framework – fertiliser management practices

	Action type		Dfull = High Risk	Cpartial	Cfull = Moderate Risk	Bpartial	Bfull = Moderate - Low Risk	Apartial	Afull = Lowest WQ Risk, commercial feasibility unproven
			Superseded		Minimum		Best Practice		Innovative
	Fertiliser Management								
1	Matching N supply to crop N requirements	60%	District rules of thumb determine applied N rate.	District rules of thumb determine applied N rate.	Nitrogen budget developed (e.g. 6ES) with estimated N demand based on a yield expectation of Estimated Highest Average Annual Yield + 20% (district yield potential) for plant or ratoon stage. Final application rates are as per calculated amount.	Nitrogen budget developed (e.g. 6ES) with estimated N demand based on targeting district yield potential for plant or ratoon stage. Accounting for legumes in budgeting, or mill mud if below 100t/ha.	Nitrogen budget (e.g. 6ES) developed with estimated N demand based on growers' own yield expectations for specific blocks and ratoon numbers and considers seasonal climate predictions. Final application rates are as per calculated amount.	NA	As for B, but with planning and application targeting **yield zones within blocks**.
2	Timing of fertiliser application	30%	Weather only impacts upon ability to complete application at that time.	Weather only impacts upon ability to complete application at that time.	Application occurs with consideration given to short term (<4 days) rainfall forecast.	Application occurs with consideration given to short term (<4 days) rainfall forecast.	Application occurs prior to expected wet season commencement and with adequate risk assessment, inc. weekly rainfall forecast.		As for B, plus utilising seasonal climate forecasts.
3	Application method	10%	Surface applied, not incorporated.				Subsurface (including surface applied and watered in).		

1.2.2 Results

Results of the APSIM modelling provided values for sugarcane fertiliser management under different management regimes. In irrigated areas within the Burdekin Irrigation Area, a range of values were determined based on the different irrigation management approaches. The results are shown in the table below.

Table 5. APSIM model results – sugarcane fertiliser management DIN load reduction

Fertiliser management (drainage DIN)	Wet Tropics	Mackay-Whitsundays	Burnett-Mary	Burdekin Low	Burdekin Med	Burdekin High
D-C	20%	36%	36%	17%	24%	29%
C-B	52%	39%	46%	7%	12%	15%
B-A	9%	5%	5%	2%	4%	5%

The results for the Burdekin showed that irrigation practice was linked to the fertiliser efficacy at different steps, as would be expected. This showed that if the irrigation practice was in the superseded category, then the amount of DIN reduction possible through fertiliser management was not as high as when irrigation practice was low risk. This is further outlined in the chart below.

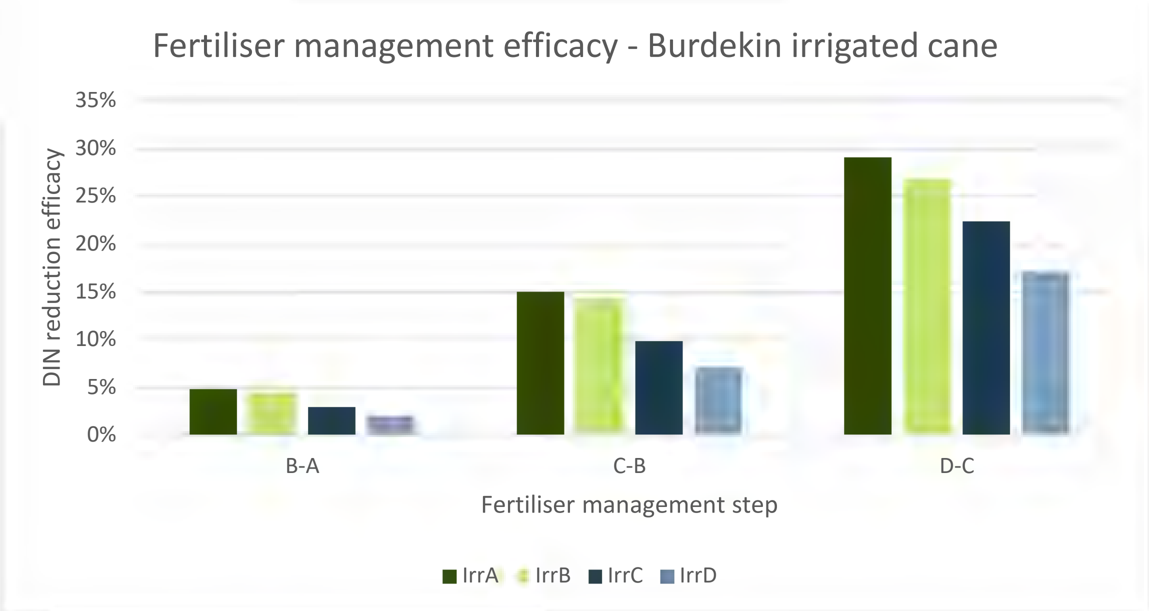


Figure 2. *Fertiliser DIN reduction efficacy for irrigated cane in the Burdekin*

These irrigation results provide the estimates of lower, middle and upper reductions for fertiliser management in the Burdekin only and are as a result of different irrigation practices influencing DIN reductions, not model uncertainty, but do provide an indication of variance likely in the Burdekin. For other regions, we have not been able determine uncertainty in the likely efficacy, so have considered an initial +/- 30% range of the reduction value (i.e. +/- 30% of the number value, not +/- 30%).

2 Results

2.1 Cost-effectiveness

The treatable area and DIN load from sugarcane for each NRM region is shown in Figure 3. The cost-effectiveness of each sugarcane practice change step based on the most likely efficacy (percentage reduction) and cost ($/ha) is shown in Table 6 to Table 8.

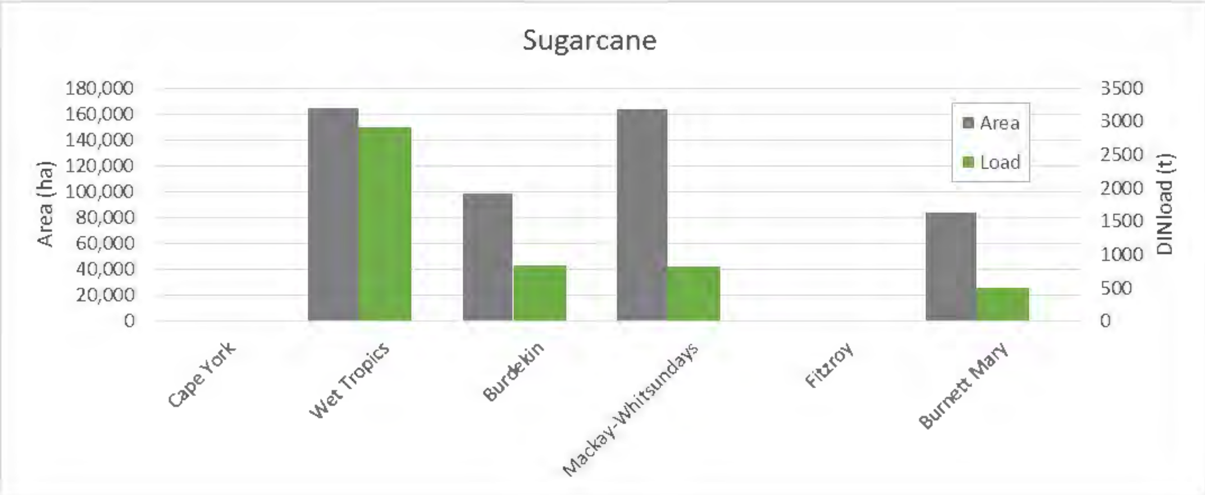


Figure 3. *Areas and annual loads from sugarcane for each NRM region*

The following tables show preliminary estimates of cost-effectiveness based on the most likely cost per hectare (Table 3) and the stated efficacy (Table 4). For each region (e.g. Wet Tropics) there are a number of basins that each have a different delivery ratio to the end of catchment as well as a different load per hectare. This has an impact on cost-effectiveness at the end of the catchment. The range of cost-effectiveness estimates presented for each region below shows the range of end of catchment costs (minimum through to 75th percentile of the basins modelled, with values above 75th percentile considered to be too expensive to warrant investment and statistical outliers).

There are a range of factors that will influence differences in cost-effectiveness between regions, but these are largely related to climate (those with higher rainfall discharge higher-loads and the practices tend to be more effective), delivery ratios (the actual amount of pollutant delivered to the catchment outlet, accounting for attenuation and/or enrichment between the point of generation and the catchment outlet) and the regional variability in costs noted above.

Table 6. Estimated cost-effectiveness and treatable area and load for sugarcane fertiliser D to C practice change

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Wet Tropics	98,488	1,906	$459	$472	$512	$570
Burdekin	59,498	572	$588	$813	$1,042	$1,516
Mackay/Whitsundays	11,824	656	$707	$720	$736	$761
Burnett Mary	41,573	302	$659	$890	$979	$1,114

Table 7. Estimated cost-effectiveness and treatable area and load for sugarcane fertiliser C to B practice change

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Wet Tropics	40,166	685	$85	$88	$100	$116
Burdekin	30,218	216	$1,618	$2,817	$3,236	$4,172
Mackay/Whitsundays	43,007	160	$419	$471	$509	$615
Burnett Mary	34,593	167	$255	$416	$489	$521

Table 8. Estimated cost-effectiveness and treatable area and load for sugarcane fertiliser B to A practice change

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Wet Tropics	25,480	314	$668	$686	$900	$1,050
Burdekin	8,802	56	$5,206	$6,481	$7,755	$9,030
Mackay/Whitsundays	2,600	7	$4,926	$5,651	$8,256	$11,363
Burnett Mary	8,000	29	$3,348	$5,440	$6,314	$8,670

The range of cost-effectiveness for each practice change, according to region, is visually represented in Figure 9 to Figure 9.

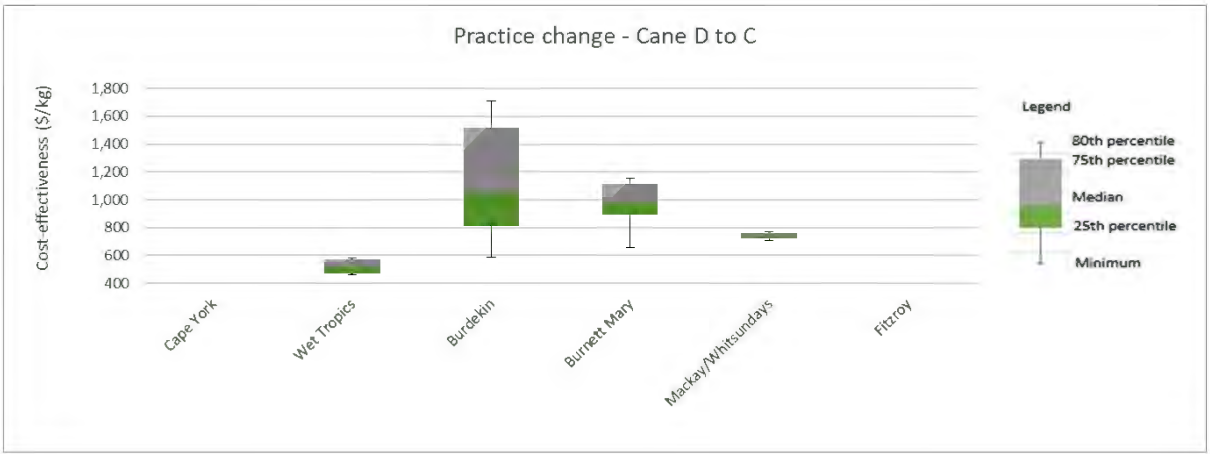


Figure 4. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for sugarcane fertiliser D to C practice change*

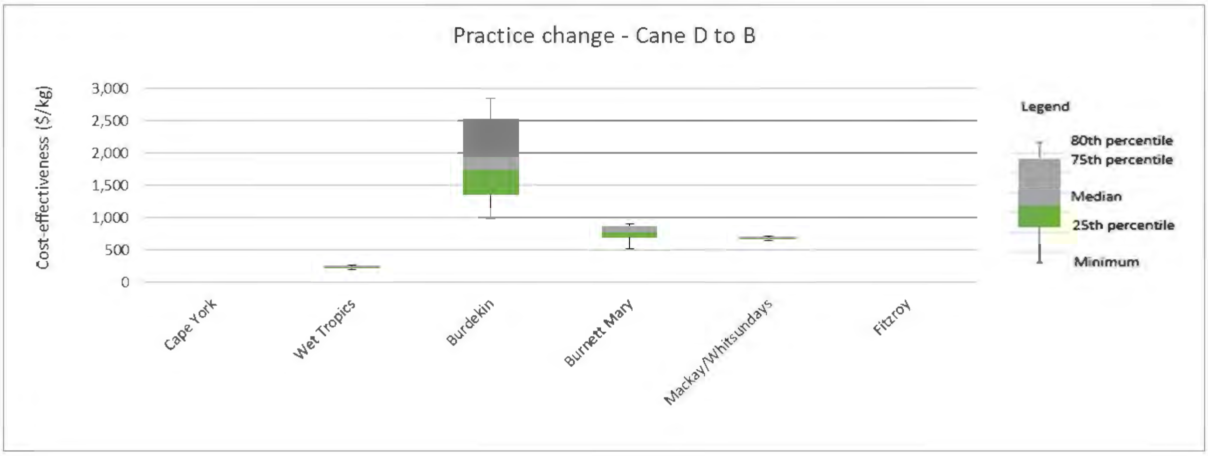


Figure 5. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for sugarcane fertiliser D to B practice change*

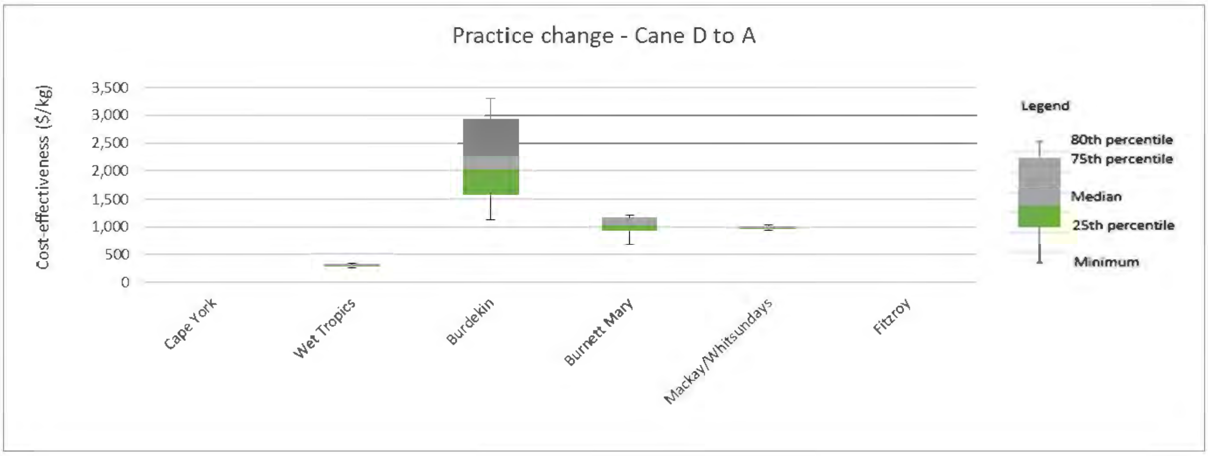


Figure 6. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for sugarcane fertiliser D to A practice change*

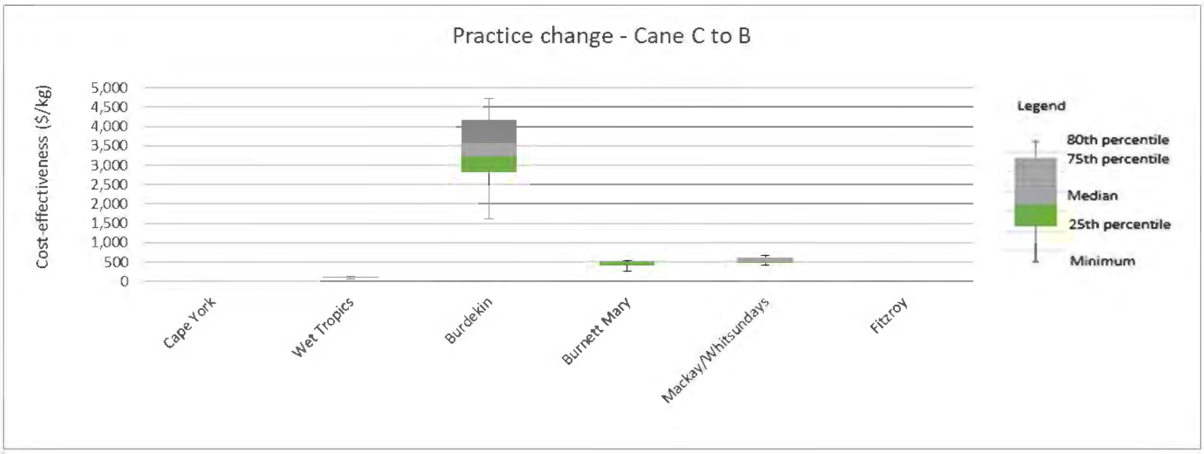


Figure 7. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for sugarcane fertiliser C to B practice change*

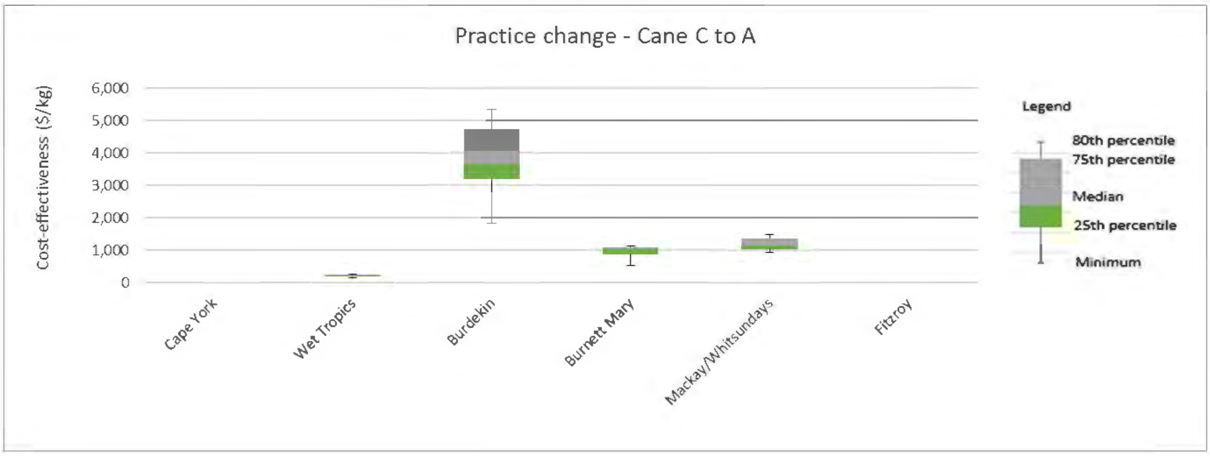


Figure 8. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for sugarcane fertiliser C to A practice change*

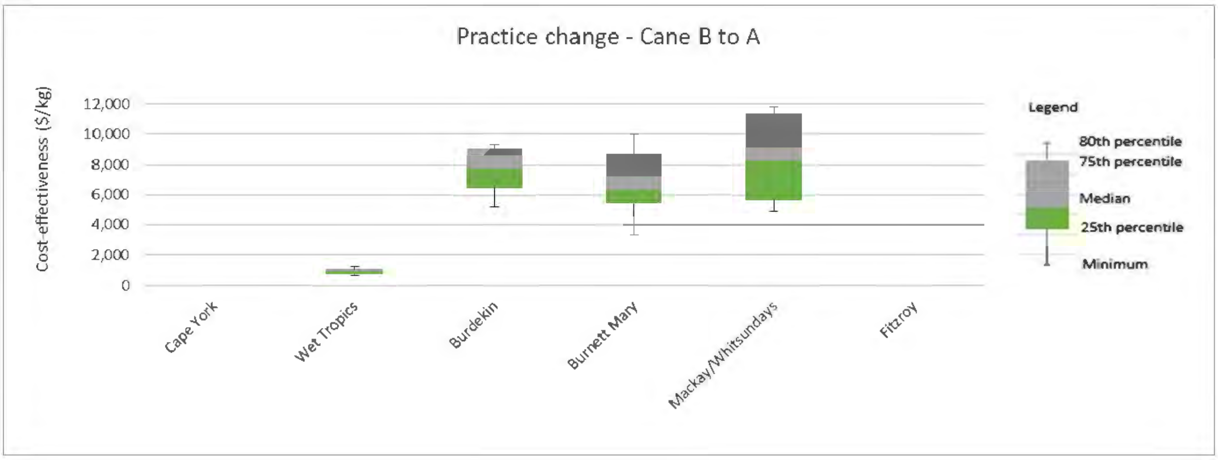


Figure 9 *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for sugarcane fertiliser B to A practice change*

2.2 Assumptions and limitations

We have assumed that each change in practice is a full step change, though in reality it is likely that farm managers would choose from a range of actions that best suited their enterprise. In addressing water quality risks then, it is likely that a combination of actions would lead to improvement, but they may not all clearly fall under a whole risk category (i.e. a farmer at High Risk may choose elements from Moderate and Low Risk from the risk framework.

Assumptions around the types of practices used to generate the results are largely those used within the APSIM modelling to generate the efficacies presented. We note that there are slight inconsistencies between the 2013 Water Quality Risk Framework that was the basis of the APSIM modelling, and the 2018 framework which was used for costing purposes. Those differences were considered negligible in producing the results used here.

3 Contributors

Melanie Shaw provided updated efficacy results from previous APSIM modelling, noting that additional modelling is currently being undertaken for the next report card iteration.

Cost information was obtained and processed by the project team to generate the results presented here.

4 References

Carroll, C., Waters, D., Vardy, S., Silburn, D.M., Attard, S., Thorburn, P.J., Davis, A.M., Halpin, N., Schmidt, M.,Wilson, B. and Clark, A. (2012). 'A paddock to reef monitoring and modelling framework for the Great Barrier Reef: Paddock and catchment component'. Marine Pollution Bulletin. DOI:10.1016/j.marpolbul.2011.11.022.

Holzworth, D.P., Huth, N.I., deVoil, P.G., Zurcher, E.J., Herrmann, N.I., McLean, G., and Chenu, K. *et al*. (2014). 'APSIM - Evolution towards a New Generation of Agricultural Systems Simulation'. Environmental Modelling & Software 62: 327-350. https://doi.org/10.1016/j.envsoft.2014.07.009.

Law, A., Rust, S., and Star, M. (2016). "Economics of Variable Rate Nutrient Application (VRA) in sugarcane." Australian Agricultural and Resource Economics Society.

Rolfe, J., and Windle, J. (2016). "Benchmarking costs of improving agricultural water management in GBR catchments. Report to the National Environmental Science Programme.." Reef and Rainforest Research Centre Limited, Cairns

Shaw, M., Silburn, D.M., Ellis, R., Searle, R., Biggs, J., Thorburn, P., Whish, G. (2013) Paddock scale modelling to assess effectiveness of agricultural management practice in improving water quality in the Great Barrier Reef Catchments, in Piantadosi, J., Anderssen, R.S. and Boland J. (eds) MODSIM2013, 20th International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2013.

Shaw, M. (2019). "Paddock to Reef Management Practices". Reef 2050 Water Quality Improvement Plan https://www.reefplan.qld.gov.au/tracking-progress/paddock-to-reef/management-practices

Van Grieken, M., Poggio, M., East, M., Page, J., and Star, M. (2010). Economic Analysis of Sugarcane Farming Systems for Water Quality Improvement in the Great Barrier Reef Catchments. Reef Rescue Integrated Paddock to Reef Monitoring, Modelling and Reporting Program.

Appendix

Paddock to Reef Sugarcane Water Quality Risk Framework – DRAFT 2018 (soil and nutrient management)

Soil Management	**Weighting**	**Relative Water Quality Risk**			
		High	**Moderate**	**Moderate - Low**	**Lowest**
Crop Residue Cover	40%	Cane trash blanket is not retained.	Cane trash blanket is retained on ratoons.	Cane trash blanket is retained, including as fallow cover after final ratoon.	
Controlled machinery traffic	20%	At least 60% of field is trafficked by machinery every year.	Between 37% and 60% of the field is trafficked by machinery every year.	Less than 36% of the field is trafficked by machinery every year.	
		Machinery operates on different wheel spacings.	Most machinery operates on the same wheel spacing and is matched to row spacing. Harvesters and haul-outs are on different wheel spacings.	All machinery wheel spacings matched to row spacing for all operations including harvesters and haul-outs. GPS guidance is used all operations **except** harvesters and haul-outs.	All machinery wheel spacings matched to row spacing for all operations including harvesters and haul-outs. GPS guidance is used for **all** field operations, **including** harvesters and haul-outs.
Land management during sugarcane fallow	20%	Bare fallow or no fallow.	Soil cover maintained during the fallow phase. Trash blanket and sprayed cane or growth of a legume/cover crop **when opportunity arises.** Weeds are controlled with knockdown herbicides.	Legume or cover crops grown on **all** fallow land, and crop residues are maintained.	Legume or cover crops are planted on **all** fallow land, without tillage. Crop residues are maintained.
Preparing land for planting	20%	6 or more passes of tillage equipment.	Up to 5 passes of tillage equipment.	Zonal tillage only, no powered implements.	No tillage.
		All plant cane blocks are prepared with a fine tilth.	Plant cane is established after a fallow using zonal tillage or the minimum number of passes required for soil and conditions.	Zonal tillage after a fallow using non-powered implements. Only the row area is cultivated, inter-rows are left un-cultivated.	Plant cane is established after fallow using zero tillage.

Nutrient Management	Weighting	Water Quality Risk			
		High	**Moderate**	**Low**	**Lowest**
Matching nitrogen supply to crop nitrogen requirements	70%	N fertiliser rate typically exceeds the Six Easy Steps baseline application rate. Non-compliant with regulated method for calculating optimum N rate.	Nitrogen fertiliser rate for each plant crop and its subsequent ratoons are derived from soil tests and the Six Easy Steps method. Rates are based on district yield potential with adjustments made according to the soil N mineralisation index (based on organic carbon percentage). Deductions are made for other significant sources of N including from irrigation water, mill mud and legumes.	Six Easy Steps Nutrient Management program is employed, which includes yield monitoring and use of the results from leaf testing and fertiliser strip trials. The amounts of N and P applied are optimal for crops on each major soil type and/or management zone.	
Matching Phosphorus supply to crop P requirements	15%	Phosphorus is regularly or routinely applied as part of plant or ratoon cane blends.		P fertiliser requirements are determined through soil testing and consideration of extractable phosphorous and the P buffer index. P is not applied unless testing indicates it is necessary.	
Application of mill mud or mud/ash	15%	Broadcast application at rates over 100 wet tonnes per hectare.	Broadcast application at rates up to 100 wet tonnes per hectare. For fallow applications, mill mud/ash is incorporated soon after application.	Mill mud is not applied where soil testing indicates P levels are adequate. Mill mud/ash is applied in a band over the crop row at <70 wet tonnes per hectare.	Do not apply mill mud or ash. OR Mill Mud/ash is deep banded at <50 wet tonnes per hectare.

Solution Statement 2: Practice Change - Grazing

1 Scenario description and context

Change in farming behaviours and practices can significantly change the frequency, magnitude and extent of pollutant export in catchments, largely because of the area of agricultural land uses within basins. Unlike engineered treatments, which are typically applied at discrete points in a catchment and therefore improve smaller areas, practice changes, if adopted well, can influence large areas and therefore can result in significant overall improvements in catchment discharges. For each agricultural industry within the Great Barrier Reef catchments there is a suite of specific management systems used to describe the water quality risk relevant to that industry. For grazing, farm system processes such as hillslope, gully and streambank management are described in the P2R Water Quality Risk Framework (previously described in Reef Plan (2019)), however for this solution statement, only hillslope erosion is considered as gully and streambank management are dealt with separately. The framework is used to define and report management practices and the predicted water quality improvements at a paddock scale. The Grazing Land Management framework describes the current state of land condition in regard to 3P pastures, bare ground and woody weeds but the changes in land condition through practice change in that framework were not costed. These practices do capture the management of declined land condition as outlined in the Hillslopes section of the Grazing Water Quality Risk Framework 2018 (see Appendix).[1].

Changes in land management practices may come at a significant cost, and the on-ground benefits to landholders from management changes to improve water quality may only be minor, e.g. improvements in pasture yield (short term) and less soil erosion (long term). However, the (short term) opportunity costs, e.g., lower stocking rates or stock exclusion on buffer areas of affected sites, coupled with high capital and maintenance costs, may outweigh the benefits. These are some of the reasons why soil conservation adoption rates by landholders are generally low in the GBR catchments and worldwide (DeGraff, 1980; Kuhlman et al., 2010; Rolfe and Gregg, 2015; Valentin et al., 2005).

This solution statement assesses the specific management practice changes for grazing categorised as shifting from high risk to lower risk management. In 2018, a new management practice framework was released that provided the basis of this study. To date there have not been any costing or prioritisation studies that have aligned with the management activities of this framework, therefore this study has relied on multiple data sources to estimate costs for shifting management across the 46 basins. The water quality risk levels range from high through moderate to low risk and there are 4 levels of practice. For simplification purposes, we have adopted the previous ABCD nomenclature to classify each level, where D is typically high or moderate to high risk and A is low to very low water quality risk.

The specific management actions being assessed for inclusion in the Investment Pathways tool are:

- Practice change Grazing D-C (High to Moderate Risk)
- Practice change Grazing C-B (Moderate to Moderate-Low Risk)
- Practice Change Grazing B-A (Moderate-Low to Low Risk)

[1] Only the hillslope section was followed for the grazing.

2 Approach

2.1 Costs

2.1.1 Data

Production systems for grazing have been reviewed and costed using previous data updated with new costing information where available. The emphasis for all the costs has been for a producer starting at the high water quality risk level and stepping through each of the management risk level.

For the purposes of this study the P2R Water Quality Risk Grazing Practices Framework (2018) focused on the component around mitigating hillslope erosion. There is increased emphasis on property maps, monitoring sites and actively rehabilitating declined land condition. The hillslope component now includes land regeneration. Therefore, the cost components that are considered are opportunity costs, capital and input costs, technical, agronomic or GIS support, and on-going maintenance costs (see Figure 1). In past studies, there have either been opportunity costs or remediation costs (Star and Donaghy (2009, 2010), Star *et al.* (2011, 2013a, 2013b, 2015), Moravek and Hall (2014)) with few accounting for capital, opportunity cost, remediation, and maintenance in the one costing. This is in part because the grazing framework (Queensland Government 2018) has been updated and is more specific and in part because past studies have focused on specific components rather than management practices. Where data is derived from previous studies, all figures have been indexed to 2018 values. Other references utilised have included Star et al. (2015) and Star et al. (2017).

Figure 1. *Cost components for grazing management actions*

The following three cost categories were estimated for grazing practice changes: (1) capital – on ground direct costs of purchasing and installing capital equipment; (2) operating and maintenance – costs associated with on farm operations and maintenance after the practice change; and (3) program – these are the costs to cover overhead expenses, extension, monitoring and evaluation to support practice change uptake.

Across the 46 management units, there is a range of land types and productivity groupings. To assess the variance between management units the dominate land types were classified into six different productivity groupings in accordance with the Paddock to Reef- Paddock scale modelling. This allows the stocking rates to be varied relative to the condition and the level of management. Fitzroy and Burdekin are the two dominant grazing catchments in the reef catchments and also have the most data. Therefore, the management units of the Cape York or the coastal catchments which have the poorest level of data were aligned to these Fitzroy and Burdekin data.

Past costings approaches have mainly focused on stocking rate and remediation in a land condition framework. The approach has focused on the requirements of a landholder seeking to implement these changes and included costs such as obtaining relevant mapping software. The full range of actions and associated costs are captured in Table 1. These property costs were then assessed on a per hectare basis by understanding the number of properties in the management unit over 200ha and the size of the catchment.

The transition from C to B included managing land in declined condition to estimate a cost for this the adoption data was used to make to derive the per hectare amount.

Where available, the costs included for solutions are: capital costs, administration costs, asset renewal, and operating/maintenance costs, and impacts on farm margins.

In all cases a range of values for the different costs was modelled to establish the most likely, 5th percentile and 95th percentile using a Monte-Carlo analysis with 20,000 iterations. The Monte Carlo analysis provides two key insights: the variability of costs and the drivers of variability in the life cycle costs.

Table 1. Actions and associated costs

	High Risk (D) to Moderate risk (C) Cost			Moderate (C) to Moderate Low (B) Risk			Moderate Low (B) risk to Low Risk (A)		
	Min ($/ha/Property)	Ave ($/ha/property)	Max ($/ha/Property)	Min ($/ha/property)	Ave ($/ha/Property)	Max ($/ha/Property)	Min ($/ha/property)	Ave ($/ha/Property)	Max ($/ha/Property)
Opportunity costs	Based on dominate land type.	Based on dominate land type.	Based on dominate land type.	Based on dominate land type.	Based on dominate land type.	Based on dominate land type.			
	Area identified in D has been destocked completely.	Area identified in D has been destocked completely.	Area identified in D has been destocked completely.						
Technical Skills	Complete GLM course $1,000.	Complete GLM course $1,000 plus $500 for basic property map with infrastructure access.	Complete GLM course $1,000 plus $700 for basic property map with infrastructure and ideal placement of monitoring site.	$1,500 Cloud based management software subscription.	$5,000 consultant property management plan basic infrastructure.	$10,000 Property management plan detailing 3P pastures, fence lines and ground cover.	GIS add-on software $360.	$500 addition to existing plan with GIS.	$800 additional planning with fencing locations and distance to water for stock.
	plus $200 for basic property hard copy map access.			Pasture Agronomist for 1 day to identify potential actions ($1000).	Pasture agronomist to help identify actions, pastures and planning for regeneration 5 days ($5,000).	Pasture agronomist to help identify actions, pastures and planning for regeneration 10 days ($10,000).			
Capital or earthworks				Crocodile plough seeding ($40/ha).	Chisel Plough $100/ha.	Deep ripping, $150/ha	Minor changes to farm infrastructure. Fencing only ($50/ha).	Realignment of water and fencing to achieve even grazing pressure across the property ($100/ha).	Shifting watering points and fencing to achieve even grazing pressure across the property ($160).
				Lower rate of seed $31.25.	Diversion bank (300m/100ha or $12/ha).	Contour bank (600m/100ha or $24/ha).			
				5km of fencing for every 100 hectares of	2kgs/ha of shrubby stylo, 2kgs/ha buffel	Extensive seed mix (see details above) $74.85/ha.			

				declined condition ($50/ha).	per hectare $40.50				
					5km of fencing for every 100 hectares of declined condition ($50/ha).	5km at $5,000/km of fencing for every 100 hectares of declined condition ($50/ha).			
Maintenance				$1,500 software subscription.	Access to pasture agronomist for on-going technical advice 2days annually ($2,000).	Access to pasture agronomist for on-going technical advice 4 days annually ($5,000).	Continued Subscription to GIS software.	Continued Subscription to GIS software.	Continued Subscription to GIS software.
				Area identified in D has been destocked completely until fully recovery.	Area identified in D has been destocked completely until fully recovery.	Area identified in D has been destocked completely until fully recovery.			

2.1.2 Results

After careful consideration of the required changes, costs were estimated for each practice change and region. Table 2 provides a summary of the estimated initial cash costs over a 5-year period A 2.5% inflation rate was used to adjust the estimated year 1 costs over subsequent years (year 1 to 5). The 5-year cash costs are the estimated funds to support practice change over the initial 5 years. For example, in the Burnett Marry region, it is estimated that the most likely cost of shifting from a D to a C practice requires capital costs of $11 per ha, and program costs of $1.9 per ha in year 1. There are no operating or maintenance costs associated with shifting grazing practices from a D to a C (in grazing practices, a shift from D to C general involves attending a course and lightening stocking rates).

Regional differences in these costs were directly attributable to the input data used. These differences would also transfer across cost categories as they tend to largely be related to capital costs.

Table 2. Cost estimates of land-use change for grazing per NRM region (AU$2018 per ha)

Practice Change		Capital	Operating and maintenance					Program				
	Year	***1***	***1***	***2***	***3***	***4***	***5***	***1***	***2***	***3***	***4***	***5***
	Region											
Grazing D-C	Burnett Mary	11.0						1.9	1.9	2.0	2.0	2.1
	Burdekin	16.2						2.8	2.8	2.9	3.0	3.0
	Cape York	21.5						3.6	3.7	3.8	3.9	4.0
	Mackay Whitsunday	6.5						1.1	1.1	1.2	1.2	1.2
	Fitzroy	18.4						3.1	3.2	3.3	3.4	3.5
	Wet Tropics	10.4						1.8	1.8	1.9	1.9	2.0
Grazing C-B	Burnett Mary	85.9	1.2	1.3	1.3	1.3	1.4	14.6	15.0	15.3	15.7	16.1
	Burdekin	164.9	2.9	3.0	3.1	3.1	3.2	28.0	28.7	29.5	30.2	30.9
	Cape York	100.2	1.5	1.6	1.6	1.7	1.7	17.0	17.5	17.9	18.3	18.8
	Mackay Whitsunday	147.2	1.5	1.5	1.6	1.6	1.7	25.0	25.7	26.3	27.0	27.6
	Fitzroy	109.3	1.6	1.6	1.7	1.7	1.8	18.6	19.1	19.5	20.0	20.5
	Wet Tropics	114.3	1.5	1.5	1.6	1.6	1.7	19.4	19.9	20.4	20.9	21.4
Grazing B-A	Burnett Mary	100.0	0.2	0.2	0.2	0.2	0.2	17.0	17.4	17.9	18.3	18.8
	Burdekin	100.0	0.1	0.1	0.1	0.1	0.1	17.0	17.4	17.9	18.3	18.8
	Cape York	100.0	0.1	0.1	0.1	0.1	0.1	17.0	17.4	17.9	18.3	18.8
	Mackay Whitsunday	100.0	0.2	0.2	0.2	0.2	0.2	17.0	17.4	17.9	18.3	18.8
	Fitzroy	100.0	0.1	0.1	0.1	0.1	0.1	17.0	17.4	17.9	18.3	18.8
	Wet Tropics	100.0	0.2	0.2	0.2	0.2	0.2	17.0	17.4	17.9	18.3	18.8

Life cycle costs over a 30-year appraisal were estimated using a 7% discount rate. Life cycle costs are the estimated costs per ha over a 30-year period in 2018 Australian dollar values. These costs include all three estimated costs categories i.e. capital, operating and maintenance, and program costs. It should be noted that there is significant variability in the range of input data and assumptions used in the modelling. Thus, data on low (best), most likely and high (worst) costs was included in our modelling to capture this variability. **Error! Reference source not found.** shows the estimated most likely costs (annual $ per ha) and the 90% prediction interval from a Monte Carlo simulation with 20,000 iterations. The best and worst values represent the 5th and 95th percentile for each reported cost estimate. These results indicate that the most likely life cycle costs for a practice change in the Burnet Mary from D – C is $36 per ha over 30 years and the 90% prediction interval ranges from $35 to $37.

It is intuitive to assess how much of an impact each of the different costs have on the bottom line estimates of lifecycle costs (LCCs). For grazing practice shift from D-C in the Burnett Mary, our Monte Carlo estimations indicate that program costs have the greatest contribution to variance in the 30-year LCCs at 84% and capital costs have 16% contribution to the variance in the LCCs. This contribution to variance is a result of the variability and/or confidence in the input parameter values.

Table 3: Estimate costs of practice change and the contribution to variance in the life cycle costs ($AU2018 per ha)

Practice change	NRM Region	30 Year life cycle costs			Contribution to variance		
		Best	Most Likely	Worst	Capital	Operating & maintenance	Program
Grazing D-C	Burnett Mary	35	36	37	16%	0%	84%
	Burdekin	43	53	59	16%	0%	84%
	Cape York	69	70	72	16%	0%	84%
	Mackay Whitsunday	21	21	22	16%	0%	84%
	Fitzroy	25	60	62	16%	0%	84%
	Wet Tropics	34	34	34	16%	0%	84%
Grazing C-B	Burnett Mary	295	298	728	16%	0%	84%
	Burdekin	445	580	828	16%	1%	83%
	Cape York	325	349	757	16%	0%	84%
	Mackay Whitsunday	433	503	789	16%	0%	83%
	Fitzroy	319	380	759	16%	0%	84%
	Wet Tropics	341	395	752	16%	0%	84%
Grazing B-A	Burnett Mary	250	330	435	16%	0%	84%
	Burdekin	250	329	435	16%	1%	83%
	Cape York	249	329	434	16%	0%	84%
	Mackay Whitsunday	252	330	437	16%	0%	83%
	Fitzroy	251	329	434	16%	0%	84%
	Wet Tropics	251	330	436	16%	0%	84%

2.2 Efficacy

2.2.1 Data

In grazing lands, different practice levels exist for pastures, streambanks and gullies. Given that streambanks and gullies are being dealt with as separate solution sets in this project, we have focussed on the changes in water quality risk associated with change in pastures or land cover, which is closely related to changes in hillslope erosion rates.

Previous work by Silburn *et al.* (in review) has provided indications of how changes in practice associated with stocking rates and land cover will improve hillslope erosion. This has formed the basis of the final efficacy numbers shown in Table 4 below, though these are also very much consistent with the summaries presented in Chapter 4 of the Scientific Consensus Statement (Eberhard *et al.* 2017). These state that improvements in hillslope erosion can be achieved through improvements to groundcover and increased forage biomass by adjusting stocking rates. It is also noted that hillslope erosion is not the dominant contributor of sediment in most catchments, but improvements in cover can also lead to reductions in gully contributions to sediment loads. This has been considered in the gully practice improvement such that we are considering the changes in gully contributions as a separate component, even though the performance of lower intervention techniques will be strongly related to practice change (i.e. they have been considered separately but are likely to be strongly correlated).

Table 4. Reduction in hillslope erosion for land condition shift (successive reductions)

Grazing practice change	Hillslope erosion rate reduction (%)
D to C	76
C to B	61
B to A	46

Assessment of areas of different practice levels was derived from the Great Barrier Reef Report Card 2016 "Management practice results" report (accessed at https://www.reefplan.qld.gov.au/measuring-success/report-cards/2016/assets/report-card-2016-management-practice-results.pdf). These provided the proportions of land in different water quality risk levels. The adopted values are shown in Table 5 below.

Table 5. Practice distributions for grazing lands (pasture/hillslope)

Region	A	B	C	D
Cape York	0%	20%	46%	33%
Wet Tropics	3%	10%	49%	38%
Burdekin	1%	31%	56%	11%
Mackay Whitsunday	8%	32%	24%	37%
Fitzroy	8%	15%	48%	29%
Burnett Mary	2%	44%	54%	0%

3 Results

3.1 Cost-effectiveness

The treatable area and fine sediment load from grazing for each NRM region is shown in Figure 2. The cost-effectiveness of each grazing practice change step based on the most likely efficacy (percentage reduction) and cost ($/ha) is shown in Table 6 to Table 8.

Figure 2. *Areas and loads from grazing for each NRM region*

The following tables show preliminary estimates of cost-effectiveness based on the most likely cost per hectare (Table 2) and the stated efficacy (Table 4). For each region (e.g. Wet Tropics) there are a number of basins that each have a different delivery ratio to the end of catchment as well as a different load per hectare. This has an impact on cost-effectiveness at the end of the catchment. The range of cost-effectiveness estimates presented for each region below shows the range of end of catchment costs (minimum through to 75^{th} percentile of the basins modelled, with values above 75^{th} percentile considered to be too expensive to warrant investment and statistical outliers).

There are a range of factors that will influence differences in cost-effectiveness between regions, but these are largely related to climate (those with higher rainfall discharge higher-loads and the practices tend to be more effective), soil types, vegetation cover differences and delivery ratios (the actual amount of pollutant delivered to the catchment outlet, accounting for attenuation and/or enrichment between the point of generation and the catchment outlet) and the regional variability in costs noted above. Of most interest is the range of cost-effectiveness results in the Fitzroy, largely as a result of the smaller loading rates per hectare of grazing land as can be seen in the graph above. While the area of grazing land is similar to the Burdekin, the load from this area is less than a quarter of that from the Burdekin. This then reflects back to cost-effectiveness, as while the $ per hectare for practice change in the Fitzroy reporting basins are similar to other regions, the lower fine sediment contribution per hectare of grazing land means the cost-effectiveness is worse by a significant amount.

Table 6. Estimated cost-effectiveness and treatable area and load for grazing D to C practice change

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Cape York	67,942	10,099	$0.60	$0.74	$0.87	$0.95
Wet Tropics	173,571	54,976	$0.02	$0.03	$0.06	$0.11
Burdekin	846,337	804,733	$0.06	$0.07	$0.07	$0.08
Mackay/Whitsundays	117,555	46,764	$0.05	$0.06	$0.07	$0.09
Fitzroy	2,227,440	181,149	$0.32	$0.58	$0.85	$1.82
Burnett Mary	0	0	-	-	-	-

Table 7. Estimated cost-effectiveness and treatable area and load for grazing C to B practice change

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Cape York	93,779	3,918	$4.50	$4.69	$6.21	$8.68
Wet Tropics	8,427	775	$0.63	$0.82	$0.99	$2.44
Burdekin	4,256,776	546,432	$6.29	$6.44	$8.49	$9.91
Mackay/Whitsundays	11,347	3,484	$1.31	$1.46	$2.12	$3.03
Fitzroy	3,651,535	88,284	$6.34	$8.05	$22.23	$33.01
Burnett Mary	919,295	84,382	$2.34	$4.37	$6.88	$7.73

Table 8. Estimated cost-effectiveness and treatable area and load for grazing B to A practice change

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Cape York	40,349	362	$5.51	$8.67	$10.09	$13.30
Wet Tropics	9	1	$1.15	$1.43	$2.23	$5.15
Burdekin	2,364,527	24,674	$48.54	$66.18	$74.23	$77.00
Mackay/Whitsundays	11,735	2,037	$1.38	$1.65	$3.48	$5.25
Fitzroy	1,144,370	2,360	$5.81	$12.03	$101.26	$294.07
Burnett Mary	743,817	4,672	$12.37	$13.03	$20.91	$23.16

The range of cost-effectiveness for each practice change, according to region, is visually represented in Figure 3 to Figure 5.

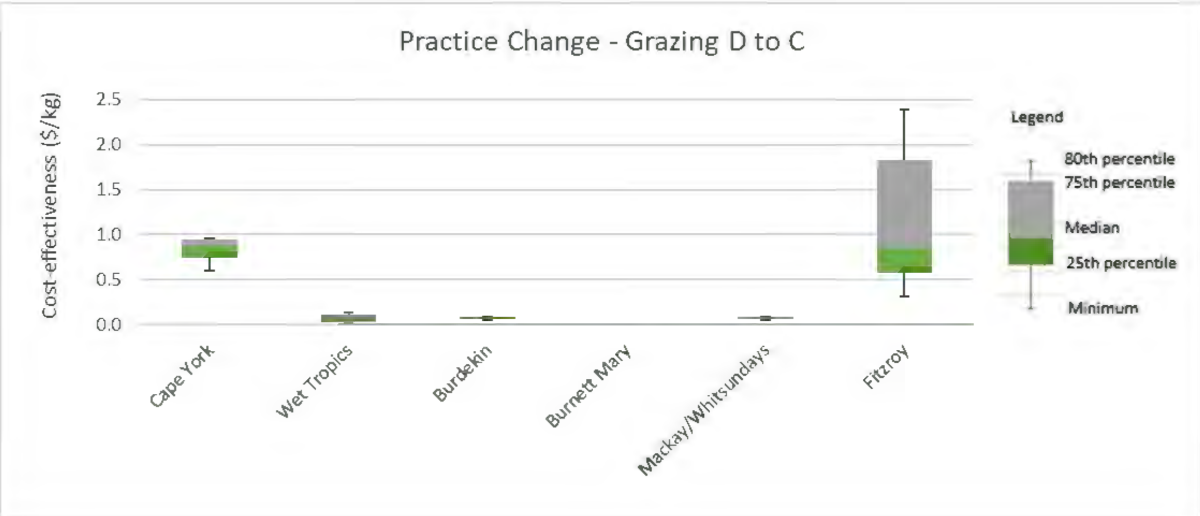


Figure 3. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for grazing D to C practice change*

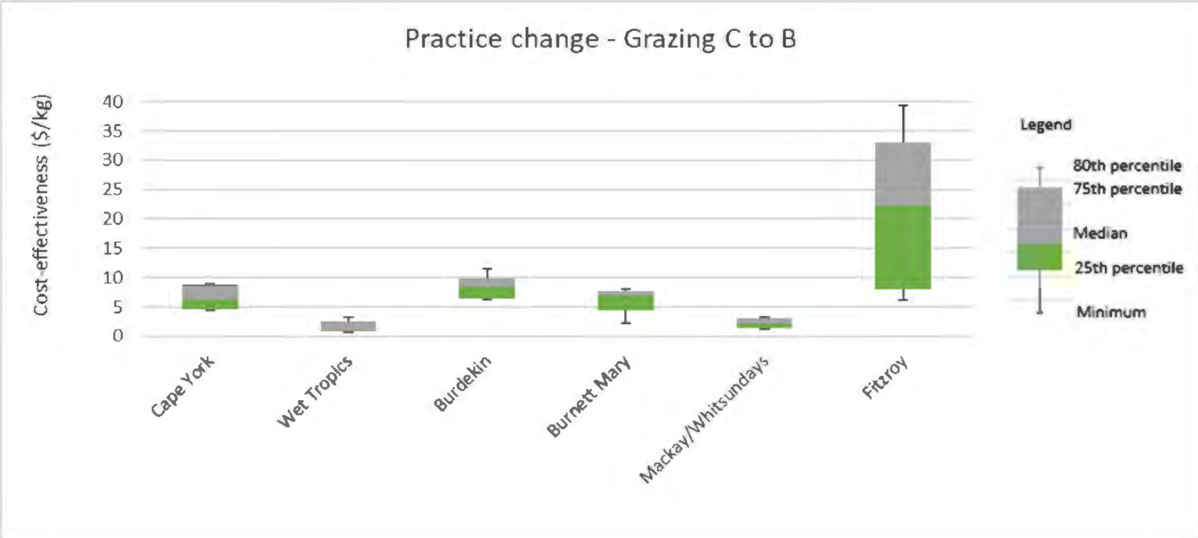


Figure 4. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for grazing C to B practice change*

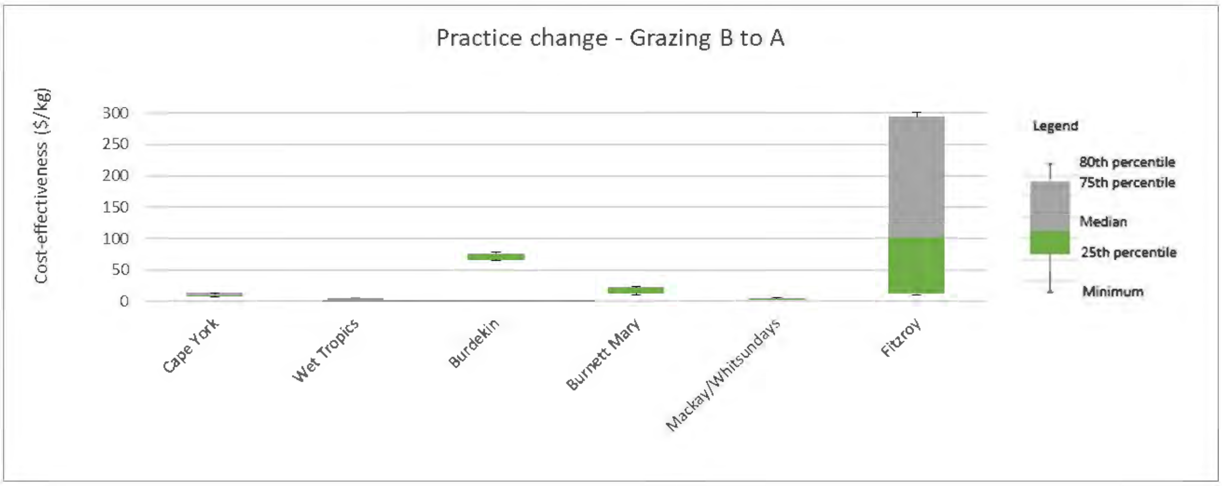


Figure 5. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for grazing B to A practice change*

3.2 Assumptions and limitations

The main assumption in this solution statement is that we have only attributed the reductions in fine sediment associated with improvements in hillslope erosion. It is likely that the actions implemented would also improve gully and streambank condition if vegetation cover is increased, those these improvements have not been accounted for in the efficacies assumed for fine sediment load reductions. There is also limited evidence on the likely reductions attributed to each practice change step, and while literature exists around the performance of key components of the changes, an evaluation of the combined performance of whole step change is lacking.

4 Contributors

Efficacy of practice improvement was discussed and agreed to by Mark Silburn and other Paddock to Reef modelling staff as part of the previous Reef Costings work (Alluvium 2016).

Cost information was obtained and processed by the project team to generate the results presented here.

5 References

Alluvium (2016). Costs of achieving the water quality targets for the Great Barrier Reef by Alluvium Consulting Australia for Department of Environment and Heritage Protection, Brisbane.

DeGraff, J. V., (1980). "Reducing man-caused gully erosion". *Rangelands* 2, 193-194.

Eberhard, R., Thorburn, P., Rolfe, J., Taylor, B., Ronan, M., Weber, T., Flint, N., Kroon, F., Brodie, J., Waterhouse, J., Silburn, M., Bartley, R., Davis, A., Wilkinson, S., Lewis, S., Star, M., Poggio, M., Windle, J., Marshall, N., Hill, R., Maclean, K., Lyons, P., Robinson, C., Adame, F., Selles, A., Griffiths, M., Gunn, J. and McCosker, K. (2017). 'Scientific Consensus Statement 2017: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef'. Chapter 4: Management options and their effectiveness. Queensland.

Kuhlman, T., Reinhard, S., Gaaff, A. (2010). "Estimating the cost and benefits of soil conservation in Europe". *Land Use Policy* 27, 22-32.

Moravek, T., Hall, T., (2014). Impacts of rehabilitating degraded lands on soil health, pastures, runoff, erosion, nutrient and sediment movement. Project RRRD.024 Final Report Part III. The State of Queensland.

Queensland Government (2018). Water Quality Risk Grazing Practices Framework (2018). Accessed at https://www.reefplan.qld.gov.au/measuring-success/paddock-to-reef/assets/paddock-to-reef-grazing-water-quality-risk-framework.pdf.

Rolfe, J., & Gregg, D. (2015). 'Factors affecting adoption of improved management practices in the pastoral industry in Great Barrier Reef catchments'. *Journal of Environmental Management*. 157, 182-193.

Shaw, M. (2019). "Paddock to Reef Management Practices". Reef 2050 Water Quality Improvement Plan. https://www.reefplan.qld.gov.au/tracking-progress/paddock-to-reef/management-practices.

Silburn D.M., Wilkinson S.N., Whish G., Stokes C.J., O'Reagain P., Thornton C., Hawdon A.A., Kinsey-Henderson A.E., Dougall C. In review. 'Paddock to Reef Synthesis of Management Practice Effectiveness in Grazing'. Queensland.

Star, M., Donaghy, P. (2009). Project Report Enhancing economic input to the CQSS2: Department of Employment, Economic Development and Innovation.

Star, M., Donaghy, P. (2010). Economic modelling of grazing systems in the Fitzroy and Burdekin catchments: Department of Employment, Economic Development and Innovation.

Star, M., Donaghy, P., Rolfe, J. (2011). Economically viable land regeneration in Central Queensland and improved water quality outcomes for the Great Barrier Reef. The Rangeland Journal, 33, 267–276. http://dx.doi.org/10.1071/RJ10005.

Star M., Rolfe, J., East M. (2013). Understanding the trade-offs of grazing management practices: A case study approach in the Burdekin Catchment. Report for the Department of Environment and Heritage Protection.

Star, M., Rolfe, J., Donaghy, P., Beutel, T., Whish, G., Abbott, B. (2013). Targeting resource investments to achieve sediment reduction and improved Great Barrier Reef health. Agriculture, Ecosystems & Environment 180, 148-156.

Star, M., Rolfe, J., Long, P., Whish, G., Donaghy, P. (2015). Improved grazing management practices in the catchments of the Great Barrier Reef, Australia: does climate variability influence their adoption by landholders? The Rangeland Journal 37 (5), 507-515.

Star, M., Rolfe, J., East, M., Beutel, T., McCosker, K., Ellis, R., Darr, S., Coughlin, T., (2017). Can paddock scale data integration achieve more cost effective outcomes in the Great Barrier Reef? A case study in the Fitzroy Basin. J. Environ. Manage. 1-15.

Valentin, C., Poesen, J., Li, Y. (2005). "Gully erosion: impacts, factors and control". *Catena* 63, 132-153.

Appendix

Grazing Water Quality Risk Framework 2018

Soil erosion & water quality risk associated with grazing land management		Low risk	Low to moderate risk	Moderate risk	High risk
Hillslope (Pasture) Management	Expectations of long term carrying capacities (LTCC[i]) (>10 years) for the whole property are strategic and realistic.	LTCC estimates are equivalent to or less than district benchmarks. LTCC is developed using: • land condition monitoring data, • district benchmarks, • historical data, • paddock records. GLM[ii] and Stocktake equivalent processes are considered and where available and appropriate, remote sensing data is also incorporated. LTCC is reviewed each year and if changes in land condition occur.	LTCC estimates are equivalent to district benchmarks. LTCC is developed using a combination of the following: • land condition monitoring data, • district benchmarks, • historical data, • paddock records. GLM and Stocktake equivalent processes are considered. LTCC is not reviewed on an annual basis.	LTCC estimates are greater than district benchmarks. LTCC is developed using at least one of the following: • land condition monitoring data, • district benchmarks, • historical data, • paddock records. LTCC is not reviewed on an annual basis.	LTCC estimates are greater than district benchmarks. LTCC is developed based on personal experience and limited additional data sources. Never reviewed.
	Expectations of seasonal and/or annual stocking rates (SR), that each paddock will carry, are realistic and tactical.	Stocking rates are estimated for all paddocks based on seasonal forage budgeting using Adult Equivalents (AE) or Livestock Units (LSU) standards. **Stocking rates do not exceed 10-30% pasture utilisation and** **>2000kg/ha pasture biomass**[iii]. Stocking rates are adjusted to meet pasture utilisation and biomass targets and the required level of ground cover.	Stocking rates are estimated for the entire property and sometimes use Adult Equivalents (AE) or Livestock Units (LSU) standards. Annual forage budgeting is sometimes taken into consideration. **Stocking rates do not exceed at least 30% pasture utilisation at least 2000kg/ha pasture biomass**. Stocking rates are occasionally adjusted to meet pasture utilisation and biomass targets and the required level of ground cover.	Stocking rates are rarely estimated for the entire property and do not use Adult Equivalents (AE) or Livestock Units (LSU) standards. **Stocking rates achieve pasture utilisation levels of 30-50% and at 1000-1500kg/ha pasture biomass.** Stocking rates are rarely adjusted to meet pasture utilisation and biomass targets and the required level of ground cover.	Stocking rates are not estimated for the entire property. **Stocking rates achieve pasture utilisation levels of <50% and at 1000kg/ha pasture biomass.**
	Groundcover[iv] thresholds are monitored and objectively managed to inform paddock management and	**Annual ground cover thresholds are maintained at >75% across the whole property**[v]. Forage	**Annual ground cover thresholds are maintained at 75-50% across the whole property**. Forage	**Annual ground cover thresholds are maintained at <50% across the whole property**. Forage	**Annual ground cover thresholds are maintained at <50% across the whole**

Soil erosion & water quality risk associated with grazing land management		Low risk	Low to moderate risk	Moderate risk	High risk
	used to inform SR and pasture management decisions.	budgets as per the GLM, Stocktake, grazing charts or equivalent process are undertaken on a seasonal basis in each paddock to monitor ground cover changes and the density of 3P pasture species. Ground cover trends and changes are monitored using FORAGE or VegMachine. Any changes are used to inform stocking rate.	budgets as per the GLM, Stocktake, grazing charts or equivalent process are undertaken on a seasonal basis across the property to monitor ground cover changes and the density of 3P pasture species. Any changes are used to inform stocking rate.	budgets as per the GLM, Stocktake, grazing charts or equivalent process are undertaken on an annual basis in most paddocks to monitor ground cover changes and the density of 3P pasture species. Changes are rarely used to inform stocking rate.	**property**. No form of forage budgeting is undertaken.
	Land condition assessments for all land types are based on: 1) Soil condition (amount of ground cover, infiltration rate, level of erosion), 2) Pasture condition (density and vigour of 3P grasses, amount of weed species), 3) Woodland condition (balance of woody weeds vs. pasture in different land types, amount of thickening).	Land condition assessments of soil, pasture and woodland condition are undertaken using photo monitoring sites and historical data (or equivalent techniques). This assessment is documented for all land types, undertaken on a seasonal basis and is considered in grazing and livestock management. Where available and appropriate, remote sensing technology is used to monitor long term trends in ground cover (FORAGE, VegMachine).	Land condition assessments of soil, pasture and woodland condition are undertaken and use photo monitoring sites or historical data (or equivalent techniques). This assessment is documented for all land types, is undertaken on an annual basis and is considered in grazing and livestock management.	Land condition assessments of soil, pasture and woodland condition are rarely undertaken. This assessment is not documented for all land types, is rarely undertaken on an annual basis and is sometimes considered in grazing and livestock management.	No assessments of land condition are undertaken.
	Management is tailored to encourage recovery of vulnerable areas, particularly those in declining (C) or poor condition (D)	Selectively grazed or vulnerable areas in C and/or D condition are identified and appropriate actions are taken to remediate these areas. The grazing management of affected area/s has been reviewed and stock have been permanently excluded for D condition areas and where appropriate for C condition areas. Additional actions include establishing diversion banks; break surface of scalded areas and sow grass seed, review placement of existing infrastructure such as watering points and incorporation of a spelling regime.	Selectively grazed or vulnerable areas in C and/or D condition are identified and appropriate actions are taken to remediate these areas. The grazing management of affected area/s has been reviewed and where possible stock have been excluded. Additional actions include establishing diversion banks; break surface of scalded areas and sow grass seed, review placement of existing infrastructure such as watering points and incorporation of a spelling regime.	Selectively grazed or vulnerable areas in C and/or D condition have mostly been identified and some actions have been taken to remediate these areas.	Selectively grazed or vulnerable areas in C and/or D condition have not been identified. No actions to remediate these areas.

Soil erosion & water quality risk associated with grazing land management		Low risk	Low to moderate risk	Moderate risk	High risk
	Property mapping and inventory of natural resources enables objective assessment of long-term carrying capacity and stocking rate.	Property map (GIS/GPS, sat image, aerial photo, farm map software etc.) including: • Actual fence line location • Actual water point location • Land types based on grazing land types for region (or equivalent) • Measured paddock areas • Measured land type areas • Grazing circles around water points • Vulnerable/sensitive land types (including frontages and wetlands)	Property map (hard copy, aerial photo, topographic map and/or farm map software etc.) including: • Estimated fence line location • Estimated water point location • Land types based on grazing land types for region • Measured paddock areas • Estimated land type areas	Limited fence line and infrastructure mapping; rough estimates of paddock areas, little or no information on paddock land types or their areas.	
Streambank Management	Grazing pressure on frontage country and wetlands is effectively managed.	Fencing as much as is practical and cost-effective; off-stream water points through-out; seeking assistance with areas which cannot be justified by benefit : cost alone	Fencing as much as is practical and cost-effective; off-stream water points or other measures (supplementary feed/shade for camps) installed to attract cattle away from riparian and wetland areas.	Limited fencing; limited offstream watering.	Generally no fencing or offstream waters.
	Grazing pressure on frontage country and wetlands is managed carefully to maintain or improve the condition of these vulnerable land types	Full stock exclusion or low stocking pressure; regular wet season spelling; weed control through fire or other means; feral pig control program.	Moderate stocking pressure; occasional wet season spelling and weed/pest control.	Some spelling but unplanned and largely incidental.	No specific management applied.
Gully Management	Remedial actions are undertaken to facilitate recovery of entire gullied area/s.	Remediation of the entire gullied area is undertaken using professional advice to inform the required remediation actions. Actions include revegetation of gullied area and stock exclusion, temporary structures such as stick traps, porous check dams, contour banks, engineered check dams and mechanical gully reshaping and earth works.	Remediation of sections of the gullied area is undertaken using a mix of actions. These include managing existing infrastructure (watering points, fences) to reduce erosion, redistributing the grazing pressure away from gullied areas, fencing to exclude stock and/or adjusting stocking rates to encourage pasture growth.	Management of gullied areas is addressed through grazing management practices such as: those aimed at increasing pasture biomass and decreasing pasture utilisation rates to 25-30%; increasing ground cover levels; redistribution of grazing pressure; using fire and weed management; and reducing the clearing of woody vegetation.	Little or no change in management for gullied areas.

Soil erosion & water quality risk associated with grazing land management		Low risk	Low to moderate risk	Moderate risk	High risk
	Managing risk of erosion associated with linear features.	Linear features (Roads, tracks and fences) planned and built with due attention to erosion risk. Where there are significant risks, an appropriate mix of actions has already been undertaken. Actions will include: locating tracks on contour where possible; **avoiding disturbance of sodic subsoils**, whoa boys or similar means to allow run-off to cross the road; table drains where required; outfalls for low usage, cross-slope roads on steep country; using invert, floodway, causeway, culvert or bridge when track crosses drainage line or creeks, fences follow contour lines where possible, or ridge lines in steep country. Where fence line is not on the contour, and slope is steep, whoa-boys are used as required.	Linear features planned and built with due attention to erosion risk. Areas with known sodic subsoils are avoided where possible. Creek crossings built at bed level to avoid changes to hydrology. Where there are significant risks, an appropriate mix of actions is in process of being completed.	Linear features not routinely planned or built with due attention to erosion risk. Whoa boys or equivalent sometimes used; some stream crossings have appropriate works in place.	Little or nothing in terms of planning or precautions for erosion risk.
Managing the Breeder Herd	Appropriate nutritional management of heifers from the time of weaning ensures heifers reach puberty and are joined at the appropriate critical mating weight (CMW) of 60-65% of their mature body weight to encourage maximum fertility.	Replacement heifers are managed to achieve target CMW weight. Heifers are weighed strategically to monitor their growth and guide decisions about grazing management and supplementation.	Replacement heifers are managed to achieve CMW by mating date.	There has been some attempt to manage heifers to join at the right weight and at the right joining age.	Target weight or age at first mating is not considered.
	Segregation of heifers from the main breeder herd allows for targeted management to ensure only highly fertile females are retained. Management of the joining period based on green date[vi] ensures heifers calve at the optimal time of year.	Heifers are joined to calve at the optimal time of year, based on the properties green date. Heifers are segregated until second mating to manage body condition i.e. supplementation and weaning management. Replacement heifers are joined for a shorter period than the main breeder herd to identify and retain fertile females.	Heifers are generally joined to calve based on normal joining period of the region. Heifers are segregated until second mating so targeted management of body condition can be implemented i.e. supplementation and weaning management. Heifers are joined for the same period as the main breeder herd.	Heifers are generally joined to calve based on normal joining period of the region. Heifers are not segregated and are joined for the same period as the main breeder herd.	Heifers are not joined to calve at the optimal time for the region. Heifers are not segregated and are joined for the same period as the main breeder herd.

Soil erosion & water quality risk associated with grazing land management		**Low risk**	**Low to moderate risk**	**Moderate risk**	**High risk**
	Managing breeder body condition pre and post gestation using appropriate nutritional management to maintain high conception rates.	Early weaning and supplementation (where costeffective) are used to achieve body condition targets for optimum reproductive performance. Breeder body condition is assessed, recorded and managed on a frequent basis. **The average breeder body condition for the entire herd before calving is >3.5[vii].**	At least one management strategy (early weaning or supplementation strategies) is used to achieve body condition targets. Breeder body condition is assessed regularly. **The average breeder body condition for the entire herd before calving is <3.5.**	Breeder body condition is not assessed or considered in management. **The average breeder body condition for the entire herd before calving is <3.5.**	
	The number (and weight) of calves branded/weaned (branding %[viii]) for the number of females joined to produce those calves monitored and used as a key indicator of herd performance and productivity.	Breeder performance is assessed annually using calving rates and weaning (branding) percentages. **Branding rates are >85%.** Foetal and calf losses are recorded annually using pregnancy testing data and weaner numbers. Individual animal performance data coupled with stock records is used to guide management decisions.	Breeder performance is assessed annually using calving rates and weaning (branding) percentages. **Branding rates range from 85-75%.** This information is used to guide management decisions.	Breeder performance is assessed annually using calving rates and weaning (branding) percentages. **Branding rates range from 75-50%.** Foetal and calf loss information is rarely measured and rarely considered in management decisions.	Breeder herd performance, and foetal and calf losses are not measured or considered in management decisions. **Branding rates are <50%.**
	Specific criteria are used when culling breeder and bulls and again when selecting replacement heifers and bulls.	Rigorous culling is undertaken annually based on specific, established criteria regarding temperament, reproductive performance, age and soundness. Only heifers which conceive and produce a calf in their first joining period are retained in the breeding herd. Bull Breeding Soundness Evaluations (BBSE) are used when purchasing replacement sires. Bulls are monitored and those which develop structural, reproductive or temperament problems are culled promptly. Bulls are culled for age at 7 years. Individual animal performance data is used to guide culling and replacement decisions.	Culling is undertaken annually using broad criteria and poorly performing heifers are often retained due to a lack of records and poor management. Bull Breeding Soundness Evaluations (BBSE) are rarely undertaken when purchasing replacement sires. Bulls are rarely monitored and are often kept longer than 7 years.	Culling is not done systematically using specific, established criteria. Bull Breeding Soundness Evaluations (BBSE), age and body condition are not considered when purchasing and managing sires. Bulls are kept for >7 years.	

Soil erosion & water quality risk associated with grazing land management		**Low risk**	**Low to moderate risk**	**Moderate risk**	**High risk**
	There are a range of fertility diseases that can infect breeding cattle and reduce weaning rates. Being able to recognise, prevent and manage these diseases is vital in maintaining herd health and productivity.	Fertility disease risks are considered and breeding stock, including bulls are vaccinated annually for 7in1 or Leptospirosis, Vibriosis and Pestivirus where appropriate. The disease status of the herd has been determined and if pregnancy test results or foetal and calf losses indicate possible disease problems further investigations have been or are being undertaken.	Fertility disease risks are considered and breeding stock, including bulls are vaccinated annually for 7in1 or Leptospirosis, Vibriosis and Pestivirus where appropriate. The disease status of the herd is unknown. The disease status of the herd is unknown.	Fertility disease risks are rarely considered and breeding stock, including bulls are rarely vaccinated. There are no specific management strategies implemented for control and prevention. Investigations are rarely undertaken if calf losses indicated possible disease problems.	
	Nutritional deficiencies can affect animal performance and in some situations contribute to health problems.	Testing is undertaken where appropriate to identify nutritional deficiencies on the property including NIRS, phosphorus maps and blood testing. This is used to guide supplementation and other strategies management and are implemented where appropriate.	Potential nutritional deficiencies are identified from local experience and land type information. Supplementation and other strategies are implemented where appropriate.	There has been an attempt to identify and manage nutritional deficiencies on the property.	Nutritional deficiencies on the property are not recognised or managed.
Weaner Management	Appropriate management and preparations for weaning ensures weaners are segregated using specific criteria that enables targeted nutritional management to ensure maximum future production.	Numbers, ages and estimated weight ranges of weaners are assessed before weaning Weaners are drafted, fed and managed according to weight, age and health. Individual animal identification is used to monitor and record performance. The nutritional requirements for weaners is understood.	Numbers, ages and estimated weight range of weaners are mostly assessed prior to weaning. Most of the time weaners are drafted, fed and managed according to weight, age and health. The nutritional requirements for weaners is sometimes understood.	Numbers, ages and estimated weight ranges of weaners are rarely assessed. Weaners are not drafted, fed and managed accordingly to weight, age or health. The nutritional requirements for weaners is not understood.	
	Adequate health management strategies are implemented during weaning to minimise the health risks associated with weaning and the susceptibility of weaners to these health risks.	Appropriate vaccinations to manage identified disease risks are administered. Treatment for internal parasites is based on visual assessments and faecal egg count testing. Treatment for external parasites is undertaken as appropriate. Health issues and treatments are routinely documented as part of a health management program.	Appropriate vaccinations to manage identified disease risks are administered. Treatment for internal and external parasites is based on visual assessment and undertaken when appropriate. Health issues and treatments are routinely documented as part of a health management program.	Appropriate vaccinations are rarely used to manage and prevent disease. Treatments for both internal and external parasites is not undertaken on a regular basis. Health issues and treatments are rarely documented.	Weaner health is not systematically planned and/or managed.

Soil erosion & water quality risk associated with grazing land management		Low risk	Low to moderate risk	Moderate risk	High risk
Use of Agriculture Chemicals	Use of Tebuthiuron[ix] (where used)	Records kept with respect to date of application, location and area of paddock(s) treated, Product trade name, application rate, spray conditions, operator details; includes map details. Conform to regulations[x] designed to minimise the run-off of tebuthiuronbased products from grazing properties (Chemical Usage (Agricultural and Veterinary) Control Regulation 1999) in addition to existing label instructions on the product.		Little or no record keeping Do not conform to regulations and/or label instructions.	
	Application of fertilisers (where used on significant areas of perennial pasture)	Records kept of areas treated, rates applied, and any soil testing done prior to application.		Little or no record keeping	
	Application of phosphorus (P) fertiliser	For establishment, applying up to 20 kg P per ha in sub-coastal and drier areas (eg, for stylos), and up to 50 kg P per ha for highrainfall coastal pastures.		Higher than recommend rates of P applied for establishment of pasture.	
	Application of nitrogen (N) fertiliser	Apply rates consistent with recommendations from a professional fertiliser advisor; Split applications over the season; Do not apply during main wet season or adjacent to waterways.		Use higher than recommended rates and/or do not spilt applications and/or apply during main wet season and/or apply adjacent to waterways.	

Erosion Process	Management Tactic	P2R Weighting
Hillslope erosion	Expectations of long term carrying capacities (LTCC) (>10 years) for the whole property are strategic and realistic.	10%
	Expectations of seasonal and/or annual stocking rates (SR), that each paddock will carry, are realistic and tactical.	35%
	Groundcover thresholds are monitored and objectively managed to inform paddock management and used to inform SR and pasture management decisions.	30%
	Land condition assessments for all land types are based on: 1) Soil condition (amount of ground cover, infiltration rate, level of erosion), 2) Pasture condition (density and vigour of 3P grasses, amount of weed species), 3) Woodland condition (balance of woody weeds vs. pasture in different land types, amount of thickening), 4) Ground cover (minimise bare areas and run-off). The assessment is done via various monitoring techniques coupled with historical data and is considered in grazing and livestock management.	10%
	Management is tailored to encourage recovery of vulnerable areas, particularly those in declining (C) or poor condition (D)	10%
	Property mapping and inventory of natural resources enables objective assessment of long-term carrying capacity and stocking rate.	5%
	Hillslope erosion assessment	100%
Streambank erosion	Grazing pressure on frontage country and wetlands is effectively managed.	100%
	Grazing pressure on frontage country and wetlands is managed carefully to maintain or improve the condition of these vulnerable land types	
	Streambank erosion assessment	100%
Gully erosion	Remedial actions are undertaken to facilitate recovery of entire gullied area/s.	40%
	Managing risk of erosion associated with linear features.	30%
	Hillslope erosion assessment	30%
	Gully erosion assessment	100%
Managing the breeder herd	Appropriate nutritional management of heifers from the time of weaning ensures heifers reach puberty and are joined at the appropriate critical mating weight (CMW) of 60-65% of their mature body weight to encourage maximum fertility.	10%
	Segregation of heifers from the main breeder herd allows for targeted management to ensure only highly fertile females are retained. Management of the joining period based on green date ensures heifers calve at the optimal time of year.	15%
	Managing breeder body condition pre and post gestation using appropriate nutritional management to maintain high conception rates.	35%
	The number (and weight) of calves weaned (weaning rate %) for the number of females joined to produce those calves monitored and used as a key indicator of herd performance and productivity.	
	Specific criteria are used when culling breeder and bulls and again when selecting replacement heifers and bulls.	5%
	There are a range of fertility diseases that can infect breeding cattle and reduce weaning rates. Being able to recognise, prevent and manage these diseases is vital in maintaining herd health and productivity.	20%

	Nutritional deficiencies can affect animal performance and in some situations contribute to health problems.	10%
	Breeder herd assessment	100%
Weaner Management	Appropriate management and preparations for weaning ensures weaners are segregated using specific criteria that enables targeted nutritional management to ensure maximum future production	30%
	Adequate health management strategies are implemented during weaning to minimise the health risks associated with weaning and the susceptibility of weaners to these health risks.	30%
	Breeder management assessment	40%
	Weaner Management assessment	100%

[i] Long Term Carrying Capacity (LTCC) or 'safe' grazing capacity is defined as the number of animals (adult equivalents) that can be carried on a land type, paddock or property in the long term without any decrease in pasture condition and without accelerated soil erosion (Johnston et al. 1996, Mckeon et al. 2009, Scanlan et al. 1994).

[ii] GLM steps for LTCC of a paddock account for area, land types, condition of land, climate, safe utilisation rates and distance to water. [iii] Pasture utilisation and biomass targets as per Scientific Consensus Statement Chapter 4 (Eberhard et al. 2017).

[iv] Groundcover thresholds are usually associated with the amount of cover below which the rate and amount of erosion starts to increase greatly; the thresholds (eg, 40% cover) operate primarily by reducing the direct erosive impact of rainfall. However, there are benefits for the overall hydrological condition of the soil from levels of organic cover above the threshold value for reducing erosion - the more organic matter from herbaceous plants that is protecting and feeding the soil, the better its hydrological condition. The threshold values of cover for soil condition and erosion reduction will obviously vary from land type to land type depending on soil, slope, fertility, and pasture type. Regional land type information sheets usually have the erosion thresholds values appropriate for each major land type. [v] Ground cover targets as per Scientific Consensus Statement Chapter 4 (Eberhard et al. 2017). [vi] Green date is defined as a three day period where greater than 50mm of rain has fallen. This information is recorded annually or can be obtained from RainMan. The information obtained from Rainman is not updated regularly and reflects district green dates and cannot be property specific. [vii] Body condition score targets as per English, B (2012) & MLA Breeding Edge workshop notes.

[viii] Branding rates were compiled form a number of sources: Burrow, H (2014), McGowan et al (2014), Tyler et al. (2004).

[ix] Tebuthiuron is a substituted urea herbicide used for control of woody regrowth and woody weeds. Tebuthiuron is absorbed by woody plants via the roots and translocated to stems and leaves where it inhibits photosynthesis.

[x] See http://www.reefwisefarming.qld.gov.au/pdf/tebuthiuron.pdf

Solution Statement 3: Practice change - Pesticides

1 Scenario description and context

The Reef 2050 Water Quality Improvement Plan identifies a range of actions to manage pesticide use in areas of sugarcane. These actions are focussed on the reduction of PSII herbicides mostly associated with sugarcane agriculture across the GBR.

In this solution statement, we have focussed on the costs and efficacies of implementing the range of actions outlined in the 2018 Water Quality Risk Management Framework. These costs are focused on if the grower was to adopt the pesticide management practices in isolation of other sugarcane management practice improvements such as water efficiency and fertiliser management.

The specific management actions being assessed for inclusion in the Investment Pathways tool are:

1. Practice change Pesticides D-C (High to Moderate Risk)
2. Practice change Pesticides C-B (Moderate to Moderate-Low Risk)
3. Practice change Pesticides B-A (Moderate-Low to Low Risk)

These correspond to improving pesticide practice through each step of the risk framework.

2 Approach

2.1 Costs

2.1.1 Data

For the purposes of this study we only focused on pesticides in sugarcane management from the four water quality risk categories, and only the PSII pesticides were assessed. Although tebuthiuron is classified as a PSII it was excluded as it is predominately used in grazing. Similarly, although grub control is captured in the Water Quality Risk framework it too was also excluded as the active ingredient is imidacloprid, which is a non PSII pesticide. Due to the focus on PSII and the exclusion of imidacloprid only two categories were costed. Moderate risk to low risk and low risk to innovative shifts.

The pesticide management component of the framework is heavily focused again on assessment and monitoring along with banding and changes to knock-down pesticides. The capital costs have a significant range with some growers' potential only requiring small adjustments to machinery (such as nozzle adjustments), with others however potentially requiring significant changes to high clearance dual herbicide spray rigs (Table 1). Costs were derived from a number of sources such as past Reef Rescue investments, and current dealership costs. Again, expert agronomy advice and the ability to use software to develop maps was also costed (Table 1). It must be highlighted that some costs such as agronomic support and soil testing have been costed in both the pesticide and nutrient scenarios, however in reality these are costs are whole farm system change costs that would not be duplicated.

Table 1. Descriptions of pesticides management changes

Moderate risk to low risk	Low risk to innovative
Minimal use of residual herbicides High clearance (out of hand) dual herbicide sprayer implemented with variable rate controller. Example range of costs from a minimum: Purchase variable rate chemical controller ($5,000) Upgrade spray boom for variable rate ($24,600) Maximum costs:	Soil test (1 every 2.5ha @ $15 per test) and EC mapping to indicate soil boundaries. Purchase of SMS for mapping and risk assessment ($910)

Purchase second-hand JD high clearance tractor & rig 1.8m space, 2 tanks, rate controllers & boom ($100,000) Prices include air inducted nozzles and Irvin legs, which have been costed separately to highlight partial shifts.	
	Expert agronomy advice and electronic record keeping of spraying events (1hr for every 10ha at $85 per hour)
Irvin legs are adopted Tracking leg s- $1,542.00. Price includes 4 legs, Dropper pod, parallelogram, tracking head all pins & hose to nozzle platform	Shielded sprayer used for inter-row applications, knockdown herbicides replace residuals where possible (minimum cost for 7 shields to modify existing - $3,500. Maximum cost of second-hand 7 row shielded sprayer - $54,000
Air inducted nozzles used to reduce drift. Nozzles - Teejet AIXR 110- $11.00 per nozzle Nozzles - Teejet XR 110 - $9.80 per nozzle	Risk assessment undertaken before spraying
Risk assessment undertaken before spraying and better timing of herbicide applications	Seasonal rainfall outlooks analysed for spraying strategies

The following costs were estimated for pesticides practice changes: (1) capital – on ground direct costs of purchasing and installing capital equipment; (2) operating and maintenance – costs associated with on farm operations and maintenance after the practice change; and (3) program – these are the additional costs to cover overhead expenses, extension, monitoring and evaluation to support practice change uptake.

2.1.2 Results

After careful consideration of the required changes, costs were estimated for each practice change and region. Table 2 provides a summary of the estimated initial cash costs over a 5-year period. A 2.5% inflation rate was used to adjust the estimated year 1 costs over subsequent years (year 1 to 5). The 5-year cash costs are the estimated funds to support practice change over the initial 5 years. For example, in the Burnett Mary region, it is estimated that the most likely cost of shifting from a C to a B practice requires capital costs of $640, operating and maintenance costs of $96 in year 1 and program costs of $109 in year 1.

Table 2. Most likely cash costs by practice change and region over a 5-year period (2018 AUD)

Practice Change	NRM Region	Capital	Operating and maintenance					Program				
	Year	1	1	2	3	4	5	1	2	3	4	5
	Region											
Pesticides C-B	Burnett Mary	640	96	98	101	103	106	109	112	114	117	120
	Burdekin	640	96	98	101	103	106	109	112	114	117	120
	Mackay Whitsunday	457	69	70	72	74	76	78	80	82	84	86
	Wet Tropics	534	80	82	84	86	88	91	93	95	98	100
Pesticides B-A	Burnett Mary	2,044	307	314	322	330	338	347	356	365	374	383
	Burdekin	3,044	457	468	480	492	504	518	531	544	557	571
	Mackay Whitsunday	2,703	405	416	426	437	447	459	471	483	495	507
	Wet Tropics	2,368	355	364	373	382	392	402	413	423	433	444

Life cycle costs (2018AUD per ha) over a 30-year appraisal were estimated using a 7% discount rate. Life cycle costs are the estimated costs per ha over a 30-year period in 2018 Australian dollar values. These costs include all three estimated costs categories i.e. capital, operating and maintenance, and program costs. It should be noted that there is significant variability in the range of input data and assumptions used in the modelling. Thus, data on low (best), most likely and high (worst) costs was included in our modelling to capture this variability. Table 3 shows the estimated most likely costs (annual $ per ha) and the 90% prediction interval from a Monte Carlo simulation with 20,000 iterations. The best and worst values represent the 5th and 95th percentile for each reported cost estimate. These results indicate that the most likely life cycle costs for a practice change in the Burnet Mary from D – C is $3,388 per ha over 30 years and the 90% prediction interval ranges from $2,847 to $4,636.

It is intuitive to assess how much of an impact each of the different costs have on the bottom line estimates of lifecycle costs (LCCs). For a sugarcane fertilizer management shift from D-C in the Burnett Mary, our Monte Carlo estimations indicate that program costs have the greatest contribution to variance in the 30-year LCCs at 51%, followed by operating and maintenance costs at 40%, and capital costs have the least effect on percentage contribution variance in the LCCs. This contribution to variance is a result of the variability and/or confidence in the input parameter values.

Table 3. Estimate costs of practice change and the contribution to variance in the life cycle costs

Practice change	Region	30 Year life cycle costs			Contribution to variance		
		Best	Most Likely	Worst	Capital	Operating & maintenance	Program
Pesticides C-B	Burnett Mary	2,847	3,388	4,636	9.7%	39.6%	50.7%
	Burdekin	2,745	3,388	3,656	9.7%	39.3%	51.0%
	Mackay Whitsunday	2,289	2,420	4,106	9.7%	39.1%	51.2%
	Wet Tropics	2,599	2,824	4,253	9.7%	39.6%	50.7%
Pesticides B-A	Burnett Mary	10,331	10,813	15,461	9.7%	39.5%	50.8%
	Burdekin	12,790	16,108	17,141	9.8%	39.6%	50.6%
	Mackay Whitsunday	12,214	14,299	19,028	9.7%	39.5%	50.8%
	Wet Tropics	11,027	12,527	15,912	9.8%	40.3%	49.8%

2.2 Efficacy

2.2.1 Data

According to the Scientific Consensus Statement Chapter 4 (Eberhard *et al.* 2017), there are a range of insights into reducing pesticide loss from agricultural lands. These have focussed around the management of:

1. Reducing the amount of pesticide applied, through precision application practices such as banded/shielded spray applications and spot spray technology (e.g. WeedSeeker®)
2. Timing pesticide applications to avoid risk of run-off from rainfall or irrigation within several weeks of the application
3. Choosing products with shorter persistence, greater efficacy (lower application rates), lower mobility and lower toxicity
4. Reducing run-off and soil erosion through retaining cover, controlled traffic, increased crop frequency and irrigation water management as per practice change actions for soil and nutrient management.

The science of these management actions is based on the following key principles (Eberhard *et al.* 2017):

- Increased confidence that reducing pesticide applications (e.g. through banded spraying) reduces pesticide losses from fields
- Increased confidence that avoiding run-off for three weeks after application substantially reduces pesticide losses
- Practices for managing losses also apply to the newly released chemicals

- Transport of most pesticides in current use is more dominant in the dissolved phase than previously thought, placing greater emphasis on the management of run-off. More pesticides are lost in deep drainage that previously thought, although the amount is still very small
- Integrated weed management in sugarcane has demonstrated the successful use of shorter-lived herbicides and/or lower application rates
- Frameworks to help choose pesticide products (balancing toxicity and run-off potential to reduce risk) are starting to be developed.

This demonstrates that the effectiveness of these actions is reliant on a similar risk management framework to other practice change actions. The likely actions to be applied at different management levels have been similarly characterised in an ABCD step change process. As with other practice changes, while the steps are discretised from high to low water quality risk, it is highly likely that different farms and enterprises will implement those practices which are most aligned with the management of the enterprise. It is therefore probable that discrete steps of, for example, D to C practice change are unlikely in real world situations, but they are used in planning as they allow for assessment of model scenarios in a consistent fashion.

The risk management framework developed for pesticides is shown in Table 4 below.

Table 4. Pesticide Risk Management Framework (Reef 2050 Water Quality Improvement Plan)

Priority	Management tactic	Weighting (Water quality assessment)	Indicative Practice Levels 2013*						
			Dfull = High Risk	**Cpartial**	**Cfull = Moderate Risk**	**Bpartial**	**Bfull = Moderate - Low Risk**	**Apartial**	**Afull = Lowest WQ Risk, commercial feasibility unproven**
			Superseded		Minimum		Best Practice		Innovative
Pesticide Management									
1	**Timing application of residual herbicides**	40%	Residual herbicides applied when it is most convenient and/or in salvage situations. Due consideration to current weather conditions including BoM radar and 48hr rainfall forecast.	Considers forecast for light rain to incorporate sprayed herbicides.	Residual herbicides applied as soon as practical after harvest, with due consideration to current weather conditions and 4-day rainfall forecast.	Residual herbicides applied as soon as practical after harvest, with due consideration to current weather conditions and 4-day rainfall forecast.	As for Min Std, plus: Plan to ensure residuals have been applied at least 3 weeks prior to anticipated wet season commencement.	NA	As for Best Practice, plus: Use of SafeGauge for Pesticides to further inform risk of off-site movement of herbicides.
2	**Targeting application to reduce the volume of herbicide applied**	40%	100% coverage through conventional boomspray for all applications. Generally use a set residual+knockdown tank mix.	100% coverage through conventional boomspray for all applications. Generally use a set residual+knockdown tank mix.	100% coverage through conventional boomspray for most applications. Tank mix tailored to weed situation in each block, with residuals not used if not required.	Herbicides applied as directed spray. Residual directed onto row only and knockdowns in interrow.	Area treated with residual herbicides is reduced through use of bandspraying, except for specific problem situations requiring more complete coverage. Interrows managed with knockdown products through directed or shielded spraying.	Manually shutting off applications within field based on weed pressure. Essentially same outcome as A therefore not modelled separately.	As for B, plus use of weed detecting equipment to further reduce total herbicide applied.
3	**Residual herbicide use in ratoons**	20%	Residual herbicides used whenever likely to be effective, in both plant and ratoon cane.	Residual herbicides used once only on ratoon crops.	Residual herbicides used once only on ratoon crops.	Residual herbicides used once only on ratoon crops.	Overall weed management strategy is based upon use of knockdown products in ratoons. Residual use in ratoons occurs only in strategic response to problem situations.		

* There is a slight mismatch between the costs being determined on the 2018 version of this risk framework and the efficacies derived from the 2013 one. This is because updated model runs were being conducted as this material was being prepared and hence were unavailable for inclusion. From discussions with the modellers, the magnitude of changes in efficacy were not likely to be significant for the practices costed.

2.2.2 Results

Results were obtained from the Report Card 2016 APSIM model runs provided by the Department of Environment and Science. These provided predictions in changes of runoff and drainage pesticides as a result of practice change steps.

Table 5. Pesticide efficacy for each practice change step (successive reductions)

Practice change step	Wet Tropics	Burdekin	Mackay-Whitsundays	Burnett-Mary
D-C	38%	54%	4%	85%
C-B	99.7%	68%	73%	56%
B-A	12%	100%	21%	100%

These results are based on the simulation of application of the risk management framework actions. The model results indicate a significant reduction in pesticide runoff moving from C to B practice in both the Wet Tropics and Mackay-Whitsunday regions, but is much less in the Burnett-Mary. The reasons for these differences are not entirely clear, because in the literature, most reduction is typically achieved in moving from boom spraying to banded spraying (part of C to B change in the risk framework).

3 Results

3.1 Cost-effectiveness

The treatable area and pesticide load from sugarcane for each NRM region is shown in Figure 1. The cost-effectiveness of each practice change step based on the most likely efficacy (percentage reduction) and cost ($/ha) is shown in Table 6 and Table 7.

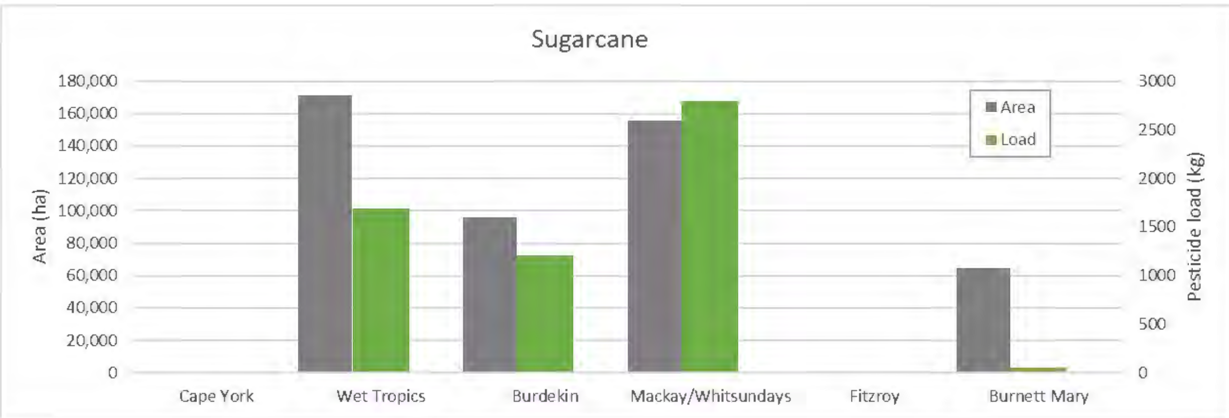


Figure 1. *Areas and loads from pesticides for each NRM region*

The following tables show preliminary estimates of cost-effectiveness based on the most likely cost per hectare (Table 2) and the stated efficacy (Table 5). For each region (e.g. Wet Tropics) there are a number of basins that each have a different delivery ratio to the end of catchment as well as a different load per hectare. This has an impact on cost-effectiveness at the end of the catchment. The range of cost-effectiveness estimates presented for each region below shows the range of end of catchment costs (minimum through to 75th percentile of the basins modelled, with values above 75th percentile considered to be too expensive to warrant investment and statistical outliers).

Table 6. Estimated cost-effectiveness and treatable area and load for pesticides C to B practice change*

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (kg)	Min	25th percentile	Median	75th percentile
Cape York	0	0	-	-	-	-
Wet Tropics	139,555	1,615	$3,043,630	$4,049,576	$4,521,316	$5,361,323
Burdekin	84,581	1,125	$210,126	$325,263	$525,052	$6,728,168
Mackay/Whitsundays	145,881	2,662	$156,891	$161,372	$173,426	$207,681
Fitzroy	0	0				
Burnett Mary	62,068	48	$2,846,724	$3,169,809	$7,188,466	$9,127,637

* *These costs are for full implementation of water quality risk framework components for the change in C to B*

Table 7. Estimated cost-effectiveness and treatable area and load for pesticides B to A practice change

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (kg)	Min	25th percentile	Median	75th percentile
Cape York	0	0	-	-	-	-
Wet Tropics	31,540	73	$7,232,732	$14,003,112	$17,717,488	$55,304,702
Burdekin	11,476	81	$2,232,806	$2,877,849	$3,522,891	$53,004,328
Mackay/Whitsundays	9,655	135	$4,628,218	$4,638,063	$4,832,208	$5,864,889
Fitzroy	0	0	-	-	-	-
Burnett Mary	2,427	1	$7,399,706	$10,508,539	$23,807,352	$39,245,667

The range of cost-effectiveness for each practice change, according to region, is visually represented in Figure 2 and Figure 3.

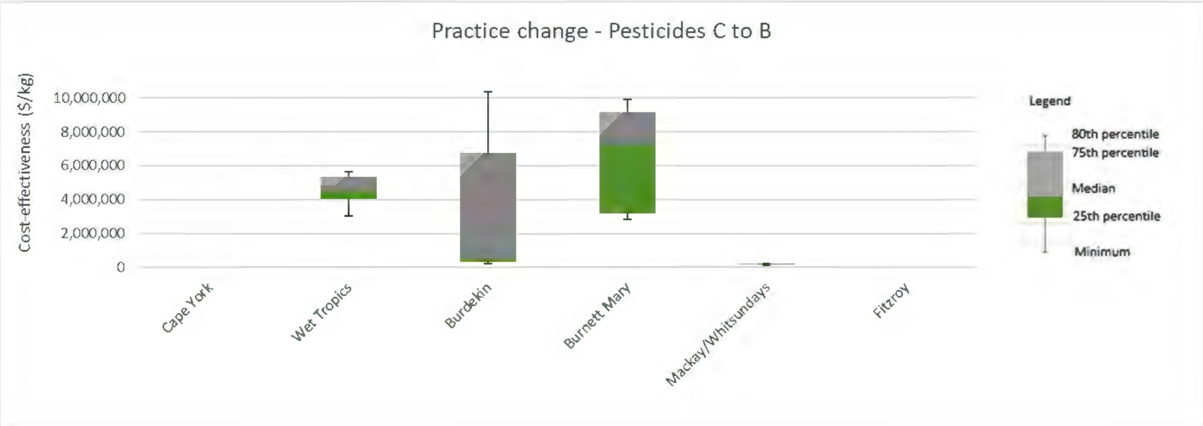


Figure 2. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for pesticides C to B practice change*

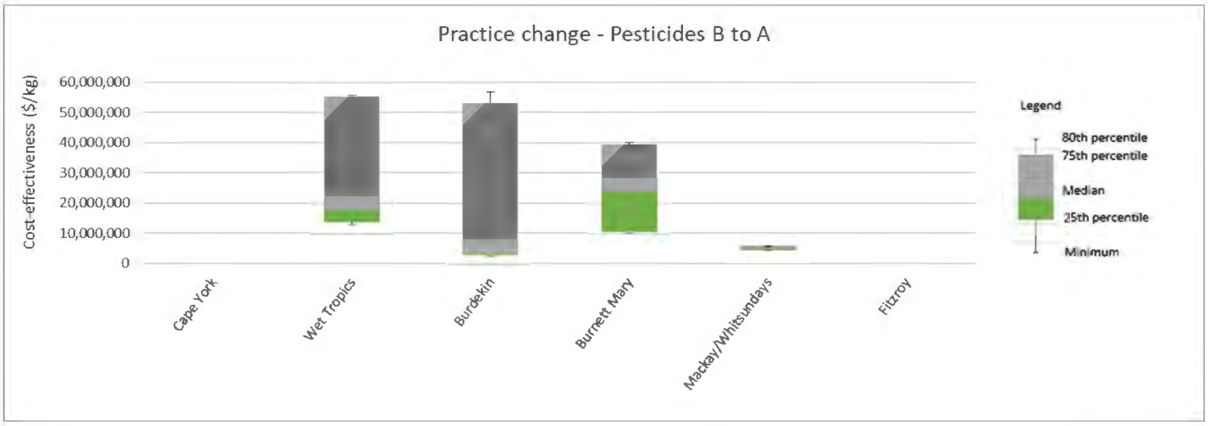


Figure 3. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for pesticides B to A practice change*

3.2 Assumptions and limitations

For this solution set, in the Burdekin Irrigation Area the efficacy of practice change improvement is affected by irrigation management, but only to a small extent. We have made the assumption that this variability in efficacy is less than the uncertainty in overall efficacy and have therefore adopted only the mid-range values for this NRM region.

We have assumed that each change in practice is a full step change, though in reality it is likely that farm managers would choose from a range of actions that best suited their enterprise. In addressing water quality risks then, it is likely that a combination of actions would lead to improvement, but they may not all clearly fall under a whole risk category (i.e. a farmer at High Risk may choose elements from Moderate and Low Risk from the risk framework.

This study has been restricted to the pesticides simulated in the Paddock to Reef modelling in the 2016 Report Card. There is considerable effort underway to improve the understanding of the range of pesticides impacting on reef ecosystems and how these may be simulated in models, in addition to updating targets and frameworks for assessment. Further efforts to then understand the impacts of these on available management actions and their efficacy is also required.

4 Contributors

Melanie Shaw provided updated efficacy results from previous APSIM modelling, noting that additional modelling is currently being undertaken for the next report card iteration.

Cost information was obtained and processed by the project team to generate the results presented here.

5 References

Eberhard, R., Thorburn, P., Rolfe, J., Taylor, B., Ronan, M., Weber, T., Flint, N., Kroon, F., Brodie, J., Waterhouse, J., Silburn, M., Bartley, R., Davis, A., Wilkinson, S., Lewis, S., Star, M., Poggio, M., Windle, J., Marshall, N., Hill, R., Maclean, K., Lyons, P., Robinson, C., Adame, F., Selles, A., Griffiths, M., Gunn, J. and McCosker, K. (2017). 'Scientific Consensus Statement 2017: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef'. Chapter 4: Management options and their effectiveness. Queensland.

Reef 2050 Water Quality Improvement Plan, Water Quality Risk Framework, Australian Government and Queensland Government. Access at www.reefplan.qld.gov.au/measuring-success/paddock-to-reef/management-practices, 14 November 2018.

Appendix

Paddock to Reef Sugarcane Water Quality Risk Framework – DRAFT 2018 (pesticides management)

Pesticide Management	Weighting	Relative Water Quality Risk			
		High	**Moderate**	**Low**	**Lowest**
Use of residual herbicides in ratoons	30%	Residual herbicides are routinely used in ratoon crops, both in response to known weed problems and as a preventative measure.		Overall strategy based on use of knockdown products only in ratoons. Residual herbicide use in ratoons only occurs as strategic response to problem situations.	Do not use residual herbicides in ratoons.
Targeting herbicide application	30%	Residual herbicides are applied through 100% coverage with conventional boomspray.		Residual herbicides are applied in a directed band over the row only. Inter-row spaces are managed with knockdown herbicides.	Residual herbicides are applied in a directed band over the row only. Inter-row spaces are managed with knockdown herbicides. AND Precise weed mapping informs zonal residual herbicide applications. Application occurs only where weed pressure is expected.
Timing of application	20%	Residual herbicides applied as soon as practical after harvest, with due consideration to current weather conditions and 4 day rainfall forecast.		Residual herbicides are applied more than 3 weeks prior to significant runoff event.	
Pesticide Selection	10%	Pesticide product choice is based on efficacy and cost effectiveness of control.		Pesticide choice is informed by assessment of control efficacy AND environmental risk, with lower toxicity products selected wherever feasible. Product choice considers the amount of active ingredient applied, its relative toxicity, half-life, solubility, and soil adsorption properties and their interaction with the soils on the farm.	

Pesticide Management	Weighting	Relative Water Quality Risk			
		High	Moderate	Low	Lowest
Managing Canegrub	10%	Insecticides are routinely applied to plant or ratoon crops. Often more than one application to a block over a crop cycle.	Control of canegrub is based on monitoring plant damage and risk assessments of likely pressure. No more than one application per crop cycle unless monitoring indicates economic thresholds are likely to be exceeded. For liquid formulations, coulter slots are completely closed or covered in.	Control of canegrub is based on monitoring plant damage and risk assessments of likely pressure. An integrated pest management approach and participation in a district monitoring program informs grub management plans. No more than one application per crop cycle unless monitoring indicates economic thresholds are likely to be exceeded. For liquid formulations, coulter slots are completely closed or covered in.	

Solution Statement 4: Practice Change – Sugarcane (Irrigation)

1 Scenario description and context

Changes in farm management are summarised into a water quality risk management framework of practices classified from low risk to high risk that involve a range of likely risk states from low, moderate-low, moderate, and high water quality risk, with moderate to low risk described as current best management. However, the rate of adoption of better management practices continues to be low across the 46 individual river basins which are contained in the six catchments that feed into the reef, with substantial variation within and across catchments.

This solution statement assesses the specific management practice changes for irrigated sugarcane categorised as shifting from high risk to lower risk management. In 2018, a new management practice framework was released that provided the basis of this study. To date there have not been any costing or prioritisation studies that have aligned with the management activities of this framework, therefore this study has relied on multiple data source to estimate costs for shifting management across the 46 basins.

This Solution Set has only been derived for the Burdekin NRM region for which data was available. While irrigated sugarcane also occurs in other regions, specifically the Burnett-Mary, no applicable information was available and the data for the Burdekin was not likely to be transferable.

The specific management actions being assessed for inclusion in the Investment Pathways tool are:

1. Practice change Irrigation D-C (High to Moderate Risk)
2. Practice change Irrigation C-B (Moderate to Moderate-Low Risk)
3. Practice change Irrigation B-A (Moderate-Low to Low Risk).

Due to limited data availability because of this change's specific nature, this is further specified to only include:

- Capacity building and technical inputs (measurement of water use, runoff etc., and design). This is aligned to Action Type 1 on the risk management framework (Table 3). Specifically, current best practice
- On-ground enhancement of irrigation configuration and infrastructure enhancement to enhance efficiency and reduce runoff. This is aligned to Action Types 2 and 3 on the risk management framework (Table 3). Specifically managing surface runoff and optimising the irrigation system.

2 Approach

The approach in developing the estimates of cost effectiveness and the inputs for the Investment Pathways Tool (IPT) requires a consideration of costs, efficacy and the area available for each solution set.

2.1 Costs

2.1.1 Data

Economic data for this solution set is very limited and should be treated with caution. Much of the data is drawn from previous studies where all values have been updated to $2018. In addition, consultation has been ongoing for current on-ground farm-based trials of water use efficiency and current efforts to reduce runoff being facilitated by agronomists (e.g. Burdekin Productivity Services). Much of these projects remain underway and no formal evaluations have been undertaken.

Two types of irrigation enhancement were identified and costed these were:

- Level 1: well-designed and managed drip and overhead low-pressure systems
- Level 2: well-designed and managed automated furrow systems

Where available, the costs included for solutions are: capital costs, administration costs, asset renewal, and operating/maintenance costs. In some situations, efficient irrigation may deliver lifecycle benefits as savings in energy and water offset capital costs. These costs were categorised into (1) capital – on ground direct costs of purchasing and installing capital equipment; (2) operating and maintenance – costs associated with on farm operations and maintenance after the practice change, these costs are the net of any gains that might accrue to farms in terms of cost savings; (3) program – these are the additional costs to cover overhead expenses, monitoring and evaluation (exclude extension); and (4) extension – these are the costs associated with extension services to support uptake of practice change.

In all cases a range of values for the different costs was modelled to establish the most likely, 5th percentile and 95th percentile using a Monte-Carlo analysis with 20,000 iterations. The Monte Carlo analysis provides two key insights: the variability of costs and the drivers of variability in the life cycle costs for each intervention type.

2.1.2 Results

Table 2 provides a summary of the estimated initial cash costs over a 5-year period. A 2.5% inflation rate was used to adjust the estimated year 1 costs over subsequent years (year 1 to 5). The 5-year cash costs are the estimated funds to support practice change over the initial 5 years. For example, in a Level 2 intervention, it is estimated that the most likely capital cost is $1,037 per ha, operating and maintenance costs are $52 in year 1 and program costs are $5.1 in year 1.

Table 1. Most likely cash costs by level of irrigation practice change over a 5-year period (2018 AUD)

Intervention level		Capital	Operating and maintenance					Program					Extension				
	Year	1	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
	Region																
Level 2	**BRIA**	1,037	52	53	54	56	57	5.1	5.2	5.4	5.5	5.7	19	20	20	21	21
Level 2	**Delta**	1,037	52	53	54	56	57	5.1	5.2	5.4	5.5	5.7	37	38	39	40	41
Level 1	**BRIA**	5,183	1,037	1,062	1,089	1,116	1,144	5.1	5.2	5.4	5.5	5.7	19	20	20	21	21
Level 1	**Delta**	5,183	1,037	1,062	1,089	1,116	1,144	5.1	5.2	5.4	5.5	5.7	37	38	39	40	41

Life cycle costs (2018AUD per ha) over a 30-year appraisal were estimated using a 7% discount rate. Life cycle costs are the estimated costs per ha over a 30-year period in 2018 Australian dollar values. These costs include all three estimated costs categories i.e. capital, operating and maintenance, and program costs. The estimated impact of irrigation practice changes included consideration of cost savings in terms or labour, energy and water use. It should be noted that there is significant variability in the range of input data and assumptions used in the modelling. Thus, data on low (best), most likely and high (worst) costs was included in our modelling to capture this variability. Table 2 shows the estimated most likely costs (annual $ per ha) and the 90% prediction interval from a Monte Carlo simulation with 20,000 iterations. The best and worst values represent the 5th and 95th percentile for each reported cost estimate. These results indicate that the most likely life cycle costs for a practice change to a level 2 irrigation system is a cost-saving of $3,140 per ha over 30 years and the 90% prediction interval ranges from a cost saving of $944 to $3,473 per ha.

It is intuitive to assess how much of an impact each of the different costs have on the bottom line estimates of lifecycle costs (LCCs). For an irrigation practice change to a Level 2 in the Burdekin BRIA region, our Monte Carlo estimates indicate that operating and maintenance costs have the greatest contribution to variance in the 30-year LCCs at 54%, followed by program costs at 69%, capital costs have a 31% contribution to the variance while program and extension services costs have very minimal impact on the variability of the estimated LCCs. This contribution to variance is a result of the variability and/or confidence in the input parameter values.

Table 2. Estimate costs of practice change and the contribution to variance in the life cycle costs

Region	Practice change	30 Year life cycle costs			Contribution to variance			
		Best	Most Likely	Worst	Capital	Operating & maintenance	Program	Extension
BRIA	Level 2	- 3,473	- 3,140	- 951	31.0%	69.0%	0.01%	0.00%
Delta	Level 2	- 3,454	- 3,122	- 944	31.3%	68.7%	0.01%	0.00%
BRIA	Level 1	4,867	5,947	17,146	97.2%	2.8%	0.00%	0.00%
Delta	Level 1	4,881	5,964	17,090	97.2%	2.8%	0.00%	0.00%

2.2 Efficacy

2.2.1 Data

The Paddock to Reef (P2R) modelling program uses a multiple lines of evidence approach (Carroll *et al.* 2012) to derive an understanding of the influence of practice change actions on pollutant export from agricultural enterprises. As part of this, the Agricultural Production Systems Simulator (APSIM) model (Holzworth *et al.* 2014) is used to predict changes in water balance, production and nutrient export from different crop types using different modules available. This is shown in the figure below.

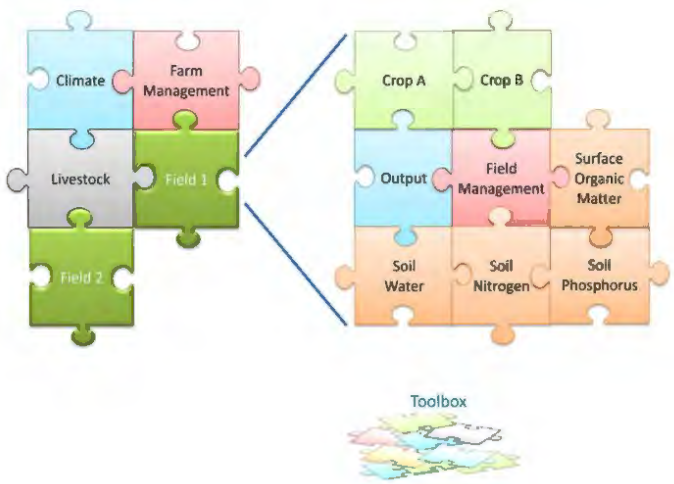


Figure 1. *APSIM model components*

The APSIM model is run for a range of agricultural enterprise configurations in different climates and different management regimes (e.g. fertiliser management, soil management, irrigation methods) to enable the development of data cubes that are then provided to the broader scale Source models to predict overall catchment runoff.

In terms of this Solution Set, the different management elements that are part of the water quality risk management framework for irrigated sugar cane have provided the model inputs and the project team have received the outputs from the model in terms of each of the practice change steps in the risk framework as outlined in the following table.

Table 3. Risk management framework – sugarcane water management practices

	Action type		Dfull = High Risk	Cfull = Moderate Risk	Bfull = Moderate - Low Risk	Afull = Lowest WQ Risk, commercial feasibility unproven
			Superseded	Minimum	Best Practice	Innovative
1	**Calculating the amount of water to apply**	70%	Amount of water applied to each block exceeds the soil water deficit by more than 50%.	Amount of water applied to each block exceeds the soil water deficit by less than 50%.	Amount of irrigation water applied to each block is less than or matches the soil water deficit.	
2	**Managing surface runoff**	20%	Headlands and drains are not specifically designed to prevent erosion and are sprayed out and/or cultivated.	Crop row orientation and surface topography ensures runoff is directed from most blocks without causing soil loss or waterlogging.	Crop row orientation and surface topography ensures runoff is directed from all blocks without causing soil loss or waterlogging.	All drainage lines are designed to minimise erosion, are maintained with grass cover, and filter sediment before entering trap or pit. Farm layout directs all runoff safely to these structures.
3	**Optimising the irrigation system**	10%	Irrigation system performance assessments have not occurred.	Irrigation system performance assessments occur on an irregular basis.	Irrigation system performance assessments occur on a regular basis.	

2.2.2 Results

Results of the APSIM modelling provided values for sugarcane irrigation management under different management regimes. A range of values were determined based on the different fertiliser management approaches. The results are shown in the table below.

Table 4. APSIM model results – sugarcane irrigation management DIN load reduction

Irrigation management (drainage DIN)	Burdekin Low	Burdekin Med	Burdekin High
D-C	28%	32%	35%
C-B	36%	40%	43%
B-A	5%	7%	9%

The results for the Burdekin showed that fertiliser practice was linked to the irrigation efficacy at different steps, as would be expected. This showed that if the irrigation practice was in the superseded category, then the amount of DIN reduction possible through fertiliser management was not as high as when irrigation practice was low risk. This is further outlined in the chart below.

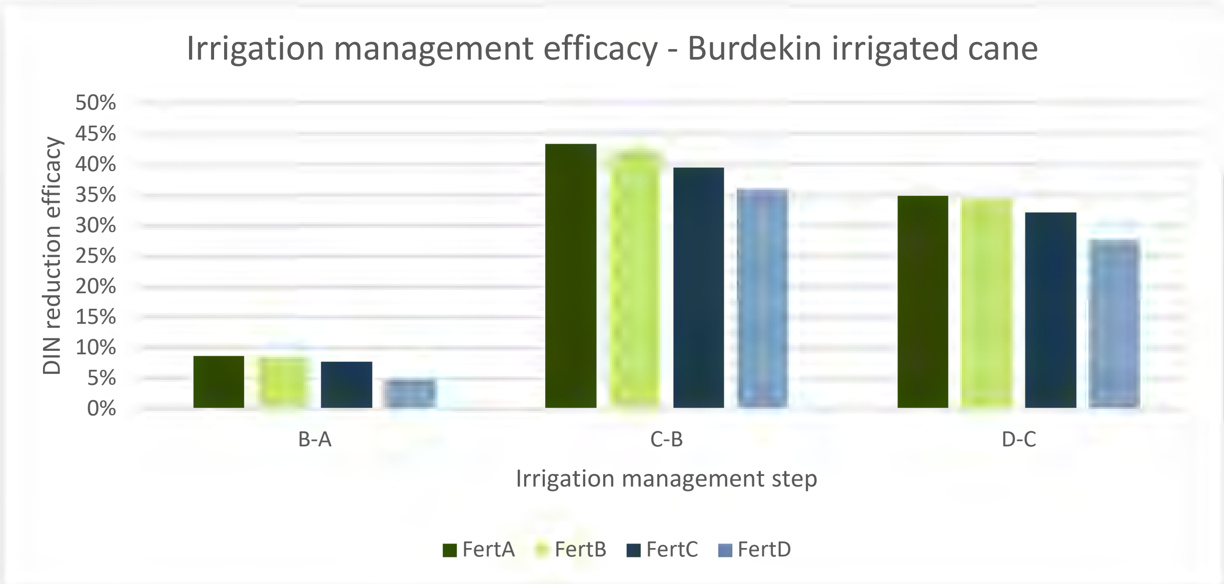


Figure 2. *Irrigation DIN reduction efficacy for irrigated cane in the Burdekin*

These results provide the estimates of lower, middle and upper reductions for irrigation management in the Burdekin.

3 Results

3.1 Cost-effectiveness

The treatable area and DIN load from irrigated sugarcane for each NRM region is shown in Figure 3. Initial analysis has shown that upgrades to furrow irrigation in areas such as the Burdekin can actually deliver marginal net changes for irrigators in the long run as energy and water savings can offset the capital investments required. However, these findings will be very susceptible to the individual circumstances of farms and should be treated with caution.

Other actions have varying net costs to irrigators and different levels of cost effectiveness.

It should also be noted that infrastructure-like and farm configuration changes can be costly to reverse. Hence the likelihood of disadoption of these actions should be relatively lower than some practice changes such as fertiliser management. This will be explored more in the subsequent analysis of non-cost risks.

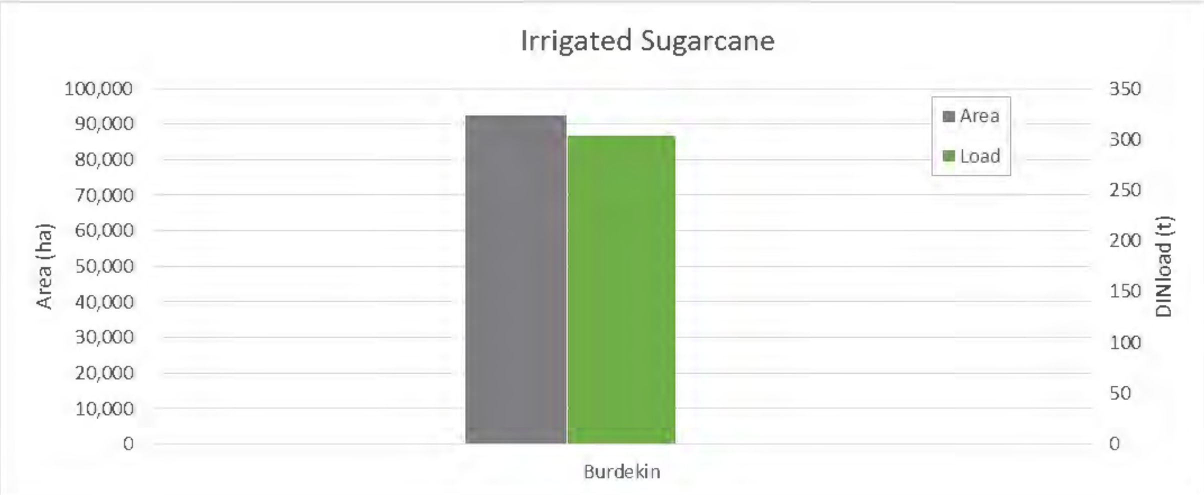


Figure 3. *Areas and loads from irrigation for each NRM region*

Table 5 and Table 6 show preliminary estimates of cost-effectiveness based on the most likely cost per hectare (Table 2) and the stated efficacy (Table 4). For each region (e.g. Wet Tropics) there are a number of basins that each have a different delivery ratio to the end of catchment as well as a different load per hectare. This has an impact on cost-effectiveness at the end of the catchment. The range of cost-effectiveness estimates presented for each region below shows the range of end of catchment costs (minimum through to 75th percentile of the basins modelled, with values above 75th percentile considered to be too expensive to warrant investment and statistical outliers).

Table 5. Estimated cost-effectiveness and treatable area and load for irrigation C to B practice change (Level 1)

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Cape York	0	0	-	-	-	-
Wet Tropics	0	0	-	-	-	-
Burdekin	46,239	304	$2,185	$2,725	$3,264	$3,804
Mackay/Whitsundays	0	0	-	-	-	-
Fitzroy	0	0	-	-	-	-
Burnett Mary	0	0	-	-	-	-

Table 6. Estimated cost-effectiveness and treatable area and load for irrigation C to B practice change (Level 2)

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Cape York	0	0	-	-	-	-
Wet Tropics	0	0	-	-	-	-
Burdekin	46,239	304	-$2,284	-$2,000	-$1,716	-$1,433
Mackay/Whitsundays	0	0	-	-	-	-
Fitzroy	0	0	-	-	-	-
Burnett Mary	0	0	-	-	-	-

The range of cost-effectiveness for each practice change, according to region, is visually represented in Figure 3 and Figure 4.

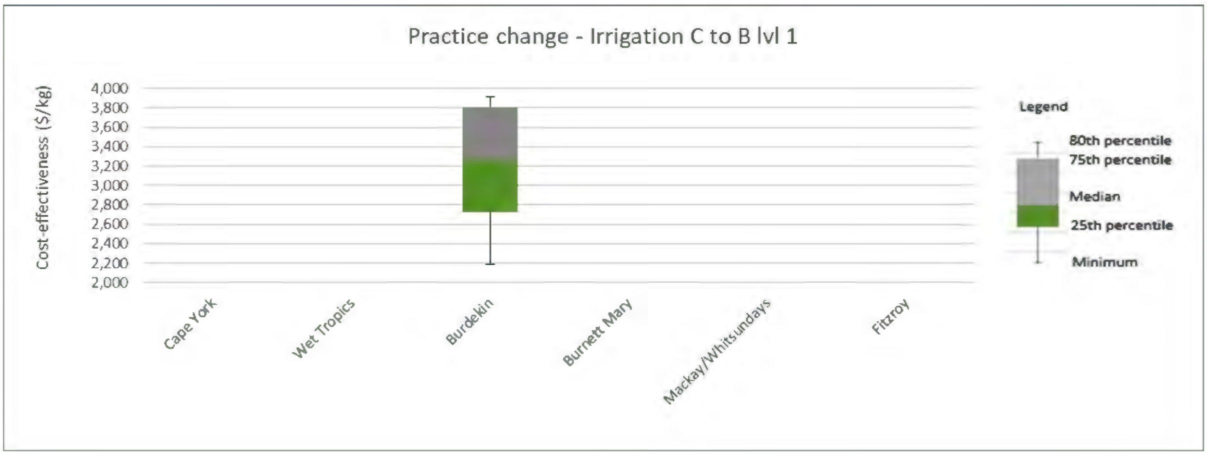


Figure 3. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for irrigation C to B practice change (Level 1)*

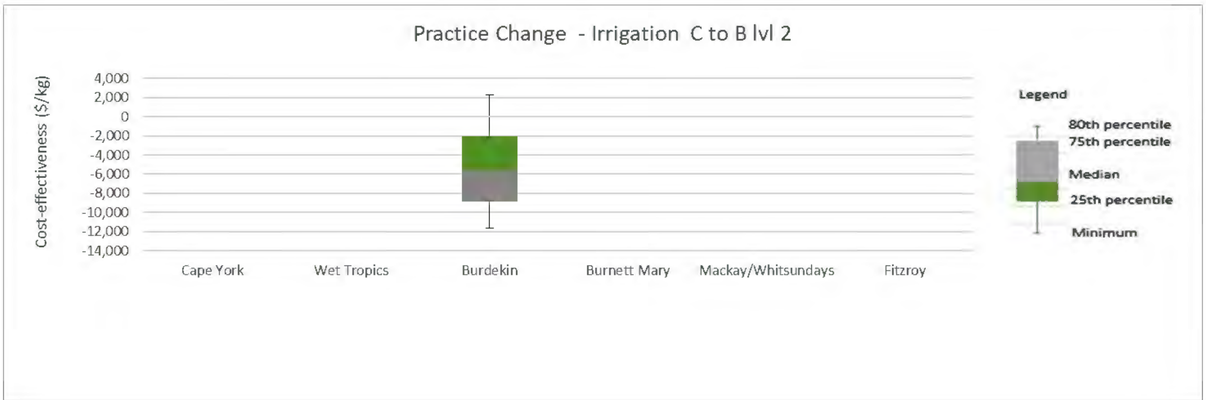


Figure 4. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for irrigation C to B practice change (Level 2)*

3.2 Assumptions and limitations

Reflecting advice from agronomists who are currently working directly with irrigators in the Burdekin, Mackay, and Wet Tropics regions, we have assumed that Action Type 1 does not directly lead to enhanced irrigation management. Rather, it is an interim/intermediate step and the prerequisite to successful implementation of Action Types 2 and 3.

We have also assumed that each change in practice is a full step change, though in reality it is likely that farm managers would choose from a range of actions that best suited their enterprise. In addressing water quality risks then, it is likely that a combination of actions would lead to improvement, but they may not all clearly fall under a whole risk category (i.e. a farmer at High Risk may choose elements from Moderate and Low Risk from the risk framework.

4 Contributors

Melanie Shaw provided updated efficacy results from previous APSIM modelling, noting that additional modelling is currently being undertaken for the next report card iteration.

Cost information was obtained and processed by the project team to generate the results presented here.

5 References

Alluvium (2016). 'Costs of achieving the water quality targets for the Great Barrier Reef'. *Australia for Department of Environment and Heritage Protection*. Brisbane, Queensland.

Carroll, C., Waters, D., Vardy, S., Silburn, D.M., Attard, S., Thorburn, P.J., Davis, A.M., Halpin, N., Schmidt, M., Wilson, B. and Clark, A. (2012). 'A paddock to reef monitoring and modelling framework for the Great Barrier Reef: Paddock and catchment component'. *Marine Pollution Bulletin.* DOI: 10.1016/j.marpolbul.2011.11.022.

DNRM (2016). Rural Water Use Efficiency Phase 4. 2010 – 2013. Program Report and Evaluation.

Gillies. M. (2017). 'Modernisation of Furrow Irrigation in the Sugar Industry'. *Sugar Research Australia.* Queensland.

Holzworth, D.P., Huth, N.I., G. deVoil, P., Zurcher, E.J., Herrmann, N., McLean, G., Chenu, K. *et al.* (2014). 'APSIM - Evolution towards a New Generation of Agricultural Systems Simulation'. *Environmental Modelling & Software* 62: 327-350. https://doi.org/10.1016/j.envsoft.2014.07.009.

NCEconomics (2018). Lower Burdekin Groundwater Strategy Project socio-economic assessment.

Rolfe, J., & Windle, J. (2016). 'Benchmarking costs of improving agricultural water management in GBR catchments'. *Reef and Rainforest Research Centre Limited.* Report to the National Environmental Science Programme. Cairns.

SRA. (2014). 'Irrigation of Sugarcane.' Technical publication. MN14002 Manual

Van Grieken, M., Poggio, M., East, M., Page, J., and Star, M. (2010).' Economic Analysis of Sugarcane Farming Systems for Water Quality Improvement in the Great Barrier Reef Catchments'. *Reef Rescue Integrated Paddock to Reef Monitoring, Modelling and Reporting Program.*

Appendix

Paddock to Reef Sugarcane Water Quality Risk Framework – DRAFT 2018 (irrigation)

Irrigation Management	**Weighting**	**Relative Water Quality Risk**			
		High	**Moderate**	**Low**	**Lowest**
Calculating the timing of irrigation	20%	Irrigation scheduled on a set cycle	Irrigation schedule is informed by in-field indicator tools such as gypsum blocks, mini pans or capacitance probes in *some* blocks.	Irrigation schedule is informed by in-field indicator tools such as gypsum blocks, mini pans or capacitance probes in the *majority* of blocks.	Irrigation schedule is informed by the use of in-field indicator tools in the *majority* of blocks, and the use of crop growth models to optimise timing.
Calculating the volume of Irrigation to apply	35%	Fixed cycle and/or fixed duration irrigation events.	Efforts made to adjust irrigation volume to match estimated crop water requirement at the time.	Irrigation applications aim to replace a measured or modelled soil water deficit.	
Minimising irrigation losses	20%	Irrigation sets are allowed to run until all/majority of furrows are completed.		Irrigation monitored closely (manual or with in-field advance sensors) and individual furrows are turned off as they reach completion. Inflow rates are increased in remaining furrows to ensure all/majority of furrows get through.	
Irrigation tailwater capture and re-use	25%	The majority of irrigation tailwater is not retained on-farm (less than 50% of farm area is captured).	The majority of irrigation tailwater is retained on-farm (tailwater from 50-90% of farm is captured).	No irrigation tailwater leaves the farm (tailwater from 100% of farm area is captured). Storages are equipped with adequate pumping capacity and captured tailwater is rapidly re-used in the short term (days/weeks).	
Production Indicator: Estimated Crop Water Use Efficiency CWUE = TCH /(gross irrigation + effective* rainfall) *Assumes 450mm average effective rainfall*		Less than 5 tonnes of cane per megalitre per hectare	5-7 tonnes of cane per megalitre per hectare	7-9 tonnes of cane per megalitre per hectare	More than 9 tonnes of cane per megalitre per hectare

Solution Statement 5: Practice change – Horticulture (bananas)

1 Scenario description and context

Changes in farm management are summarised into a water quality risk management framework of practices classified from low risk to high risk that involve a range of likely risk states from low, moderate-low, moderate, and high water quality risk, with moderate to low risk described as current best management. However, adoption levels of better management practices continue to be low across the 46 individual river basins which are contained in the six catchments that feed into the reef, with substantial variation within and across catchments.

This solution statement assesses the specific management practice changes for bananas categorised as shifting from high risk to lower risk management. In 2018, a new management practice framework was released that provided the basis of this study. To date there have not been any costing or prioritisation studies that have aligned with the management activities of this framework, therefore this study has relied on multiple data source to estimate costs for shifting management across the 46 basins.

The specific management actions being assessed for inclusion in the Investment Pathways tool are:

- Practice change Bananas C-B
- Practice change Bananas B-A.

2 Approach

2.1 Costs

2.1.1 Data

For bananas, nutrient reduction focussed actions from the banana water quality risk framework were costed for the Johnstone, Tully and Murray. The management practices centre around improving soil and leaf understanding to better respond to what can be used by the plant. The framework also only has two steps in it, and the costs were largely based off Holligan *et al.* (2017).

Table 1. Costs associated with practice changes for the 40ha property

Management	Weighting (WQ Risk assessment)	High Risk	Moderate Risk	Moderate - Low Risk
High Risk to moderate changes to management		Soil and leaf testing completed at a rate of 1 to every 1 ha (leaf test $56, soil test $15 per test, Purchase spreader capable of banded application $137.50 per ha ($5,500 per farm). Agronomy support on-going at $80 per hour per 2ha		
Changes to management.			Purchase spreader capable of banded application; fertigation infrastructure $387.50 per hectare ($15,500 per farm). Agronomy support on-going at $80 per hour per 2ha	

Table 2. Banana management framework

Management	Weighting (WQ Risk assessment)	High Risk	Moderate Risk	Moderate - Low Risk
Nutrients				
Soil testing	10%	No soil testing before planting.	Soil testing before planting is infrequent and/or does not occur on all blocks being planted.	All blocks are soil tested pre-planting. Fertiliser rates for plant crop are adjusted based on soil test results.
Matching nutrient supply to crop demand	60%	N & P fertiliser rates are based on historical target rates with infrequent testing and/or no adjustment for yield potential.	N & P fertiliser rates are supported by soil and leaf testing and yield monitoring.	Fertiliser program is based on recommended rates for N & P and supported by leaf and soil testing and yield monitoring. Revised annually to ensure targets are achieved.
Fertiliser application frequency	15%	Fertiliser is applied less frequently than monthly.	Monthly fertiliser applications all year round.	Aim to apply fortnightly during high growth periods and less frequently during low growth periods.
Fertiliser application method	15%	Fertiliser broadcast over rows and inter-row spaces.	Banded surface fertiliser application on row area only.	All fertigation. Banded surface application if wet weather rules out fertigation.
High Risk to moderate changes to management		Soil and leaf testing completed at a rate of 1 to every 1 ha (leaf test $56, soil test $15 per test, purchase spreader capable of banded application $5,500. Agronomy support on-going at $80 per hour per 2ha.		
Changes to management			Purchase spreader capable of banded application; fertigation infrastructure Total $15,500 per farm. Agronomy support on-going at $80 per hour per 2ha.	

The following costs were estimated for bananas practice changes: (1) capital – on ground direct costs of purchasing and installing capital equipment; (2) operating and maintenance – costs associated with on farm operations and maintenance after the practice change; and (3) program – these are the additional costs to cover overhead expenses, extension, monitoring and evaluation to support practice change uptake.

2.1.2 Results

After careful consideration of the required changes, costs were estimated for each practice change for bananas. Table 3 provides a summary of the estimated initial cash costs over a 5-year period A 2.5% inflation rate was used to adjust the estimated year 1 costs over subsequent years (year 1 to 5). The 5-year cash costs are the estimated funds to support practice change over the initial 5 years. For example, it is estimated that the most likely cost of shifting from a D to a C practice requires capital costs of $33,738 per ha, operating and maintenance costs of $1,600 in year 1 and program costs of $5,735 per ha in year 1.

Table 3. Most likely cash costs by practice change and region over a 5-year period (2018 AUD)

Region	Cost type	Capital	Operating and maintenance					Program				
	Year	1	1	2	3	4	5	1	2	3	4	5
	Practice change											
Wet Tropics	Bananas D-C	33,738	1,600	1,640	1,681	1,723	1,766	5,735	5,879	6,026	6,176	6,331
	Bananas C-B	388	1,600	1,640	1,681	1,723	1,766	66	68	69	71	73

Life cycle costs (2018AUD per ha) over a 30-year appraisal were estimated using a 7% discount rate. Life cycle costs are the estimated costs per ha over a 30-year period in 2018 Australian dollar values. These costs include all three estimated costs categories i.e. capital, operating and maintenance, and program costs. It should be noted that there is significant variability in the range of input data and assumptions used in the modelling. Thus, data on low (best), most likely and high (worst) costs was included in our modelling to capture this variability. Table 4 shows the estimated most likely costs (annual $ per ha) and the 90% prediction interval from a Monte Carlo simulation with 20,000 iterations. The best and worst values represent the 5th and 95th percentile for each reported cost estimate. These results indicate that the most likely life cycle costs for a practice change from D to C is $132,098 per ha over 30 years and the 90% prediction interval ranges from $112,100 to $238,024.

It is intuitive to assess how much of an impact each of the different costs have on the bottom-line estimates of lifecycle costs (LCCs). For a banana practice management shift from D to C in the Wet Tropics, our Monte Carlo estimations indicate that program costs have the greatest contribution to variance in the 30-year LCCs at 79 %, followed by capital costs at 15%, and operating and maintenance costs have the least effect on percentage contribution variance in the LCCs. This contribution to variance is a result of the variability and/or confidence in the input parameter values.

Table 4: Estimate costs of practice change and the contribution to variance in the life cycle costs

Region	Practice change	30 Year life cycle costs			Contribution to variance		
		Best	Most Likely	Worst	Capital	Operating & maintenance	Program
Wet Tropics	Bananas D-C	112,100	132,098	238,204	14.98%	6.24%	78.78%
	Bananas C-B	15,257	22,725	46,850	0.04%	99.77%	0.19%

2.2 Efficacy

2.2.1 Data

The Paddock to Reef (P2R) modelling program uses a multiple lines of evidence approach (Carroll *et al.* 2012) to derive an understanding of the influence of practice change actions on pollutant export from agricultural enterprises. As part of this, the Agricultural Production Systems Simulator (APSIM) model (Holzworth *et al.* 2014) is used to predict changes in water balance, production and nutrient export from different crop types using different modules available. This is shown in the figure below.

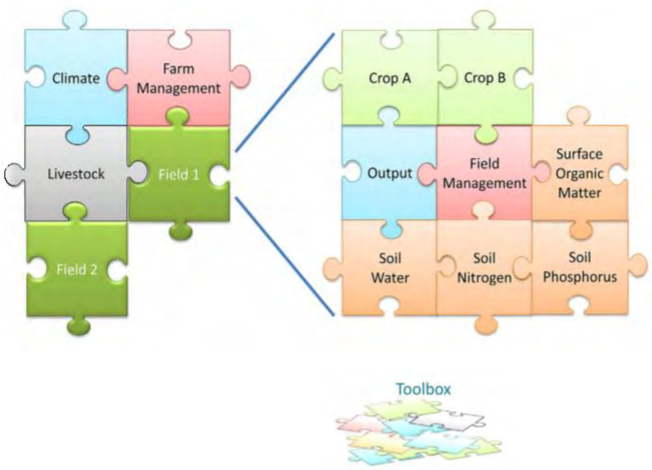


Figure 1. *APSIM model components*

The APSIM model is run for a range of agricultural enterprise configurations in different climates and different management regimes (e.g. fertiliser management, soil management, irrigation methods) to enable the development of data cubes that are then provided to the broader scale Source models to predict overall catchment runoff.

In terms of this Solution Set, the different management elements that are part of the water quality risk management framework for bananas have provided the model inputs and the project team have received the outputs from the model in terms of each of the practice change steps in the risk framework as outlined in the following table.

2.2.2 Results

Results of the APSIM modelling provided values for bananas under different management regimes. The results are shown in the table below. We note there are different classifications of practice level between the costing data and the efficacy data. There appears to be a degree of uncertainty over what the level classification of current and improved practice should be in previous versions of the water quality risk framework and while they are labelled D to C and C to B in the table below, we believe they are consistent with step changes from High to Moderate Risk and Moderate to Moderate-Low Risk. The APSIM modelling has labelled these D-C and C-B and hence these results are labelled similarly below.

Table 5. APSIM model results – Banana Practice Change DIN load reduction

Banana practice change step	Wet Tropics	Cape York
D to C	23%	35%
C to B	6%	10%

3 Results

3.1 Cost-effectiveness

The treatable area and DIN load from bananas for the Wet Tropics NRM region is shown in Figure 2. While there is a small amount of bananas in the Cape York NRM region, the load is negligible and therefore hasn't been represented in the graph. The cost-effectiveness of each practice change step based on the most likely efficacy (percentage reduction) and cost ($/ha) is shown in Table 6 and Table 7.

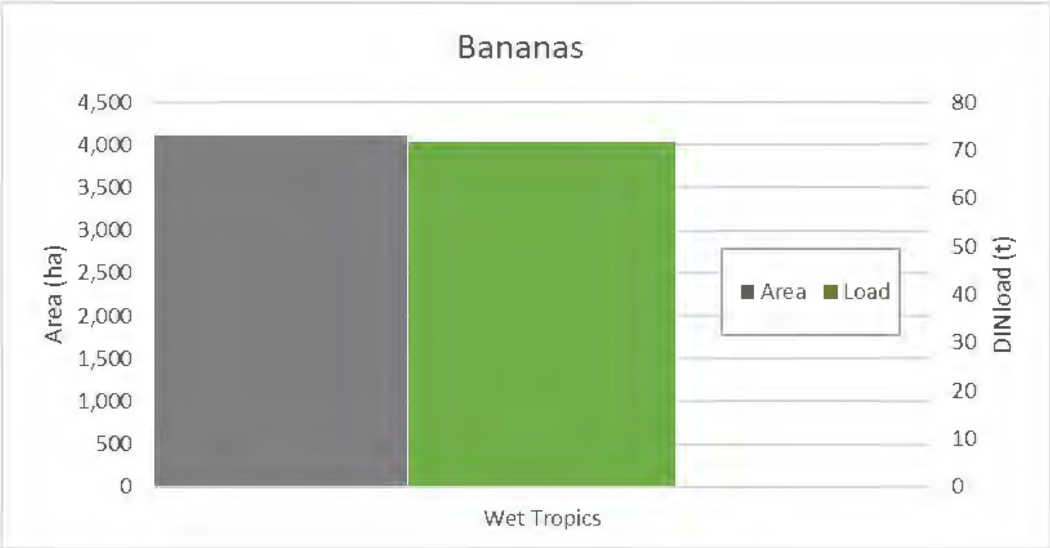


Figure 2. *Areas and loads from horticulture (bananas) for each NRM region*

The following tables show preliminary estimates of cost-effectiveness based on the most likely cost per hectare (Table 1) and the stated efficacy (Table 4). For each region (e.g. Wet Tropics) there are a number of basins that each have a different delivery ratio to the end of catchment as well as a different load per hectare. This has an impact on cost-effectiveness at the end of the catchment. The range of cost-effectiveness estimates presented for each region below shows the range of end of catchment costs (minimum through to 75th percentile of the basins modelled, with values above 75th percentile considered to be too expensive to warrant investment and statistical outliers).

Table 6. Estimated cost-effectiveness and treatable area and load bananas D to C fertiliser management

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Cape York	35	0	$83,798.9	$83,798.9	$83,798.9	$83,798.9
Wet Tropics	1,690	29	-	-	-	-

Table 7. Estimated cost-effectiveness and treatable area and load bananas C to B fertiliser management

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Cape York	213	0.267	$247,044	$247,044	$247,044	$247,044
Wet Tropics	2,418	43	$14,730	$19,166	$21,898	$36,632

The range of cost-effectiveness for each practice change, according to region, is visually represented in Figure 3.

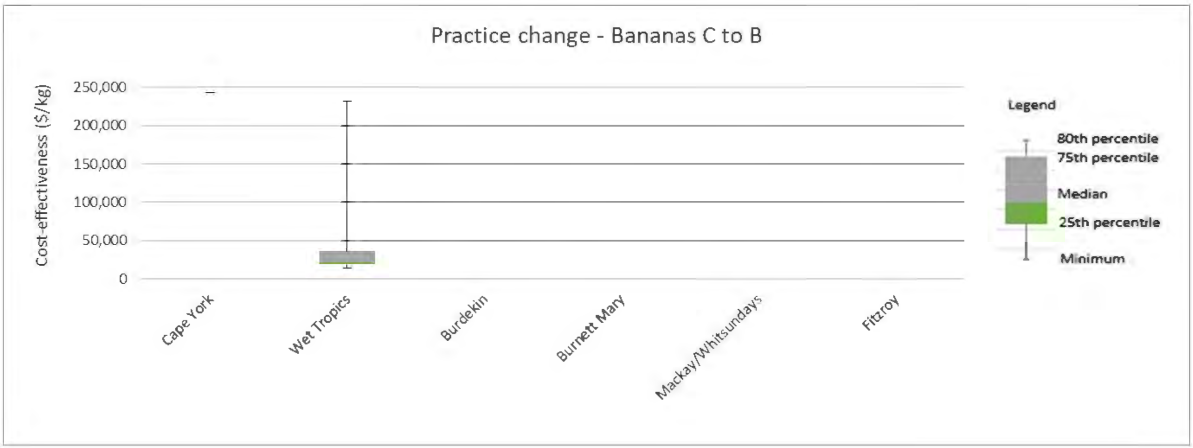


Figure 3 *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for banana C to B fertiliser practice change*

3.2 Assumptions and limitations

We have assumed that each change in practice is a full step change, though in reality it is likely that farm managers would choose from a range of actions that best suited their enterprise. In addressing water quality risks then, it is likely that a combination of actions would lead to improvement, but they may not all clearly fall under a whole risk category (i.e. a farmer at High Risk may choose elements from Moderate and Low Risk from the risk framework.

4 Contributors

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Holligan, E., Cook, S., Poggio, M. and Rattray, D. (2017) Economic assessment of best management practices for banana growing, Report to the Department of Environment and Heritage Protection through funding from the Reef Water Quality Science Program, RP140B Technical Report. Department of

Agriculture and Fisheries (DAF) and the Department of Natural Resources and Mines (DNRM), Queensland.

Holzworth, D.P., Huth, N.I., deVoil, P.G., Zurcher, E.J., Herrmann, N.I., McLean, G., and Chenu, K. *et al*. (2014). 'APSIM - Evolution towards a New Generation of Agricultural Systems Simulation'. Environmental Modelling & Software 62: 327-350. https://doi.org/10.1016/j.envsoft.2014.07.009

Appendix

2015 P2R Water Quality Risk Framework - BANANAS

Management	Weighting (WQ Risk assessment)	High Risk Superseded	Moderate Risk Minimum	Moderate - Low Risk Best Practice
Runoff & Soil Loss				
Crop Removal	10%	Banana crop is removed through being knocked down and repeated disc ploughing	Banana crop is removed through mulching and/or light discing which minimises soil disturbance.	Banana crop is killed with herbicide and plants are left to break down in the row area before cultivation.
Fallow management	20%	Land is maintained bare between crop cycles, or there is no fallow period between crop cycles	Weedy fallow grows between banana crop cycles	Fallow crop is planted between banana crop cycles, or a volunteer grass fallow is maintained between crop cycles.
Tillage - plant crop	15%	Whole block is cultivated in preparation for planting	Minimum tillage of whole block area, with row area only subject to more cultivation necessary to establish row profile and plant.	Crop planted into permanent beds. Row area only receives minimum tillage necessary for establishment.
Ground cover	35%	Inter-rows and headlands are sprayed or cultivated bare.	Living or dead, at least 60% cover is maintained in inter-row space and headlands.	Living ground cover is maintained in the interrow space and headlands.
Controlling runoff - contouring	10%	Production areas with gradient of 3% or more, but no control structures in place.	For gradient over 3%, MOST blocks planted on the contour and incorporating diversion banks and constructed waterways	For gradient over 3%, ALL blocks planted on the contour and incorporating diversion banks and constructed waterways
Controlling runoff - drains	5%	Constructed drains are mostly box drains with straight sides.	Most constructed drains are vegetated shallow spoon drains. Any box drains have a batter suited to the soil type to minimise erosion.	All constructed drains are vegetated shallow spoon drains

Sediment traps	5%	No sediment trapping structures in place.	Some sediment trapping structures. Insufficient capacity and/or design issues mean that significant amount of sediment can leave the farm in heavy events.	Expert advice informs design, construction and location of sediment traps that are effective across the entire production area.
Nutrients				
Soil testing	10%	No soil testing before planting	Soil testing before planting is infrequent and/or does not occur on all blocks being planted.	All blocks are soil tested pre-planting. Fertiliser rates for plant crop are adjusted based on soil test results.
Matching nutrient supply to crop demand	60%	N & P fertiliser rates are based on historical target rates with infrequent testing and/or no adjustment for yield potential	N & P fertiliser rates are supported by soil and leaf testing and yield monitoring.	Fertiliser program based on recommended rates for N & P and supported by leaf and soil testing and yield monitoring. Revised annually to ensure targets are achieved.
Fertiliser application frequency	15%	Fertiliser is applied less frequently than monthly.	Monthly fertiliser applications all year around	Aim to apply fortnightly during high growth periods and less frequently during low growth periods.
Fertiliser application method	15%	Fertiliser broadcast over rows and inter-row spaces.	Banded surface fertiliser application on row area only.	All fertigation. Banded surface application if wet weather rules out fertigation.
Water				
Irrigation method	35%	Some overhead irrigation	All irrigation is drip or micro sprinkler system, manually operated.	All irrigation is automated drip/micro sprinkler system underneath trees
Irrigation scheduling	65%	No soil moisture monitoring tools are used in scheduling irrigation.	Irrigation schedules are based on capacitance probes or tensiometers. Manually operated.	Irrigation schedules are based on capacitance probes and weather stations and are fully automated.

Solution Statement 6: System Repair - Gully remediation

1 Scenario description and context

Gully erosion is one of the major sources of fine sediment being delivered to the Great Barrier Reef. Sub-surface erosion (gully and streambank) is the dominant sediment contributor in the Burdekin, Fitzroy and Burnett Mary NRM regions (Bartley *et al.* 2017). Gully erosion is likely to be the largest contributor in the Burdekin region, associated with the Bowen Bogie, East Burdekin, and Upper Burdekin basins (Wilkinson *et al*. 2019).

Considerable research into gullying processes and potential remediation actions have occurred over the last decade with a number of projects in the Burdekin and Cape York regions being evaluated. Much of this research has been embodied in the development of the Gully Erosion Control Program within the Australian Government Reef Trust Phase II investments. So far, 210 gullies across 88 properties have had gully erosion controls implemented through this program. Data from the Gully Erosion Control Program was used to inform the analysis in this solution statement. Additional data from the recent implementation of the Landholders Driving Change program in the Burdekin Dry Tropics NRM region was also used.

For the purposes of this project, careful consideration of the available data dictated that it was not possible to separate alluvial and hillslope gullies in the modelling and cost-effectiveness analysis. Reference throughout the document therefore simply refers to "gullies".

2 Approach

2.1 Costs

2.1.1 Data

There is are a range of remedial works that can be undertaken to repair a gully and reduce soil erosion. These different interventions are driven by several factors including current nearby land use, hydraulic and geomorphic conditions. Three levels of intervention were used to estimate the costs of using gullies to reduce fine sediment load delivery to the reef, these are:

1. **Intervention 1 -** Low intervention – fencing for stock/feral animal exclusion, porous check dams
2. **Intervention 2 -** Medium intervention - fencing for stock/feral animal exclusion and hydroseeding
3. **Intervention 3 -** High intervention - fencing for stock/feral animal exclusion, hydroseeding and gully reshaping.

Costing data for the above interventions were based on Wilkinson *et al.,* (2015). Whereas costs were initially reported on a per km unit or per gully head basis, the per km costs were converted to per ha basis through the assumption of a 10m gully width, so gully length in km equals gully area. The following costs were estimated for gully remediation works: (1) capital – on ground direct costs of purchasing and installing capital equipment; and (2) operating and maintenance – costs associated with operations and maintenance of gully remediation works to ensure achievement of load reductions.

The capital costs reported by Wilkinson *et al.* (2015) were updated to 2018-dollar values and used in our life cycle costs estimations. These costs are shown in Table 1.

Table 1. Estimated capital costs for gully erosion remediation

Cost type	Cost range ($)	Unit
Fencing and stabilisation using gully stick trap or other revegetation	4,724-9,448	$ per km
Hydroseeding	10,498 -31,493	$ per ha
Fencing, stabilisation, hydroseeding and gully reshaping earthworks	31,493 – 52,488	$ per gully head

Adapted from Wilkinson *et al*. (2015), costs adjusted to 2018 dollar-values

Maintenance costs for gullies were estimated at $9 per ha based on a single officer working 200 days a year to inspect 2 km per day.

2.1.2 Results

Table 2 provides a summary of the estimated initial cash costs over a 5-year period. A 2.5% inflation rate was used to adjust the estimated year 1 costs over subsequent years (year 1 to 5). The 5-year cash costs are the estimated funds to support gully works over the initial 5 years. For example, in a low intervention (Intervention 1), it is estimated that the most likely capital cost is $7,086 per ha and operating and maintenance costs are $8.9 in year 1.

Table 2. Most likely cash costs per ha by gully intervention type over a 5-year period (2018 AUD)

Cost type		Capital	Operating and maintenance				
	Year	1	1	2	3	4	5
Intervention							
Intervention 1		7,086	8.9	9.2	9.4	9.6	9.9
Intervention 2		28,081	8.9	9.2	9.4	9.6	9.9
Intervention 3*		70,072	8.9	9.2	9.4	9.6	9.9

*Includes gully head cost

Life cycle costs over a 30-year appraisal were estimated using a 7% discount rate. Life cycle costs are the estimated costs per ha in 2018 Australian dollar values. These costs include all estimated costs categories i.e. capital, and operating and maintenance. It should be noted that there is significant variability in the range of input data and assumptions used in the modelling. Thus, data on low (best), most likely and high (worst) costs was included in our modelling to capture this variability. Table 3 shows the estimated most likely costs (annual $ per ha) and the 90% prediction interval from a Monte Carlo simulation with 20,000 iterations. The best and worst values represent the 5th (best) and 95th (worst) percentile for each reported cost estimate. These results indicate that the most likely life cycle costs for an intervention 1 gully remediation work are $7,206 per ha over 30 years and the 90% prediction interval ranges from a cost saving of $5,592 to $8,821 per ha.

It is intuitive to assess how much of an impact each of the different costs have on the bottom line estimates of lifecycle costs (LCCs). For an intervention 1, our Monte Carlo estimates indicate that capital costs have the greatest contribution to variance in the 30-year LCCs, while operating and maintenance costs have an insignificant contribution to the variance. Give the relatively very low maintenance costs of operating and maintaining a gully, the operating and maintenance costs for interventions 2 and 3 have an insignificant contribution to the variance in lifecycle costs. This contribution to variance is a result of the variability and/or confidence in the input parameter values.

Table 3. Estimated life cycle costs of gully remediation and the contribution to variance by cost type

Intervention	30 Year life cycle costs			Contribution to variance	
	Best	Most Likely	Worst	Capital	Operating & maintenance
Intervention 1	5,592	7,206	8,821	100%	0%
Intervention 2	19,405	28,201	37,000	100%	0%
Intervention 3	54,222	70,192	86,157	100%	0%

2.2 Efficacy

2.2.1 Data

Gully loads and area were derived from information provided from the Paddock to Reef modelling with updated data provided by CSIRO (Wilkinson pers comm 2018). Recent information on gully lengths in some catchments was provided through DNRME (Darr pers. Comm., 2018). This information was used to evaluate typical gully densities in priority catchments which was a key input into costing of gully practices.

Gully intervention efficacy were classed as either low intervention (fencing, revegetation and porous check dams) or high intervention (as per low intervention plus earthworks or control structures and hydroseeding). Previous work (Wilkinson *et al.* 2014) showed that increased vegetation cover would reduce runoff with infiltration increasing by up to 4 times, and overall runoff reducing by 20%, compared to a control site with low cover. Wilkinson (2019) contained data around the overall reductions of interventions for gullies and in the gully toolbox cost-effectiveness template, a value of 50% reduction was suggested for low level intervention. Further discussions (Wilkinson pers comm 2019) suggested performance may be as high as 60% for lower level interventions. Given the likelihood that flow reductions and increased sedimentation are both processes facilitated by the lower level interventions, a conservative reduction of 40% was assumed. Brooks *et al*. (2016) suggested that high intervention works could reduce gully erosion rates by 90% in 4 years, whereas previous estimates of a number of gullies completed during the 2016 Reef Costings study (Alluvium 2016) suggested these works would be 70% effective. We have therefore adopted the following efficacies for low and high intervention.

Table 4. Reduction in gully erosion for different interventions

Intervention	Hillslope erosion rate reduction (%)
1 (low) – revegetation, fencing, stick traps	40
3 (high) – low + earthworks, control structures, hydroseeding	80

There were no data available for the intervention level 2 actions (Intervention 1 + hydroseeding) so there have been no efficacies attributed to this intervention step.

2.2.2 Results

The following gully areas, loads and lengths were used in the determination of cost-effectiveness. Gully area was derived from the gully length in km multiplied by an assumed average gully width of 10m (Wilkinson pers comm 2018). Because of unit conversions, the value for gully length in km and gully area in hectares are the same numeric value.

We note that there may be a mismatch between the sediment loads from the P2R modelling results that were provided and current mapping of gully lengths (i.e. different lengths of gully may have been assumed in the P2R models at the time the results were run), so the gully loading rates in the Bowen Bogie and East Burdekin are likely to be over estimates, though again these are within the ranges reported in Wilkinson et al 2019. The loading rates themselves were not used in the final calculations in the cost-effectiveness, only the gully area and gully loads, so the potential mismatch will not affect the overall cost-effectiveness results.

Table 5. Gully results for reporting basins

Reporting Basin	Catchment Area (ha)	Gully load (t/yr)	Gully area (ha) and gully length (km)	Gully loading rate (t/ha/yr)
Bowen Bogie	1,171,843	1,123,660	2746	409
East Burdekin	329,921	134,789	686	196
Pioneer River	166,431	1,340	797	2
Mary River	941,985	24,803	1500	17
Lower Burdekin	483,349	98,178	2996	33
Fitzroy River	1,133,946	138,517	6000	23
Don River	346,632	103,335	4200	25
O'Connell River	230,522	3,527	1103	3
Herbert River	985,181	23,400	4000	6
Johnstone River	231,650	3,027	1109	3
Black River	104,052	17,608	500	35
Mulgrave-Russell River	197,472	380	945	0
Upper Burdekin	4,041,282	661,870	19344	34
Ross River	164,710	20,216	1100	18
Mackenzie	1,312,842	87,948	7800	11
Burnett River	3,327,364	96,486	24500	4
Styx River	299,511	10,861	1300	8
Tully River	166,845	343	799	0
Plane Creek	254,680	2,147	1219	2
Murray River	112,502	214	539	0
Proserpine River	251,283	2,401	1203	2
Calliope	217,715	6,878	1200	6
Kolan River	289,066	7,236	1300	6
Normanby River	2,440,153	160,151	3133	51
Daintree River	210,527	98	1008	0
Shoalwater Creek	361,609	9,267	600	15
Barron River	218,824	2,653	1047	3
Isaac	2,222,580	78,277	16400	5
Baffle Creek	410,113	12,831	1963	7
Dawson	5,073,433	151,944	37700	4
Stewart River	58,456	4,416	280	8
Boyne River	28,354	1,531	1357	3
Endeavour River	249,748	941	600	3
Olive Pascoe River	218,616	4,784	1046	1
Burdekin River	417,245	42,315	1997	2
Theresa Creek	1,857,708	20,097	8892	5
Comet	847,300	38,151	4056	5
Burrum River	1,729,049	2,231	8276	5
Cape Campaspe	334,559	32,956	300	7
Waterpark Creek	2,025,531	2,322	9695	3
Mossman River	184,786	6	100	23
Belyando	47,677	40,145	228	0
Jacky Jacky Creek	3,535,199	2,461	16922	2
Lockhart River	299,035	85	1431	2
Jeannie River	278,604	2,316	1334	0
Nogoa	363,720	9,092	1741	1

3 Results

3.1 Cost-effectiveness

The treatable area and fine sediment load from gully erosion for each NRM region is shown in Figure 1. The cost-effectiveness of the two types of gully treatment based on the most likely efficacy (percentage reduction) and cost ($/ha) is shown in Table 6 and Table 7.

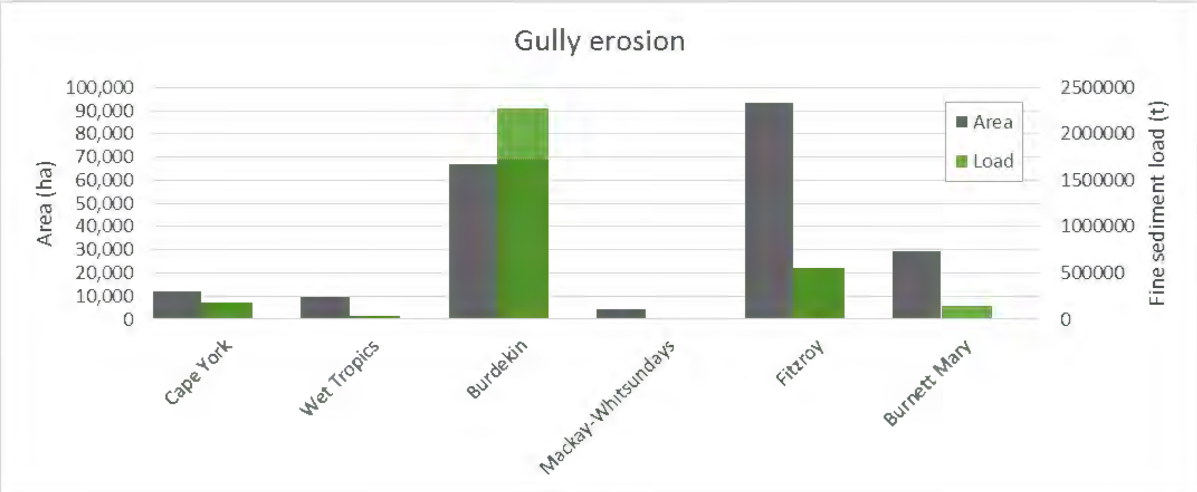


Figure 1. *Areas and loads from gully erosion for each NRM region*

The following tables show preliminary estimates of cost-effectiveness based on the most likely cost per hectare (Table 2) and the stated efficacy (Table 4). For each region (e.g. Wet Tropics) there are a number of basins that each have a different delivery ratio to the end of catchment as well as a different load per hectare. This has an impact on cost-effectiveness at the end of the catchment. The range of cost-effectiveness estimates presented for each region below shows the range of end of catchment costs (minimum through to 75^{th} percentile of the basins modelled, with values above 75^{th} percentile considered to be too expensive to warrant investment and statistical outliers).

Table 6. Estimated cost-effectiveness and treatable area and load for gully type 1 treatment

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Cape York	12,040	175,154	$0.70	$13.06	$20.95	$33.58
Wet Tropics	9,675	30,122	$6.16	$13.97	$86.76	$160.24
Burdekin	67,082	2,275,070	$0.09	$1.03	$1.28	$6.17
Mackay/Whitsundays	4,322	9,415	$11.27	$16.36	$19.26	$20.70
Fitzroy	93,220	554,884	$1.55	$2.98	$6.78	$8.10
Burnett Mary	29,563	143,587	$2.18	$4.85	$5.51	$6.47

Table 7. Estimated cost-effectiveness and treatable area and load for gully type 3 treatment

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Cape York	12,040	175,154	$1.72	$31.80	$51.02	$81.76
Wet Tropics	9,675	30,122	$15.00	$34.02	$211.29	$390.22
Burdekin	67,082	2,275,070	$0.21	$2.51	$3.12	$15.02
Mackay/Whitsundays	4,322	9,415	$27.45	$39.83	$46.89	$50.41
Fitzroy	93,220	554,884	$3.78	$7.26	$16.51	$19.72
Burnett Mary	29,563	143,587	$5.31	$11.80	$13.42	$15.76

The range of cost-effectiveness for each practice change, according to region, is visually represented in Figure 2 and Figure 3.

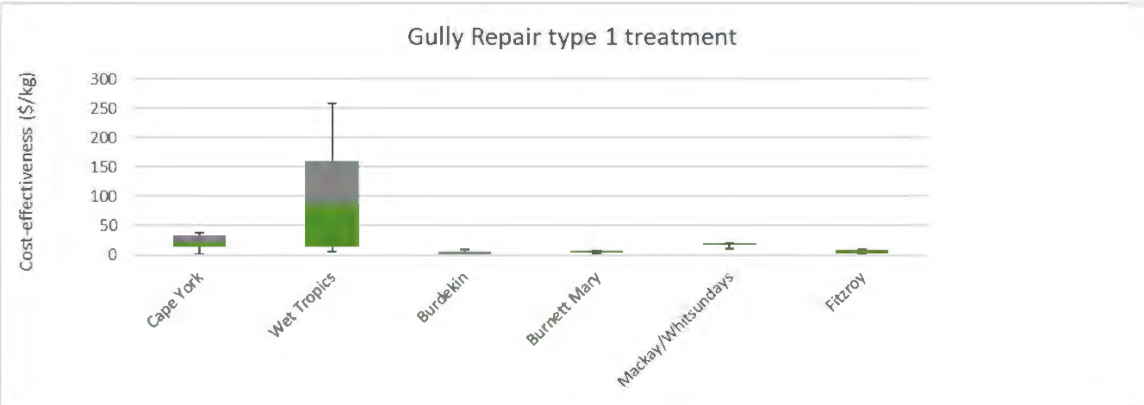


Figure 2. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region gully repair type 1 treatment*

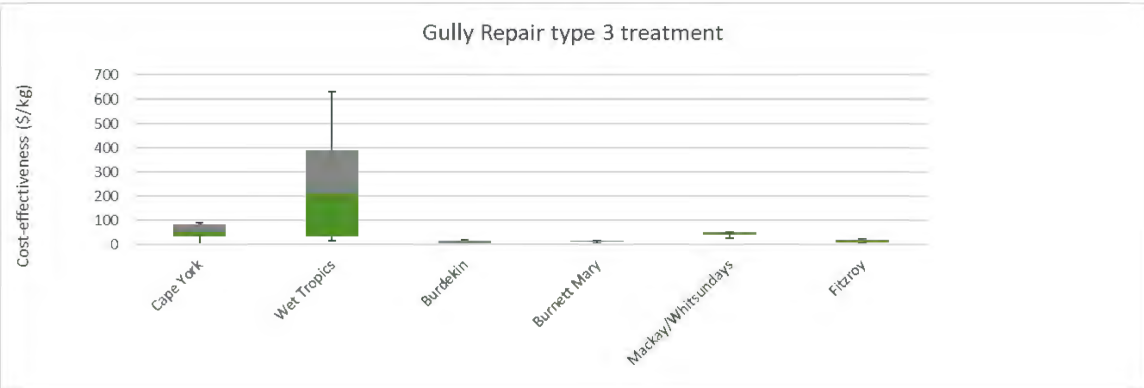


Figure 3. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region gully repair type 3 treatment*

3.2 Assumptions and limitations

An average gully width of 10m has been assumed based on discussions with Scott Wilkinson, though we note that cross-sectional areas in the Paddock to Reef modelling have recently been reduced from $10m^2$ to $5m^2$. Gully length data was provided by both Scott Wilkinson and Shaun Darr and some inconsistencies in lengths and basin naming was noted. Where gully lengths were not provided (mostly in basins where gully contributions were minor), an average gully density was used based on the provided data. This may be an overestimation of gullying within certain basins, but given that this will result in a unit gully load (in t/ha/yr), this will mean the cost-effectiveness is a conservative estimate.

4 Contributors

Scott Wilkinson (CSIRO) provided data from the Reef Trust Gully Erosion Control Program including gully exports, suggested gully remediation unit costs and gully areas.

Shaun Darr from Department of Natural Resources, Mines and Energy, Queensland Government provided updated gully lengths for a number of catchments.

5 References

Alluvium (2016). 'Costs of achieving the water quality targets for the Great Barrier Reef'. Report to the Department of Environment and Heritage Protection. Brisbane, Queensland.

Bartley, R., Waters, D., Turner, R., Kroon, F., Wilkinson, S., Garzon-Garcia, A., Kuhnert, P., Lewis, S., Smith, R., Bainbridge, Z., Olley, J., Brooks, A., Burton, J., Brodie, J. and Waterhouse, J. (2017). 'Scientific Consensus Statement 2017: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef'. Chapter 2: Sources of sediment, nutrients, pesticides and other pollutants to the Great Barrier Reef. Queensland.

Brooks, A., Spencer, J., Curwen, G, Shellberg, J., Garzon-Garcia, A, Burton, J. & Iwashita, F. (2016) Reducing sediment sources to the Reef: Managing alluvial gully erosion. Report to the National Environmental Science Programme. Reef and Rainforest Research Centre Limited, Cairns.

Wilkinson, S. N., Kinsey-Henderson, A. E., Hawdon, A. A., Hairsine, P. B., Bartley, R., & Baker, B. (2018). Grazing impacts on gully dynamics indicate approaches for gully erosion control in northeast Australia. Earth Surface Processes and Landforms.

Wilkinson S.N., Bartley R., Hairsine P.B., Bui E.N., Gregory L., Henderson A.E. (2015). 'Managing gully erosion as an efficient approach to improving water quality in the Great Barrier Reef lagoon'. *CSIRO Land and Water.* Report to the Department of the Environment. Australia.

Wilkinson S.N., Hairsine P.B., Hawdon A.A., Austin J. (2019) Technical findings and outcomes from the Reef Trust Gully Erosion Control Programme. CSIRO, Australia

Solution Statement 7: Catchment Remediation - Streambanks

1 Scenario description and context

Streambank erosion is a natural and essential process in alluvial systems; however human activities such as land clearing and stripping of riparian vegetation can result in accelerated rates of erosion. Accelerated rates of erosion in the GBR has major impacts on catchment sediment loads. Other impacts include damage to public assets (bridges, culverts, road embankments, power lines etc.) and degradation of, and damage to, river health through, for example, infilling of pools by large sediment loads, erosion of bank habitat niches (e.g. under cut banks) and loss of large wood.

Riparian vegetation is the most effective long-term solution to limiting streambank erosion. However, in some cases the risk (likelihood and/or consequence) of erosion is so great that waiting for vegetation to reach a level of maturity required to protect streambanks from erosion may not be acceptable. There are a range of other engineering approaches which can be implemented to assist native vegetation establishment. These include bank toe protection, bank reprofiling, alignment training and grade control. While these engineering approaches may be required at specific locations to increase the likelihood vegetation establishment, it is difficult to determine the required extent without a more detailed understanding of the hydraulic and geomorphic conditions.

In the previous Reef Costings work (Alluvium, 2016), the remediation of eroding and degraded streambanks was limited to repair of 5-10% of streambank length in the Mary, O'Connell, Tully and Herbert Rivers. Bartley (2017) reports that streambank erosion is the least understood process within the Great Barrier Reef catchments, but the modelling and literature also indicates that it can be a significant source of sediment in some catchments. In terms of scientific consensus, it has been agreed that the importance of gully and streambank erosion is higher than previously thought (Eberhard *et al.* 2017). The quantification of streambank erosion and the potential for repair of this is therefore an important solution to be considered for investment in improving water quality for the Reef.

In this solution set, we have examined the sources of streambank sediment reported in the Paddock to Reef modelling and then assessed the costs and efficacy based on previous projects completed in a number of reef catchments over the last several years.

2 Approach

2.1 Costs

2.1.1 Data

A range of management options are available to reduce to the rates of erosion providing the necessary time for the vegetation to reach maturity. Thus, there is significant variability in costs associated with streambank sediment control. Given the level of assessment achievable at the scale required for this project, three levels of management intervention were costed, these include:

1. **Intervention 1 - Low intervention** – Stock/feral animal control (exclusion fencing during vegetation establishment and offsite watering) and facilitated vegetation establishment (weed control and isolated planting)
2. **Intervention 2 - Medium intervention** - Stock/feral animal control (exclusion fencing during vegetation establishment and offsite watering) and active revegetation
3. **Intervention 3 - High intervention** - Stock/feral animal control (exclusion fencing during vegetation establishment and offsite watering), some bank reprofiling and facilitated vegetation establishment with the aid of jute matt and some significant toe protection (e.g. rock revetment, pile fields etc.)

The capital costs for the low and medium levels of intervention were largely based on figures derived from Bartley *et al*. 2015 as well as indicative costs from the Sunshine Coast Council area for the Mary River in the (Alluvium, 2016). A list of the indicative costs used is provided in Table 1.

Table 1. Indicative capital and establishment costs

Activity	Cost
Fencing	$15,000/km (assuming 10 ha per kilometre for both banks) (pers. comm. Sunshine Coast Council)
Facilitated revegetation	$27,900/km (assuming 10 ha per kilometre for both banks) (Bartley *et al.* (2015))
Active revegetation	$150,000 /km (assuming 10 ha per kilometre for both banks and 2500 plants/ha) (pers comm. SCC)
Offsite watering	$8,700 /km (Bartley *et al.* (2015))

The costs for the high level of intervention were based on the "Mary River Restoration Plan" (Alluvium, 2014). In this plan the implementation cost for a high level of management intervention was estimated to be $1,000,000/km/bank, this cost based on recent stream restoration works in south-east Queensland. This was chosen as a guide because a range of management techniques were recommended within a kilometre of the stream, including bank reprofiling, facilitated vegetation establishment with the aid of jute mat and significant toe protection (i.e. rock revetment and pile fields etc.).

All estimated costs were categorised into: (1) capital – on ground direct costs of purchasing and installing capital equipment; and (2) operating and maintenance – costs associated with the operation and maintenance of streambank stabilisation works to ensure achievement of load reductions.

Given the high variability in streambank condition and site-specific nature of the level of management intervention required, a range of +/-30% has been applied. It is understood that not all sites will require fencing and off-site watering and equally some sites may require more structural engineering works than others and this is reflected in the results.

The level of management intervention required for a degraded streambank will be highly variable and dependent on several factors including hydraulic and geomorphic condition and the level of risk. The level of management intervention in any one location will need to be determined by the investors (stakeholders) and site-specific objectives, however, these cost estimates are useful as a guide.

2.1.2 Results

Table 2 provides a summary of the estimated initial cash costs over a 5-year period. The 5-year cash costs are the estimated funds to support streambank works over the initial 5 years. For example, in an intervention 1 streambank remediation project, it is estimated that the most likely capital cost is $5,635 per ha and operating and maintenance costs are $8.9 in year 1.

Table 2. Most likely cash costs by streambank intervention type over a 5-year period (2018 AUD per ha of streambank)

Cost type	Capital	Operating and maintenance				
Year	**1**	**1**	**2**	**3**	**4**	**5**
Intervention						
Intervention 1	5,635	8.9	9.2	9.4	9.6	9.9
Intervention 2	18,970	8.9	9.2	9.4	9.6	9.9
Intervention 3	200,000	8.9	9.2	9.4	9.6	9.9

Life cycle costs (2018AUD per ha) over a 30-year appraisal were estimated using a 7% discount rate. Life cycle costs are the estimated costs per ha over a 30-year period in 2018 Australian dollar values. These costs include all estimated costs categories i.e. capital, and operating and maintenance. The estimated impact of irrigation practice changes included consideration of cost savings in terms or labour, energy and water use. It should be noted that there is significant variability in the range of input data and assumptions used in the modelling. Thus, data on low (best), most likely and high (worst) costs was included in our modelling to capture this variability. **Error! Reference source not found.** shows the estimated most likely costs (annual $ per ha) and the 90% prediction interval from a Monte Carlo simulation with 20,000 iterations. The best and worst values represent the 5th (best) and 95th (worst) percentile for each reported cost estimate. These results indicate that the most likely life cycle costs for an intervention 1 work is $5,755 per ha over 30 years and the 90% prediction interval ranges from a cost saving of $4,598 to $6,910 per ha.

It is intuitive to assess how much of an impact each of the different costs have on the bottom line estimates of lifecycle costs (LCCs). For an intervention 1, our Monte Carlo estimates indicate that capital costs have the greatest contribution to variance in the 30-year LCCs at 99.87%, while operating and maintenance costs have a minimal contribution to the variance at less than 1%. This contribution to variance is a result of the variability and/or confidence in the input parameter values.

Table 3. Estimate costs of practice change and the contribution to variance in the life cycle costs

Intervention	30 Year life cycle costs			Contribution to variance	
	Best	Most Likely	Worst	Capital	Operating & maintenance
Intervention 1	4,598	5,755	6,910	99.87%	0.13%
Intervention 2	15,194	19,090	22,979	99.99%	0.01%
Intervention 3	159,090	200,120	241,147	100.00%	0.00%

2.2 Efficacy

2.2.1 Data

Stream types and conditions are highly variable across the reporting basins and difficult to determine under a high-level assessment. In order to determine the extent of streambank degradation across the reporting basins, results from the 2016 Report Card Paddock to Reef modelling were used.

The primary plugin used to model sediment transport processes in the GBR Paddock to Reef modelling is Dynamic SedNet. Dynamic Sednet enables temporally and spatially variable inputs to represent erosion processes. Streambank erosion is simulated by estimates of Mean Annual Bank Erosion (MABE t/y). Where MABE = Retreat rate (m/y) x mass conversion x erodibility. The retreat rate is the product of total bankfull stream power (i.e. not mean specific stream power) and calibration and erosion management factors. As a result, total bankfull stream power is the primary driver of the bank retreat rate. Mass conversion is determined by bank height and soil density. Bank erodibility considers vegetation and soil properties and is between 0-1.

To enable an estimate of the extent of sediment loads for each catchment, riparian vegetation coverage is used as a measure of a bank's susceptibility to erosion. Using the streambank parameter inputs from the modelling, the stream length with vegetation coverage less than 70% was determined. It was assumed that streambanks with riparian vegetation coverage greater than 70% are unlikely to be significantly contributing to the fine sediment load determined by the modelling and are less degraded. The sediment load for each catchment was then determined based on the modelling output loads derived from stream lengths with riparian vegetation cover less than 70%.

The scientific understanding of the role riparian vegetation plays in limiting streambank erosion is relatively advanced. However, there are limited studies which quantitatively evaluated the effectiveness of revegetating streams which have degraded riparian zones (Bartley *et al.* 2015). Bartley *et al.* (2015) found 12 published peer reviewed studies that have documented the response of bank remediation on sediment yields, water quality or erosion rates from around the world. Five of the studies did not result in improved sediment yields, water quality or reduced erosion following remediation.

In the seven studies which showed restoration of riparian vegetation having a positive impact on sediment loads, rates of erosion were reduced by between 40-80%. Based on this information and the level of intervention suggested, efficacies for the low and medium intervention were estimated to be 30% and 60% respectively. An efficacy of 90% was estimated for the high level of intervention. This was based on estimated reductions determined using the BSTEM sediment modelling approach for a site designed using engineering approaches on the Fitzroy River (Alluvium, 2018).

It should be noted that efficacy estimates are based on riparian vegetation at maturity and there are risks to the works during the vegetation establishment period.

2.2.2 Results

Given the uncertainty around what proportion of sites within each basin would be appropriate for low, medium and high levels of intervention, the information used above was also used as the range of efficacies for streambank remediation, with 60% being most likely.

3 Results

3.1 Cost-effectiveness

The treatable area and fine sediment load from streambanks for each NRM region is shown in Figure 1. The cost-effectiveness of each practice change step based on the most likely efficacy (percentage reduction) and cost ($/ha) is shown in Table 4.

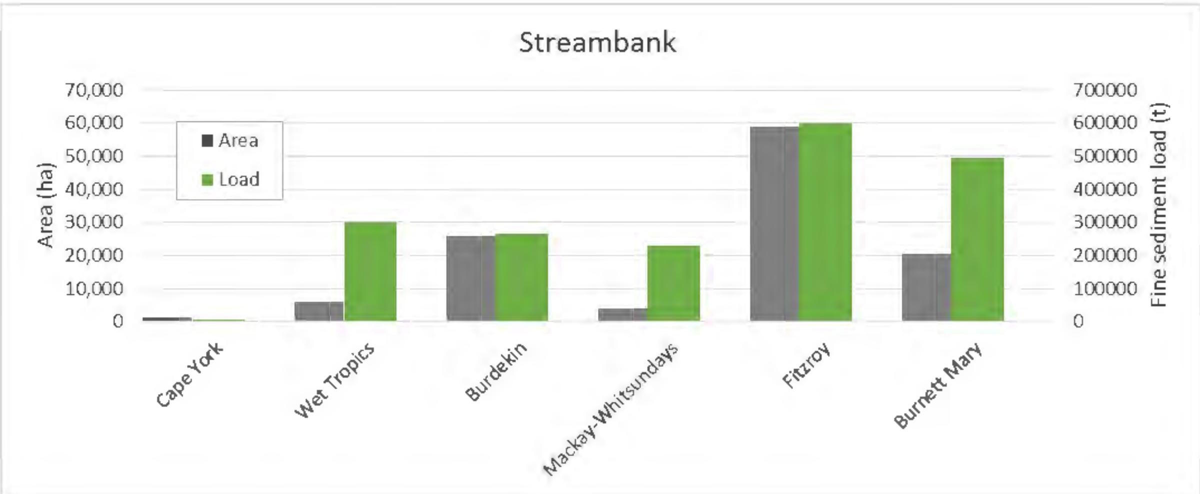


Figure 1. *Areas and loads from streambanks for each NRM region*

The following table show preliminary estimates of cost-effectiveness based on the most likely cost per hectare (Table 2) and the stated efficacy of 60% load reduction. For each region (e.g. Wet Tropics) there are a number of basins that each have a different delivery ratio to the end of catchment as well as a different load per hectare. This has an impact on cost-effectiveness at the end of the catchment. The range of cost-effectiveness estimates presented for each region below shows the range of end of catchment costs (minimum through to 75th percentile of the basins modelled, with values above 75th percentile considered to be too expensive to warrant investment and statistical outliers).

Table 4. Estimated cost-effectiveness and treatable area and load for streambank repair

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Cape York	1,279	5,403	$1.58	$2.77	$5.39	$25.41
Wet Tropics	5,961	298,645	$0.37	$0.99	$1.73	$10.50
Burdekin	25,755	264,098	$0.39	$2.37	$3.97	$64.96
Mackay/Whitsundays	3,995	227,784	$0.35	$0.40	$0.81	$1.22
Fitzroy	59,021	597,801	$0.37	$4.05	$7.02	$85.06
Burnett Mary	20579	493,861	$0.33	$4.25	$4.53	$5.35

The range of cost-effectiveness for each practice change, according to region, is visually represented in Figure 2.

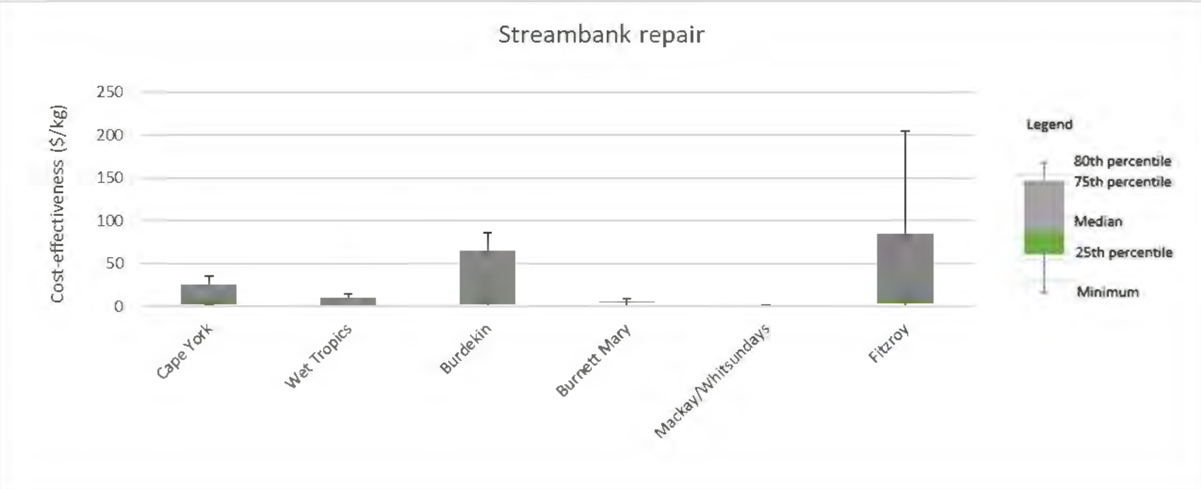


Figure 2. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for streambank repair*

3.2 Assumptions and limitations

The method adopted relies on the modelling estimates of streambank erosion within each link modelled. The efficacy of management practices will be estimated as a percentage reduction of the modelled streambank erosion estimates. As a result, the cost benefit ratio for streambank management is heavily reliant on the modelled streambank erosion estimates at the reach scale.

Streambank erosion is estimated within the Source model using the Dynamic SedNet model. The model, and the data inputs currently utilised, is a reasonable tool for estimating the relative contribution of bank erosion at large whole catchment scales. However, its applicability at smaller spatial scales (i.e. reach or sub-catchment) to estimate erosion rates and undertake prioritisation is limited due to the coarse datasets used, the size of the model links and sub-catchment areas and modelling assumptions.

The limitations of the Dynamic SedNet model have been outlined in the *Stream bank management in the Great Barrier Reef catchments: a handbook* (Bartley *et al.* 2015). Some of these issues include:

- The bank erosion equation in the SedNet model was based on the empirical relationships presented in Walker and Rutherfurd (1999) and Rutherfurd (2000) that used meander migration rate as a surrogate for bank erosion. Many rivers in Queensland have a macro channel configuration which are confined by resistant floodplain/terrace material, limiting lateral adjustment. Most of the channel erosion occurs on inset benches and floodplains within the macro channel. The modelling currently cannot account for the differing erodibility of benches, inset floodplains and terraces

- There is the potential for large systematic errors without sufficient model calibration (De Rose *et al.* 2005). Furthermore, calibration of end of catchment loads which is typically completed in the GBR catchments can result in significant under/over prediction of sediment sources within the catchments, including streambank erosion rates (Brooks *et al.* 2013)
- The models provide a reach averaged estimate which doesn't consider the explicit erosion process (e.g. incision/widening vs meander migration) that can often vary within a reach, and even vary on different banks within the same reach. As a result, there could be large zone of concentrated sediment loss within a broader reach (links can be 10s of km in length)
- Using riparian vegetation coverage as a proxy for streambank degradation is an oversimplification of the complex erosional processes involved.

4 Contributors

Cost information was obtained and processed by the project team to generate the results presented here.

5 References

Alluvium (2018). Fitzroy River NDRRA Stabilisation Designs, project completed on behalf of the Fitzroy Basin Association, Rockhampton

Alluvium (2016). 'Costs of achieving the water quality targets for the Great Barrier Reef'. Report to the Department of Environment and Heritage Protection. Brisbane.

Alluvium (2014). Mary River Restoration Plan, project completed on behalf of the Mary River Catchment Coordinating Committee.

Bartley, R., Henderson, A. Wilkinson, S., Whitten, S. and Rutherfurd, I. (2015). 'Stream Bank Management in the Great Barrier Reef Catchments: A Handbook'. *CSIRO Land and Water*. Report to the Department of Environment. Australia.

Bartley, R., Waters, D., Turner, R., Kroon, F., Wilkinson, S., Garzon-Garcia, A., Kuhnert, P., Lewis, S., Smith, R., Bainbridge, Z., Olley, J., Brooks, A., Burton, J., Brodie, J. and Waterhouse, J. (2017). 'Scientific Consensus Statement 2017: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef'. Chapter 2: Sources of sediment, nutrients, pesticides and other pollutants to the Great Barrier Reef. Queensland.

Brooks ,A., Spencer, J., Olley, J., Pietsch, T., Borombovits, D., Curwen, G., Shellberg, J., Howley, C., Gleeson, A., Simon, A., Bankhead, A., Klimetz, D., Eslami- Endargoli, L., Bourgeault, A. (2013) An Empirically -based Sediment Budget for the Normanby Basin: Sediment Sources, Sinks, and Drivers on the Cape York Savannah . Griffith University, 506pp.

De Rose, R., Wilson, D.J., Bartley, R. and Wilkinson, S., 2005. Riverbank erosion and its importance to uncertainties in large-scale sediment budgets.

Eberhard, R., Thorburn, P., Rolfe, J., Taylor, B., Ronan, M., Weber, T., Flint, N., Kroon, F., Brodie, J., Waterhouse, J., Silburn, M., Bartley, R., Davis, A., Wilkinson, S., Lewis, S., Star, M., Poggio, M., Windle, J., Marshall, N., Hill, R., Maclean, K., Lyons, P., Robinson, C., Adame, F., Selles, A., Griffiths, M., Gunn, J. and McCosker, K. (2017). 'Scientific Consensus Statement 2017: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef'. Chapter 4: Management options and their effectiveness. Queensland.

Rutherfurd, I., 2000. Some Human Impacts on Australian Stream Channel Morphology. In: S. Brizga and B. Finlayson (Editors), River Management (The Australasian Experience). John Wiley and Sons, England, pp. 11-50.

Walker, M. and Rutherfurd, I.D., 1999. An approach to predicting rates of bend migration in meandering alluvial streams. In: I.D. Rutherfurd and R. Bartley (Editors). CRC for Catchment Hydrology, Melbourne, pp. 659-665.

Scenario 8: Catchment remediation – Treatment systems

1 Scenario description and context

This scenario assesses the costs and effectiveness of installing landscape wetlands, constructed wetlands, recycle pits and bioreactors in cane and horticultural (banana) areas.

The specific management actions being assessed for inclusion in the Investment Pathways tool are:

1. Wetland (landscape)
2. Wetland (constructed)
3. Dry weather recycle pit (tailwater)
4. Wet weather recycle pit
5. Bioreactors

1.1 Landscape wetlands

Landscape wetlands are typically low-lying existing or former wetland areas that are re-engaged with a suitable hydrologic regime through the installation of weirs, valves, pipes or culverts that redirect flows in a way that is conducive to wetland vegetation. They are a relatively “informal” treatment, in that there is only minimal effort made to optimise the internal configuration of the wetland, the major focus simply being to re-engage flows to pass through the area of degraded or isolated wetland. A number of these have been designed and installed in the Wet Tropics and Burdekin Dry Tropics NRM regions though there is a paucity of data on their performance as yet. Some theoretical assessments have been made based on hydraulic effectiveness and nutrient uptake and these are assessed further below.

1.2 Constructed wetlands

Constructed wetlands for agricultural run-off are usually situated ‘on-farm’, in areas that had previously yielded low to marginal crop production or were often former wetlands or drainage paths where the opportunity cost of foregone commercially viable irrigation is negligible. For water quality improvement services, they are located downstream of tail-water or irrigation discharge areas, or down-land of overland flows of run-off. The ideal size is dependent on the size of the catchment area, or the number of hectares which drain into the wetland and how much water the wetland will generally be treating. Constructed wetlands also require an impermeable bottom layer, either clay or man-made material, to protect the groundwater from infiltration of pollutants. They are normally vegetated (as distinct from recycle pits) (Figure 1) but also require an area of sufficient size to allow biogeochemical processes to occur over a sufficient residence time. The primary pollutant removal processes of constructed wetlands are through enhanced sedimentation for fine particulates, and through biological uptake by bacterial and fungal films (biofilms) adhering to plants and sediments (Pollard 2010, Kadlec and Wallace 1996).

Constructed wetlands usually have a built-in high flow bypass design, driven by hydraulic/backward flow into an upstream sediment basin. Bypass designs redirect large flows around the wetland to avoid flushing of the wetland downstream. Design options for adaptive management, such as water level gauges and pumps, etc., can also be included in constructed wetlands. Important issues that are considered when designing wetlands, other than upstream catchment area, include hydraulic efficiency, vegetation composition, bathymetry, hydraulic grade changes in the land (i.e. direction of water flow) and water table depth.

Figure 1. *Constructed wetland on a banana farm in the Johnstone River basin (from DeBose et al. 2014).*

Numerous studies have been conducted on the effectiveness of constructed wetland for the mitigation of high nutrient wastewater in temperate areas, sub-tropical areas and in urban catchments, however very little work has been conducted in tropical areas which are prone to seasonal high flow events and flooding. Many factors influence the ability of constructed wetlands to reduce pollutants and improve the quality of water exiting the system. These factors include climatic conditions (e.g. amount of rainfall, surface temperature), background levels of organic matter, age, type and distribution of vegetation in the wetland, nutrients and solids generated within the wetland (such as dissolved organic nitrogen and phosphorus, and detritus), and overall residence time of the water within the wetland.

1.3 Recycle pits (dry and wet weather)

Recycle pits (also known as sumps) are ponds or basins that supply irrigation water (from captured tailwater) back to the surrounding agricultural land (Figure 2). They are found in irrigation areas where the tail water from irrigated land is collected and stored. This water is often high in nutrients and pesticides which is then used to irrigate agricultural land. Recycle pits are excavated to provide an on-farm water resource point; to receive irrigation tailwater and runoff; and be used to irrigate out of. They normally do not have planted vegetation and are easily able to be excavated regularly to remove trapped sediment and particulate nutrients. When operated effectively they can capture near 100% of irrigation tailwater, with its contained fine sediment, nutrients and pesticides, and return it onto the farm. They have little or no direct biodiversity benefits. They may also be effective at reducing off-farm event runoff if they are sufficiently sized to capture a significant proportion of runoff events, though the sizing of these pits will be similar to that of wetlands.

Wet weather recycle pits are similar to dry weather pits but are used to treat “first flush” runoff from farms which may contain higher concentrations of nutrients, sediment and pesticides at the commencement of larger runoff events. They operate in a similar fashion to conventional ponds and sediment basins.

Treatment trains are often utilised for treating runoff and consist of a series of nutrient and sediment trapping mechanisms, such as grassed/vegetated drains, recycle pits and sediment basins prior to entering the constructed wetland. Treatment trains are often effective, especially when they include different types of flow regimes (e.g., deep pools with slower flow, subsurface flow, turbulent flow through shallow marsh areas, among others).

Figure 2. *On-farm recycle pit (reclamation sump) in the lower Burdekin River catchment (Photo credits: J. DeBose and D. O'Brien*)

1.4 Bioreactors

Bioreactors are a newer technology being implemented in sugarcane areas. They utilise the process of denitrification to intercept and process nutrients contained in shallow sub-surface flows. Constructed of a linear trench filled with organic matter (typically woodchips), they facilitate the processing of soluble nutrients through to nitrogen gas through denitrification. Some monitoring data on nutrient processing rates has become available from installations in both Queensland and internationally with further examples currently underway in the Wet Tropics NRM region. The latter systems are to be more fully evaluated as part of the Major Integrated Project (MIP) program that is being implemented in the Johnstone and Tully catchments of the Wet Tropics.

2 Approach

The approach in developing the estimates of cost effectiveness and the inputs for the Investment Pathways Tool (IPT) requires a consideration of costs, efficacy and the area available for each solution set. For this solution set, we have utilised data available from both previous Reef Costings work and the results of implementing the Wet Tropics and Burdekin Dry Tropics Major Integrated Projects. Costs and updated efficacies have been provided through the latter projects which has supplemented previous data.

2.1 Costs

2.1.1 Data

Five types of treatment systems were costed, these are:

(1) Landscape wetlands - these costs are largely drawn from recent projects undertaken for the Wet Tropics Major Integrated Project
(2) Constructed wetlands - costed using updated data from MUSIC
(3) Dry weather recycle pits - costed using data from sourced from Alluvium (2016)
(4) Wet weather recycle pits - costed using data from sourced from Shannon and McShane (2013)
(5) Bioreactors were estimated by Alluvium in consultation with the Australian Wetlands Consulting.

All costs have been updated to 2018-dollar values. Data on sugarcane operating margins was calculated for both the dry tropics and wet tropics using the Department of Agriculture and Fisheries Farm Economic Analysis Tool (DAF, 2016). Grazing operating margins were sourced from a beef data from NCE (2017, 2018).

The costs included for all wetlands are: capital costs, administration costs, asset renewal, operating/maintenance costs and opportunity cost of land. The opportunity cost of land is based on the operating margins ($/ha) for either grazing and/or cane growing. In some instance, no opportunity cost was applied to reflect the fact that wetlands are often established on areas of land that have little or no commercial value.

All estimated costs were categorised into: (1) capital acquisition costs – costs associated with preliminary works around location identification, feasibility and design works, (2) capital establishment costs – costs associated with ensuring that the treatment device/measure is properly established where that establishment cost is not included in the acquisition cost, (3) operating and maintenance – frequent costs associated with the operation and maintenance of streambank stabilisation works to ensure achievement of load reductions, and (4) general program administration costs not covered under either of the capital costs.

In all cases a range of values for the different costs were modelled to establish the most likely, 5th percentile and 95th percentile using a Monte-Carlo analysis with 20,000 iterations. The Monte Carlo analysis provides two key insights, the variability of costs and the drivers of variability in the life cycle costs for each treatment system type.

2.1.2 Results

After careful consideration of the candidate treatment systems, costs were estimated for each the systems and region. Table 1 provides a summary of the estimated initial cash costs over a 5-year period. A 2.5% inflation rate was used to adjust the estimated year 1 costs over subsequent years (year 1 to 5). The 5-year cash costs are the estimated funds to support construction and operation of treatment system over the initial 5 years. For example, in the Wet Tropics region, it is estimated that the most likely cost for a constructed wetland requires capital costs of $28,613, operating and maintenance costs of $1,533 in year 1 and program costs of $1,533 in year 1.

Table 1. Most likely cash costs by practice change and region over a 5-year period (2018 AUD)

Region	Cost type	Capital-acquisition	Capital-establishment	Operating and maintenance					Program admin				
	Year	*1*	*1*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
	Solution Asset												
Wet Tropics	Constructed wetland	28,613		1,533	1,571	1,611	1,651	1,692	1,533	1,571			
	Wet weather recycle pits	19,176		65	67	68	70	72					
	Bioreactors	25,667	8,400	1,600	1,640	1,681	1,723	1,766					
	Landscape wetlands	2,190	9,600	212	218	223	229	234	14	15	15	16	16
Burdekin Dry Tropics	Constructed wetland	28,613		1,479	1,516	1,554	1,593	1,633	1,479	1,516			
	Wet weather recycle pits	19,176		15	15	15	16	16					
	Dry weather recycle pits	1,140	315	58	60	61	63	64					
	Bioreactors	25,667	8,400	1,600	1,640	1,681	1,723	1,766					
	Landscape wetlands	2,190	9,600	212	218	223	229	234	14	15	15	16	16

Life cycle costs (2018AUD per ha) over a 30-year appraisal were estimated using a 7% discount rate. Life cycle costs are the estimated costs per ha over a 30-year period in 2018 Australian dollar values. These costs include all estimated cost categories. It should be noted that there is significant variability in the range of input data and assumptions used in the modelling. Thus, data on low (best), most likely and high (worst) costs was included in our modelling to capture this variability. Table 2 shows the estimated most likely costs (annual $) and the 90% prediction interval from a Monte Carlo simulation with 20,000 iterations. The best and worst values represent the 5th and 95th percentile for each reported cost estimate. These results indicate that the most likely life cycle costs for a constructed wetland in the Burdekin is $63,618 over 30 years and the 90% prediction interval ranges from $49,383 to $86,546.

It is intuitive to assess how much of an impact each of the different costs have on the bottom line estimates of lifecycle costs (LCCs). For a constructed wetland in the Burdekin region, our Monte Carlo estimations indicate that capital costs have the greatest contribution to variance in the 30-year LCCs at 50%, followed closely by operating and maintenance costs at 42%, and program and opportunity cost of lost cane operating margins each have about 4% contribution variance in the LCCs, and asset renewal costs have lowest contribution at 0.1%. This contribution to variance is a result of the variability and/or confidence in the input parameter values.

Table 2. Estimate costs of practice change and the contribution to variance in the life cycle costs

Region	Solution asset	30 Year life cycle costs			Contribution to variance				
		Best	Most Likely	Worst	Capital - acquisition	Operating and maintenance	Program (establish-ment)	Cane operating margin	Asset renewal
Wet Tropics	Constructed wetland	49,383	63,618	86,546	49.9%	42.2%	3.5%	4.4%	0.1%
	Wet weather recycle pits	21,735	31,823	48,921	87.6%	0.1%		8.2%	4.2%
	Bioreactors	66,136	69,592	85,360	48.0%	33.0%	5.0%		14.0%
	Landscape wetlands	13,684	15,434	17,186	46.7%	41.2%	0.9%	11.2%	0.0%
Burdekin Dry Tropics	Constructed wetland	49,516	64,263	87,247	77.1%	0.0%	0.0%	19.2%	3.7%
	Wet weather recycle pits	24,714	35,653	53,525	41.3%	36.1%	22.5%		
	Dry weather recycle pits	1,791	2,236	2,689	53.1%	36.6%	5.6%		4.7%
	Bioreactors	59,756	63,258	78,027	2.9%	7.8%	89.1%		
	Landscape wetlands	13,684	15,434	17,186	49.9%	42.2%	3.5%	4.4%	0.1%

2.2 Efficacy

2.2.1 Data

The ability of wetlands to improve the quality of water has long been recognised and has led to the proliferation of wetlands as a means to treat, diffuse and point source pollutants from a range of land uses. However, much of the existing research has been undertaken in temperate climates with a paucity of information on the effectiveness of wetlands in tropical regions. The effectiveness of some wetlands for trapping sediment is moderate but for trapping dissolved nutrients very low (Hunter and Lukacs 1999, 2000; McJannet *et al*. 2011, 2012; DeBose *et al.* 2014) in typical Burdekin and Wet Tropical areas of the GBR catchment.

DeBose *et al*. (2014), in a review investigating the effectiveness of a variety of vegetated systems at sites within the South Johnstone, Tully, Herbert and Burdekin catchments, conclude that *"the residence time of contaminants in vegetated systems, especially for dissolved and fine particulate material, is the most important factor in determining trapping effectiveness. As particulate material is generally easier to trap than dissolved matter, properties of contaminants which predispose them to be present in a particulate form or to adsorb onto particulate matter will strongly regulate trapping effectiveness. Thus, large hydraulic volume traps or systems with relatively low input volumes will be the most effective at trapping agricultural pollutants."*

A principal finding of the DeBose *et al.* (2014) study is that *"the residence time of water in trapping mediums is an important measure of likely effectiveness of any vegetated area. Long residence times lead to effective trapping while short residence times are unlikely to trap anything.*

Field studies in constructed wetlands and recycle pits across the Wet Tropics and Burdekin regions in cane and bananas DeBose *et al.* (2014) found some trapping of sediment and nutrients in the dry season but very little (effectively zero) trapping in the wet season in times of maximum pollutant delivery but short residence times.

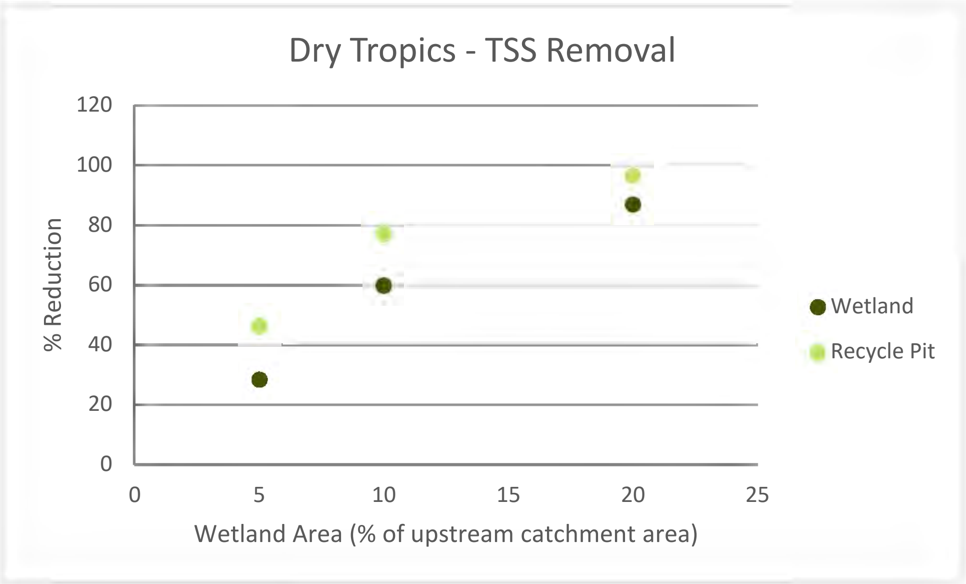
Similar results were found by Hunter and Lukacs (1999, 2000) in studies of constructed wetland trapping in the lower Burdekin: "*where the potential for using constructed wetlands to improve the quality of irrigation drainage waters (tailwater) was assessed at an experimental site in the Burdekin River Irrigation Area in north Queensland. Two detailed performance trials were undertaken in 1999 to quantify changes in concentrations and loads of suspended solids, phosphorus and nitrogen between wetland inlets and outlets. Intake water to the wetlands during the trials contained mean concentrations of suspended solids of < 95 mg L-1, total phosphorus < 0.09 mg L-1, and total nitrogen < 0.63 mg L-1.* ***The wetlands removed 60-70% of the suspended solids load (compared with 16-49% from a control bay without vegetation) and concentrations at bay outlets were significantly lower than at inlets****. However, there was a net increase (ranging from 0.4% to 67%) in total phosphorus loads, and concentrations at the outlets of vegetated bays were significantly higher than at inlets.* ***Changes in total nitrogen loads were relatively small and variable (within the range ± 22%), and concentrations at outlets were generally not significantly different from those at inlets.*** *The wetlands at the time of these trials had been established for five years. Results from monitoring in 1994/95 indicated a much greater ability of the wetlands to remove phosphorus, although results for suspended solids and nitrogen were comparable. Reasons for the diminished phosphorus removal in 1999 may have been due to the changed condition of the wetlands as well as differences in the phosphorus composition of water entering the wetlands."*

Overall, it is clear that a constructed wetland would only trap dissolved nitrogen in the time of maximum input i.e. the wet season if they were of sufficient size to provide an effective residence time for biological processes to operate. Recycle pits can trap dissolved nutrients from irrigation tailwater in the dry season and as the water is returned to the farm can also be very effective in removing this component of paddock nitrogen loss. However, this really only applies to the lower Burdekin where there is a surplus of irrigation delivery due to furrow irrigation and this is the least critical time for delivery of nitrate to the GBR. In other catchments, recycle pits are being used where they may be acting as a runoff harvesting scheme and providing both an irrigation source and pollutant trapping mechanism.

Some data exists for the efficacy of recycle pits in the Lower Burdekin region and this will be used directly in the modelling. To quantify the likely performance of wetlands and recycle pits, modelling was undertaken in the MUSIC modelling software. While typically applied in urban environments, MUSIC can easily be configured to provide simulations of non-urban catchments. Previous work undertaken in the region to model wetlands (DPI 2009) had identified relevant modelling parameters to use and these were applied to representative wet tropics and dry tropics climatic conditions. The results of this analysis are shown below. Note that MUSIC simulates Total Suspended Solids and Total Nitrogen only but does account for both particulate and dissolved nutrient treatment processes. As such, the treatment removals outlined below are indicative only and need to be refined to account for fine sediment and DIN only.

2.2.2 Results

Results in terms of TSS and TN removal are shown in the figures below. These are used as parameters within the model. For this project, we have assumed that wetlands and recycle pits would be sized to be effective for the upstream catchment area (i.e. not oversized or undersized). For these assessments we have therefore adopted a median wetland size of 10% of upstream catchment area. Recycle pits have also been sized similarly, but it is highly likely that recycle pits for irrigation could be reduced in size due to the smaller treatment volumes of irrigation tailwater.



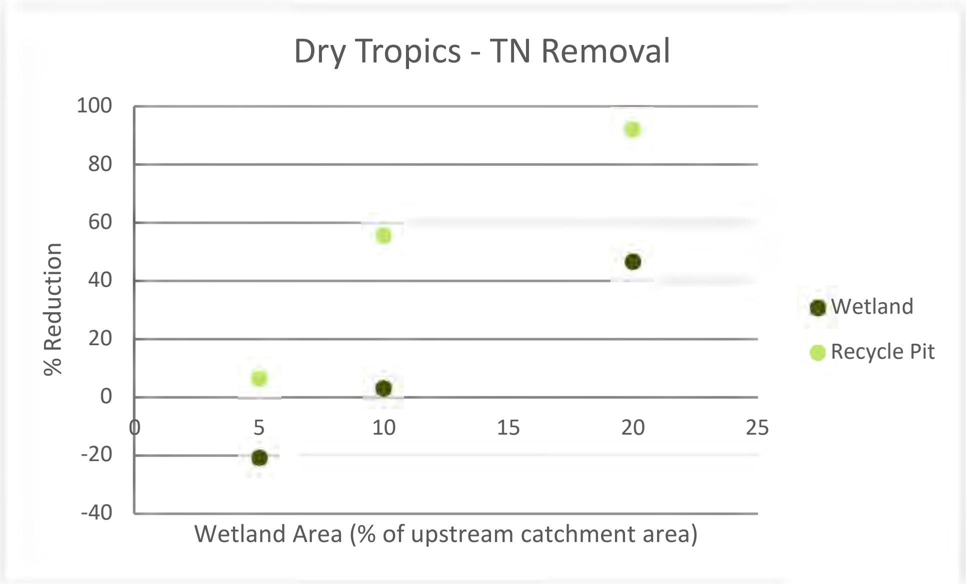
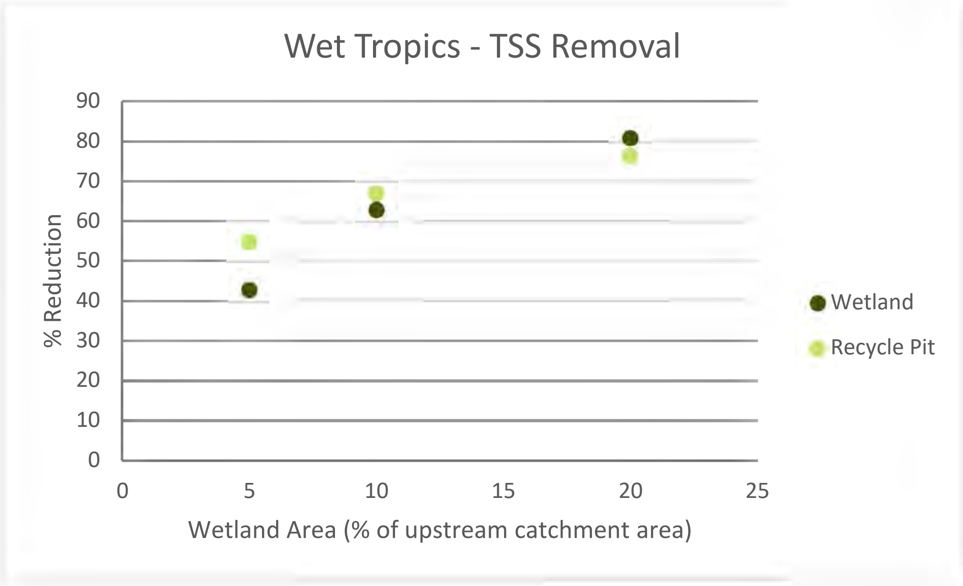


Figure 3. *Wetland and Recycle Pit Performance for Event Runoff – Dry Tropics*



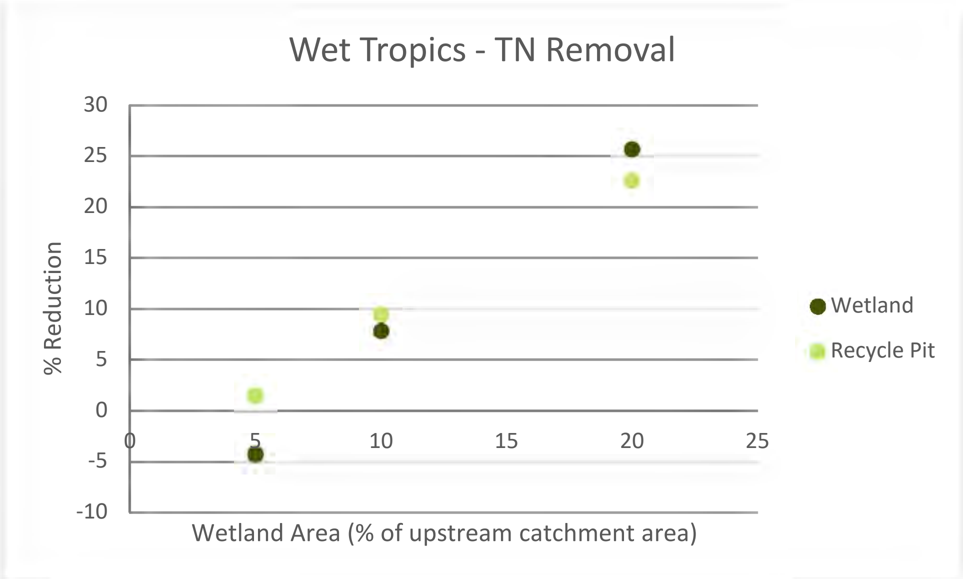


Figure 4. *Wetland and Recycle Pit Performance for Event Runoff – Wet Tropics*

For landscape wetlands, only one project was available based on existing work being conducted as part of the Wet Tropics Major Integrated Project. This was used as the basis for understanding the performance of landscape wetlands in other climatic regions by conducting modelling of the configuration of the wetland in the MUSIC model and extracting the % reduction of DIN for these regions.

2.3 Area available

The primary region where constructed wetlands and treatment facilities such as recycle pits have been proven to have value in pollutant trapping is in the lower Burdekin cropping lands (sugarcane mostly) for trapping dissolved nutrients and herbicides (the pollutants of concern in this area). The scenarios focus on that region but provide quantitative evidence that the sizing of constructed wetlands needs to be at least 100% greater than a recycle pit to have a similar level of treatment. In other regions like the Wet Tropics, due to in the volumes of rainfall runoff events, constructed wetlands are somewhat effective for sediment but have lower effectiveness for dissolved nutrients and herbicides. In the majority of areas of sugar cane, fine sediment is not a priority because the areas are typically flatter and therefore have lower sediment generation potential. However, in some catchments, particularly the Mackay-Whitsunday, sediment from cane lands can be a dominant source and therefore wetlands may be worthy of consideration.

3 Results

3.1 Cost-effectiveness

Initial analysis has shown that recycle pits can be more effective at pollutant trapping (and hence reducing end-of-catchment loads) than constructed wetlands (as each is defined below) in some catchments, however constructed wetlands have considerable potential biodiversity gains which recycle pits do not. The treatable area and DIN load from sugarcane land uses for each NRM region is shown in Figure 5. The cost-effectiveness of each practice change step based on the most likely efficacy (percentage reduction) and cost ($/ha) is shown in Table 3 to Table 7.

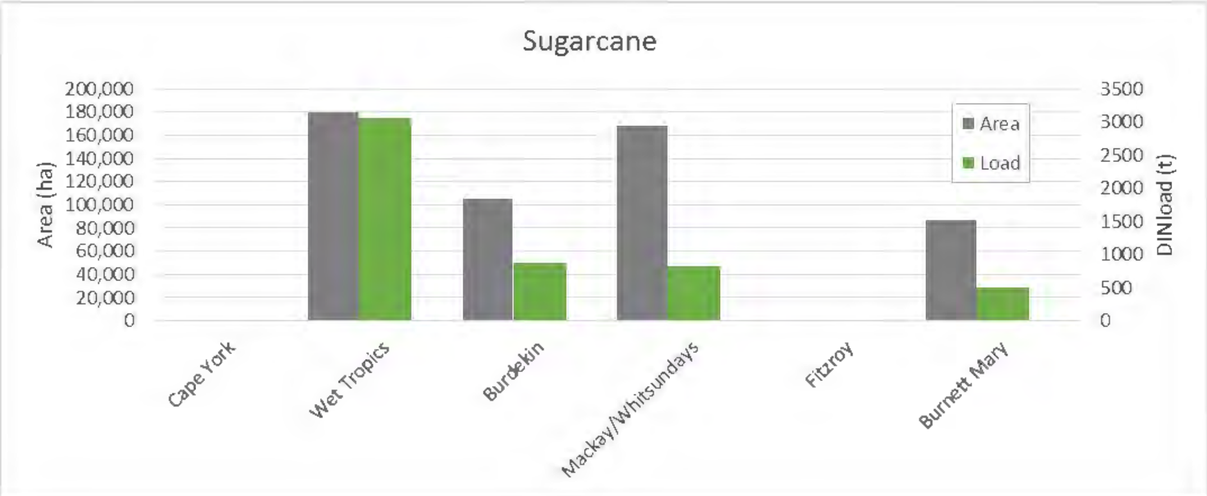


Figure 5. *Areas and loads from wetlands for each NRM region*

The following tables show preliminary estimates of cost-effectiveness based on the most likely cost per hectare (Table 2) and the stated efficacy. For each region (e.g. Wet Tropics) there are a number of basins that each have a different delivery ratio to the end of catchment as well as a different load per hectare. This has an impact on cost-effectiveness at the end of the catchment. The range of cost-effectiveness estimates presented for each region below shows the range of end of catchment costs (minimum through to 75th percentile of the basins modelled, with values above 75th percentile considered to be too expensive to warrant investment and statistical outliers).

Table 3. Estimated cost-effectiveness and treatable area and load for wet weather recycle pit

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Cape York	0	0	-	-	-	-
Wet Tropics	0	0	-	-	-	-
Burdekin	104,759	876	$3,892	$6,031	$7,289	$9,990
Mackay/Whitsundays	0	0	-	-	-	-
Fitzroy	0	0	-	-	-	-
Burnett Mary	0	0	-	-	-	-

Table 4. Estimated cost-effectiveness and treatable area and load for wetland (constructed)

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Cape York	0	0	-	-	-	-
Wet Tropics	179,986	3,062	$11,225	$11,400	$12,712	$15,262
Burdekin	104,759	876	$8,442	$13,082	$15,811	$21,671
Mackay/Whitsundays	167,717	833	$24,610	$24,702	$25,562	$27,433
Fitzroy	0	0	-	-	-	-
Burnett Mary	86,389	505	$10,354	$15,981	$17,901	$18,657

Table 5. Estimated cost-effectiveness and treatable area and load for wetland (landscape)

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Cape York	0	0	-	-	-	-
Wet Tropics	179,986	3,062	$4,937	$5,014	$-	$6,713
Burdekin	104,759	876	$5,249	$8,134	$9,830	$13,474
Mackay/Whitsundays	167,717	833	$18,707	$18,777	$19,431	$20,854
Fitzroy	0	0	-	-	-	-
Burnett Mary	86,389	505	$7,407	$11,432	$12,806	$13,347

Table 6. Estimated cost-effectiveness and treatable area and load for bioreactors

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Cape York	0	0	-	-	-	-
Wet Tropics	179,986	3,062	$3,728	$3,786	$4,222	$5,069
Burdekin	104,759	876	$9,306	$14,422	$17,430	$23,891
Mackay/Whitsundays	167,717	833	$18,580	$18,649	$19,298	$20,712
Fitzroy	0	0	-	-	-	-
Burnett Mary	86,389	505	$8,574	$13,233	$14,823	$15,450

Table 7. Estimated cost-effectiveness and treatable area for dry and wet weather recycle pits

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Cape York	0	0	-	-	-	-
Wet Tropics	0	0	-	-	-	-
Burdekin	104759	876	$1,513	$2,345	$2,834	$3,885
Mackay/Whitsundays	0	0	-	-	-	-
Fitzroy	0	0	-	-	-	-
Burnett Mary	0	0	-	-	-	-

The range of cost-effectiveness for each practice change, according to region, is visually represented in Figure 6 to Figure 10.

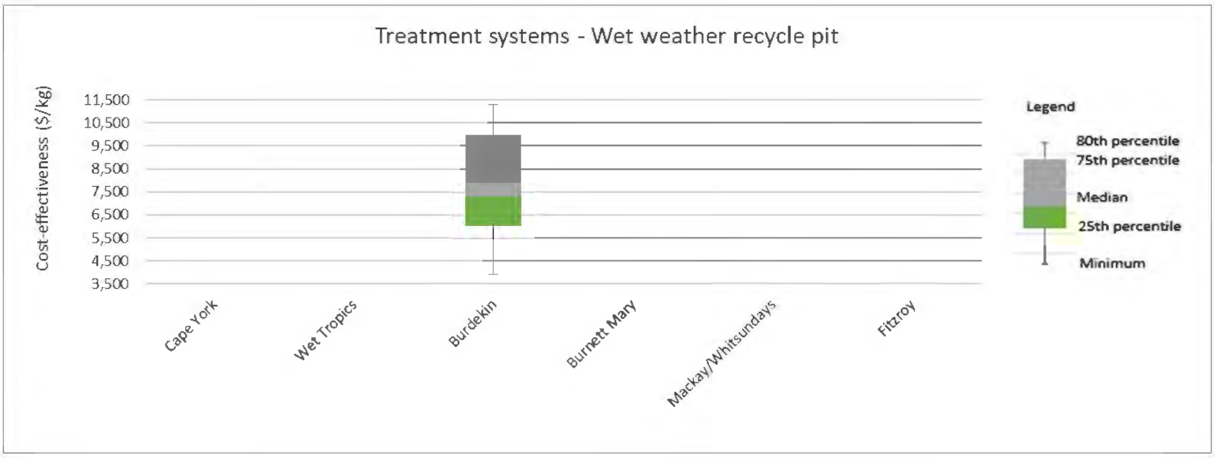


Figure 6. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for wet weather recycle pit*

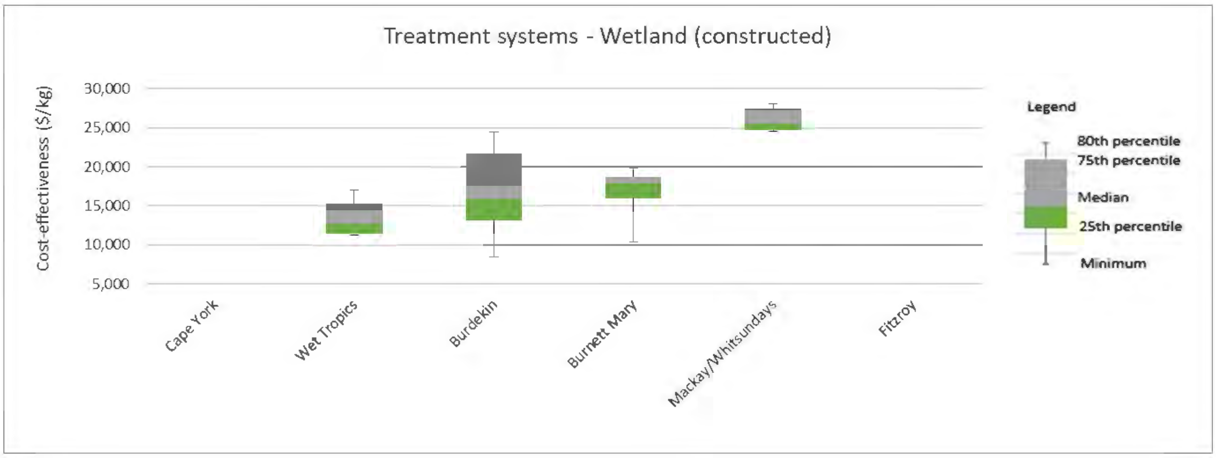


Figure 7. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for wetland (constructed)*

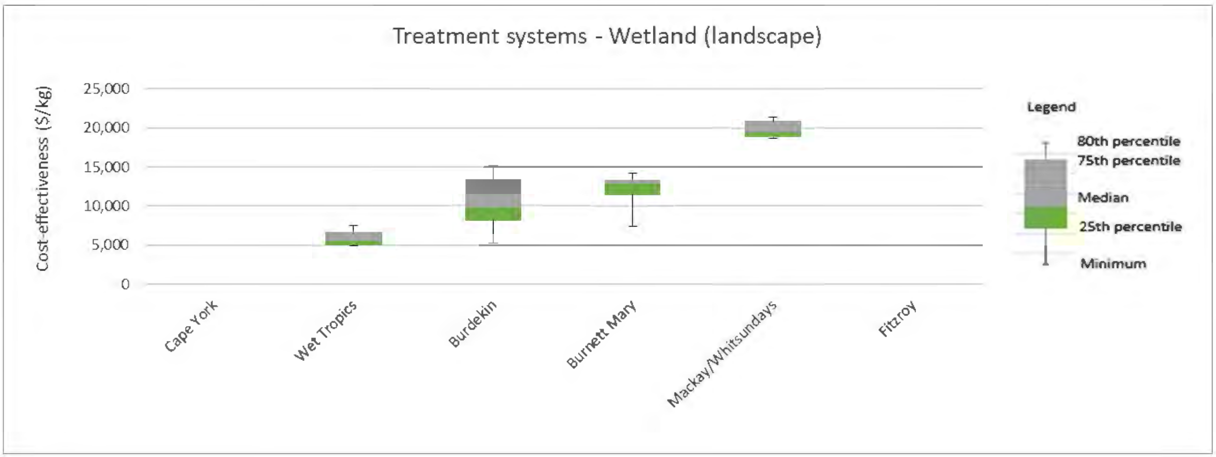


Figure 8. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for wetland (landscape)*

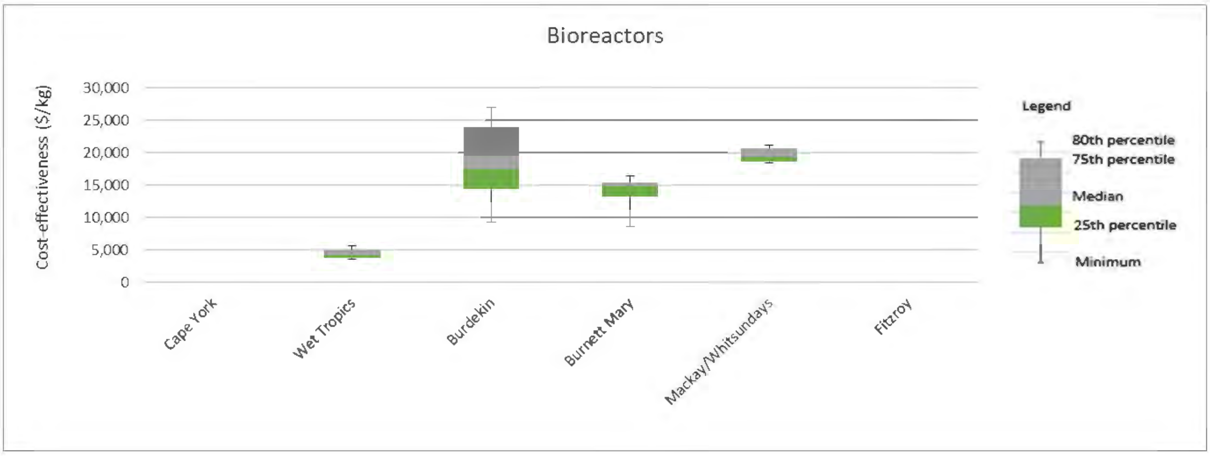


Figure 9. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for bioreactors*

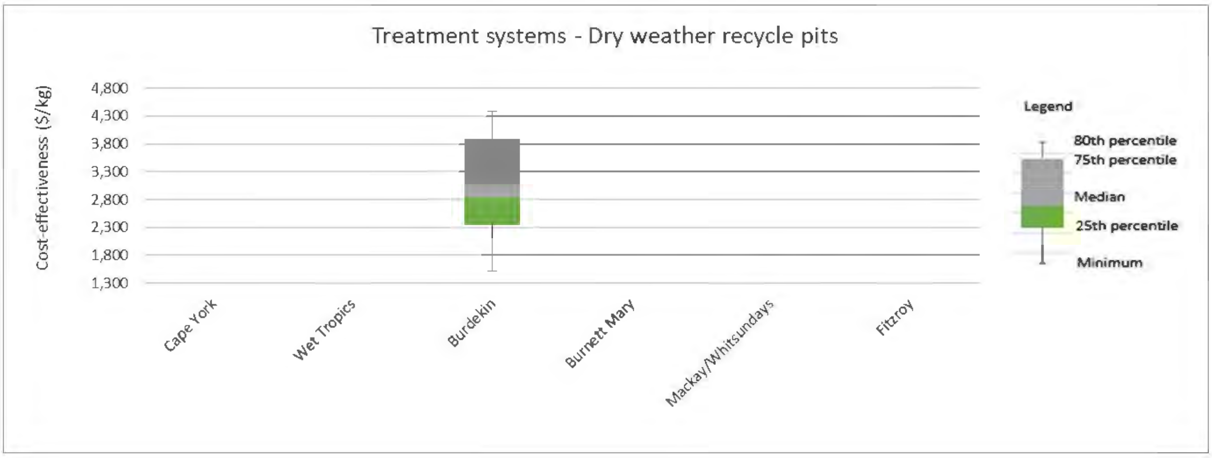


Figure 10. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for dry and wet weather recycle pits*

3.2 Assumptions and limitations

Assumptions had to be made to take data from the Burdekin (fully irrigated cane with furrow irrigation) and then apply it in other regions such as Mackay Whitsunday (supplementary irrigation with overhead) or the Wet Tropics (rainfed sugarcane) for recycle pits.

The type of wetland constructed needs to consider rainfall and irrigation regimes, objectives – e.g. trapping fine sediment, dissolved nutrients and/or dissolved herbicides; biodiversity gains; long-term effectiveness, degree of protection of the GBR versus other high value ecosystems, for example, Ramsar sites. In addition to these broad issues, in any catchment there are likely to be local constraints relating to land ownership and tenure, existing wetland condition, location with respect to existing cropping areas, local drainage and hydrology, access, presence of irrigation, distance to valued ecosystems, issues of disturbing Potential Acid Sulphate Soils, land area availability and hydrological factors.

4 Contributors

Mike Ronan and Matthew Griffiths of DES reviewed the modelling and input data for the landscape wetlands, constructed wetlands and bioreactors and were satisfied that they were reasonable representations of performance.

5 References

Alluvium (2016). 'Costs of achieving the water quality targets for the Great Barrier Reef'. Report to the Department of Environment and Heritage Protection. Brisbane, Queensland

DAF (2016). FEAT Regional Scenarios, Department of Agriculture and Fisheries, Queensland Government.

Davis, A., Pearson, R., Brodie, J., Butler, B. (2016). 'Review and conceptual models of agricultural impacts and water quality in tropical and sub-tropical waterways of the Great Barrier Reef catchment area'. *Marine and Freshwater Research.*

Davis, A. (2007). 'Overview of Research and Environmental Issues Relevant to Development of Recommended Farming Practices for Sugar Cane Farming in the Lower Burdekin Region'. *Centre for Tropical Freshwater Research.* ACTFR Report No. 07/35, James Cook University, Townsville, Queensland, Australia.

DeBose, J., Coppo, C., McIntyre, R., Nelson, P., Karim, F., Davis, A., and Brodie, J. (2014). 'Effectiveness of vegetated systems in managing contaminated runoff from sugarcane and banana farms to protect off-farm aquatic ecosystems, particularly the Great Barrier Reef'. *Centre for Tropical Water and Aquatic Ecosystem Research.* Report 14/10, James Cook University, Townsville, Queensland, Australia.

DPI (2009). "Course Notes: Modelling Rural Catchments using MUSIC", prepared under a Caring for our Country grant for the Queensland Department of Primary Industries, Townsville, 2009.

Hunter, H. and Lukacs, G. (2000). LWRRDC Project QPI 26 nutrient control in irrigation drainage systems using artifi cial wetlands. Department of Natural Resources and Mines; the Australian Centre for Tropical Freshwater Research; and the Land and Water Research Development Corporation, Brisbane.

Hunter, H. & Lukacs, G. (1999). 'Use of Constructed Wetlands to Improve Water Quality in the Burdekin River Irrigation Area'. *Department of Natural Resources, Queensland*. Presentation to ANCID and LWRRDC workshop on: Management of Nutrients and Sediment in Irrigation Return Water.

Kadlec, R.H. & Wallace, S. (1996) (reprinted 2009). 'Treatment Wetlands, Second Edition'. *Hydrological Processes*. CRC Press, Florida.

McJannet, D., Wallace, J., Keen, R., Hawdon, A. and Kemei, J. (2012). 'The filtering capacity of a tropical riverine wetland: II. Sediment and nutrient balances'. *Hydrological Processes.* 26(1), 53-72.

NCE (2018). 'Burdekin Coastal Hazard Assessment Strategy'. Report to the Burdekin Shire Council.

NCE (2017). Analysis of rural lot sizes for Isaac Regional Council'. Report to the Isaac Regional Council.

Pollard P.C. (2010), 'Bacterial activity in plant (*Schoenoplectus validus*) biofilms of constructed wetlands'. *Water Research.* 44(20):5939-48

Shannon, E.L. and McShane, T.J., 2013. Options for tailwater capture and reuse in the Barratta Creek catchment (A scoping study). Report funded through the Wetland Management in Agricultural Production Systems Programme. QWP Phase 11 2012-2013. 24 pp

Solution Statement 9: Upgrading Sewage Treatment Plants

1 Scenario description and context

Sewage treatment plants (STPs) provide an opportunity for engineered treatments at discrete points controlled by government-owned bodies. They also provide a high level of certainty in outcomes and opportunities for cost recovery via charges to households. However, the amount of total emissions produced by STPs is small, especially relative to diffuse emissions from agriculture.

An increasing share of discharged wastewater is tertiary treated. The process of upgrading is ongoing, with the major population centres of Bundaberg, Gladstone and Rockhampton still operating STPs to secondary treatment standards (qldwater 2017).

Upgrading existing secondary STPs to tertiary standards is the specific management action assessed herein for inclusion in the Investment Pathways Tool (IPT). Costs and effectiveness are assessed, contained to those STPs located less than 50km from the coast for which sufficient data was available.

1.1 Tertiary treatment

While a strict definition of 'tertiary treatment' does not exist, this report applies the same definition used by qldwater (2017) that accords with the GBRMPA (2005) policy for island STPs: a long-term median reduction to or better than total nitrogen (TN) to 5 mg/L, and phosphorous of 1-2 mg/L. Development application licence conditions also refer to long-term 50th percentile rate of emissions, rather than long-term median. For this report, the definitions are considered equivalent, and only TN is assessed.

In the absence of data or otherwise stated performance requirements, a review of Queensland Government issued licence requirements (DES, 2018) indicates 10 mg/L emitted TN or larger is considered to signify secondary treatment performance. Emissions below 10 mg/L are considered to equate to tertiary treatment. Licences for STPs on Cape York require treatment to 20 mg/L TN or better. For Cape York STPs, performance at or above 20 mg/L TN is considered secondary treatment. Insufficient data was available to assess Cape York STPs, and so the region was not assessed.

1.2 Approach

The approach in developing the estimates of cost effectiveness and the inputs for the Investment Pathways Tool (IPT) requires a consideration of costs, efficacy and the area available for each solution set. For this solution set, we have utilised data available from the Queensland Water Directorate (qldwater), local government STP factsheets, annual performance reports and operational plans, the National Pollutant Inventory (NPI), the Queensland Government Department of Environment and Resource Management (DERM) development approvals, and the Queensland Government Department of Energy and Water Supply (DEWS) planning guidelines for water supply and sewage. Coastal catchments were the focus of modelling due to the risk posed to the Reef.

It should be noted from the outset that, despite STPs with an equivalent population (EP) above 21 being prescribed environmentally relevant activities under the Environmental Protection Regulation 2008 (DES, 2018), very little performance data (throughput, discharge) is available. This was the case even with some of the larger STPs. Interrogation of the database of performance data provided by qldwater and DES found only 21% of STPs actually had reported data for discharge. Therefore, we have relied on a number of assumptions and previous analysis by qldwater to parameterise our modelling.

Our basic approach was to:

1. Based on the database of all STPs[1], isolate the STPs within scope of this assessment. A total of 38 STPs were identified. The average EP was 12,200, while the median EP was 3,300. The 38 STPs were allocated to their respective regions to establish regional estimates that includes all relevant STPs for that region.
2. For current discharge, we used the estimated load from the qldwater (DES, 2018) database, or from actual reported discharge (when available). See Section 1.4.
3. For post investment loads, we estimated the post tertiary treatment loads at a 5mg/L TN.
4. The *difference* between estimated current discharge and discharge at 5mg/L provides an estimate of the efficacy of STP upgrades.
5. For capital costs and operating costs we used the average CAPEX/EP and OPEX/EP developed by qldwater (DES, 2018) for STPs larger than the median of the assessed sample (i.e., >3,300EP). An STP scale of 10,000 EP was used as being broadly representative of all of the STPs that could be upgraded. It is worth nothing that using the standardised costing multipliers (DEWS 2014) there is only limited differences between STPs of 3,000 to >10,000 EP) (<10%). However, capital costs per EP rise sharply for very small STPs (e.g. <300EP).
6. Life cycle costs (LCCs) were then estimated for each region. The variance in the regression provided the broad range of capital and operating costs per EP used in the Monte Carlo assessments.
7. Cost effectiveness estimates were then established.

1.3 Costs

1.3.1 Data

Assessed costs were for capital and operating and maintenance only. Asset renewal costs, administration and program costs, and opportunity costs of land were not assessed because they were considered to already be factored in to the operation of existing facilities and would not be materially affected by potential upgrades. Where data is dated, all values have been updated to 2018 values unless stated otherwise.

Our approach to costings built on the recent work completed by qldwater, and their work to establish indicative cost functions and 10,000EP as the independent input variable. All estimated costs were categorised into: (1) capital – on ground direct costs of purchasing and installing capital equipment; and (2) operating and maintenance – costs associated with the operation and maintenance of sewerage treatment plants.

Based on the review of actual capital and operating costs data undertaken by qldwater (2017) for STP upgrades undertaken in recent years, we established updated estimates for each of those respective plants. For STPs that were smaller than the range where data was available, we utilised the DEWS (2014) scaling curves to estimate the capital and operating costs for those plants. A similar approach was used for plants greater than 10,000 EP. This enabled us to estimate capital and operating expenditure for all of the STPs within the scope of the assessment.

There were significant limitations and variability in the range of input data and assumptions used in the modelling. Both capital and operating and maintenance costs are higher and increasingly variable with reducing STP size, especially under about 1,000 EP. Conversely, as STP size increases, both capital and operating and maintenance costs decrease and are observed to be less variable, with CAPEX/EP stable for an STP above 10,000 EP (i.e., CAPEX/EP assumed equivalent for a 10,000 EP and 100,000 EP STP).

The relative predictability of unit capital and operating costs above 10,000 EP supported the development of a theoretical 10,000 EP unit STP (hereafter 'unit STP'). The very low variability of observed unit costs per EP and ML for STPs above 10,000 EP suggested 10,000 EP would be suitable as a basis for a unit STP. Supporting this was the improved fit and lower variance of observations of unit costs from 1,000 through 10,000 EP and larger (qldwater 2017).

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[1] Issued by qldwater 23 November 2018, and augmented with local government reported observations from STP factsheets, operational plans and annual performance reports.

The unit STP was calibrated to available observed data and the equations for costs per ML and EP developed by qldwater (predominantly using qldwater supplied data and local government reports), were scaled using the sewage planning guidelines cost relationship curves (DWS 2014). These were then adjusted for cost variance with STP size based on our Monte Carlo analyses of individual STPs of varying sizes where input data was available (flows, emissions, serviced EP/STP). The range of costs for a unit STP was estimated based on 13 STPs as reported in (qldwater 2017). Of the 13 STPs above 3,300 EP (the assessed sample median), the minimum, average and maximum values for CAPEX/EP were 333, 3003 and 11,111, and for OPEX/EP 9, 78 and 247. All 13 STPs had data on OPEX/EP, however 3 (*italicised)* of the 13 did not have CAPEX/EP and their values were inferred using a simple log regression based on the 10 STPs, year of upgrade and size in EP for which the CAPEX/EP data was available. The unit cost and scaling relationships are described below.

Table 1. CAPEX/EP and OPEX/EP from recent tertiary treatment STPs from GBR catchments

			Cost per EP (2014$ unless otherwise stated)	
14/15 load (EP)	Year of upgrade	Licence limit	CAPEX/EP	OPEX/EP
3,600	2013	5N/1P	11,111	166.00
4,000	2014	5N/1P	*7,386*	247.28
4,100	2011	5N/1P	537	139.00
4,500	2015	5N/2P	3,667	86.44
10,000	2016	5N/2P	1,700	50.00
10,000	2015	5N/1P	*4,012*	68.18
16,200	2015	5N/1P	*4,221*	91.85
18,000	2009	5N/1P	333	17.17
24,800	2009	5N/1P	1,492	17.14
58,800	2009	5N/1P	935	9.47
65,000	2011	5N/1P	2,000	53.85
68,000	2009	5N/1P	882	10.62
105,000	2008	5N/1P	762	52.38

Source: qldwater (2017)

A caveat: While these equations were developed from the best data available, qldwater noted that further data was needed to fully characterise the relationship of unit costs with STP size. Therefore, whilst noting that although a Monte Carlo analysis generally captures the likely variability of results successfully, it is also acknowledged that a revised equation (changing inputs into the Monte Carlo analysis) could significantly affect output results and so impact subsequent analyses and decisions.

The qldwater (2017) data was informed by the DEWS (2014) sewage planning guidelines for estimating unit capital and operating costs to allow for diseconomies of scale for STPs under 10,000 EP in size. The DEWS curves were used for adjusting the unit STP for diseconomies of scale for 100 to 10,000 EP and are reproduced below from Figures 4.3 and 4.4 of DEWS (2014). Note the plots from 10,000 to 200,000 EP reflect the author's assumptions to scale the unit STP above 10,000 EP. Specifically, it is assumed that no further economics of scale are gained for capital costs/EP over 10,000 EP or operating costs/EP over 100,000 EP. This assumption is illustrated by the flattening of the scale multiplier curve in Figure 1 below.

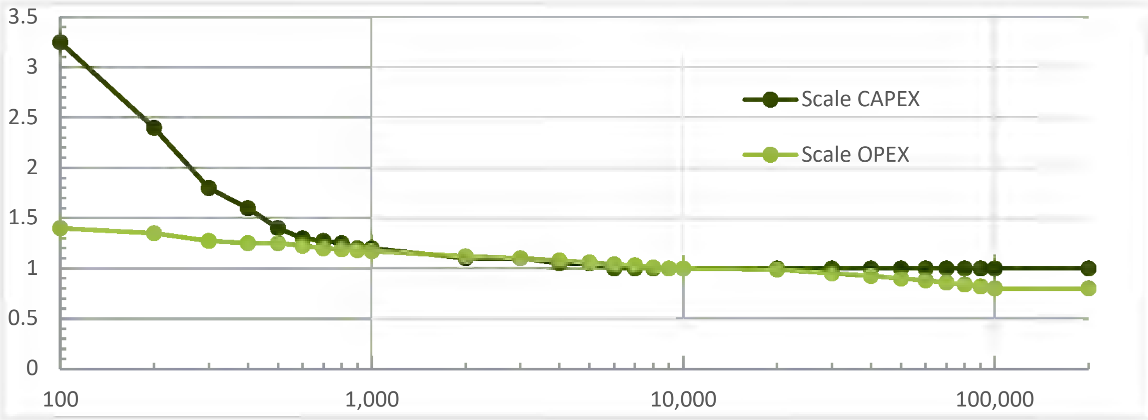

Figure 1. *Multiplier curves for capital and operational costs/EP varying with EP (x-axis). Source: reproduced with modifications from figures 4.3 and 4.4 of DEWS 2014.*

In all cases a range of values for the different costs was modelled to establish the most likely, 5th percentile (low cost) and 95th percentile (high cost) using a Monte-Carlo analysis with 20,000 iterations. The Monte Carlo analysis provides two key insights, the variability of costs and the drivers of variability in the life cycle costs of tertiary STPs.

1.3.2 Results – present value of costs

Table 2 provides a summary of the estimated initial cash costs over a 5-year period. The 5-year cash costs are the estimated funds to support upgrading works over the initial 5 years. For example, in Burdekin region, it is estimated that the most likely capital cost is $3,333 per plant and operating and maintenance costs are $86 in year 1.

Table 2. Most likely cash costs of upgrading to a tertiary plant by region type over a 5-year period (2018 AUD)

	Capital	Operating and maintenance				
Year	**1**	**1**	**2**	**3**	**4**	**5**
Region						
Burdekin	3,333	86	88	91	93	95
Burnett-Mary	3,474	88	90	92	95	97
Fitzroy	3,271	83	85	87	89	91
Mackay Whitsunday	3,840	97	99	102	104	107
Wet Tropics	3,400	87	89	92	94	96

Life cycle costs (2018AUD per ha) over a 30-year appraisal were estimated using a 7% discount rate. Life cycle costs are the estimated costs per ha over a 30-year period in 2018 Australian dollar values. These costs include all estimated costs categories i.e. capital, and operating and maintenance. It should be noted that there is significant variability in the range of input data and assumptions used in the modelling. Thus, data on low (best), most likely and high (worst) costs was included in our modelling to capture this variability. Table 3 shows the estimated most likely upgrade costs per region and the 90% prediction interval from a Monte Carlo simulation with 20,000 iterations. The best and worst values represent the 5th (best) and 95th (worst) percentile for each reported cost estimate. These results indicate that the most likely life cycle costs for sewerage treatment plant in the Burdekin is $4,489 per equivalent person over 30 years and the 90% prediction interval ranges from $3,346 to $13,435 per equivalent person.

It is intuitive to assess how much of an impact each of the different costs have on the bottom line estimates of lifecycle costs (LCCs). For upgrades in the Burdekin region, our Monte Carlo estimates indicate that capital costs have the greatest contribution to variance in the 30-year LCCs at 92.5%, while operating and maintenance costs have a 7.5% contribution to the variance. This contribution to variance is a result of the variability and/or confidence in the input parameter values.

Table 3. Estimated life cycle costs of upgrading sewerage treatment plants and contribution to variance by cost type

Region	30 Year life cycle costs			Contribution to variance	
	Best	Most Likely	Worst	Capital	Operating & maintenance
Burdekin	3,346	4,489	13,435	92.5%	7.5%
Burnett-Mary	3,358	4,653	13,428	92.5%	7.5%
Fitzroy	3,280	4,377	13,390	92.4%	7.6%
Mackay Whitsunday	3,578	5,138	13,527	92.5%	7.5%
Wet Tropics	3,385	4,570	13,416	92.5%	7.5%

1.4 Efficacy

1.4.1 Data

STP nutrient loads (measured and/or maximum licenced), daily and/or annual flows, and EP were collated from a number of sources. These included qldwater supplied datafiles, local government published sources (STP factsheets, annual performance reports, and annual operational plans), DERM STP development approvals with licence conditions, and the National Pollutant Inventory (NPI).

Where multiple points of data were available, the following orders of precedence were applied:

- TN loads: WaTERS measurements (kg/year), maximum TN load approved (kg/year), DERM STP licence approval, NPI, local government measurements
- Sewage flows: qldwater (ML/day), local government measurements
- EP: local government as reported, scaled from local government reported flows, scaled from qldwater reported daily flows.

Where data was not directly provided it was generated from available data using the following assumptions:

- EP was generated from flows at the rate of 170L/person/day
- Where emission data was not available 10 mg/L TN was assumed for STPs identified as using secondary treatment; 5 mg/L TN was the assumed load post-upgrade.

Total, design or peak capacities were not used in lieu of observations, even where available because methods to scale or reliably estimate actual figures were not identified.

1.4.2 Results

The table below shows the results of the efficacy estimates for each region. Due to an absence in data for the Burdekin and Mackay-Whitsunday, the 50% efficacy is assumed (i.e. a reduction from 10 to 5 mg/L).

Table 4. Reduction in emitted nitrogen (% TN) for STP upgrade from secondary to tertiary treatment

Intervention	Burdekin	Burnett-Mary	Fitzroy	Mackay-Whitsunday	Wet Tropics
Upgrade to tertiary STP	50	59	52	50	59

2 Results

The analysis of efficacy and costs is produced for individual assets.

2.1 Cost-effectiveness

Table 5 shows the estimated cost effectiveness ($/tonne TN) and the estimates of load reduction for each STP where there was sufficient data available.

Table 5. Cost effectiveness of STP upgrade to tertiary treatment ($/tonne TN)

STP code	Council	STP name	P5 cost ($/tonne)	P50 cost ($/tonne)	P95 cost ($/tonne)	Reduction (tonnes)
STP-062	Whitsunday Regional Council	Collinsville	15,079,741	21,450,154	56,258,441	1.46
STP-061	Whitsunday Regional Council	Bowen	62,401,239	88,494,620	232,719,529	6.39
STP-053	Burdekin Shire Council	Home Hill	61,074,322	88,494,620	233,263,881	6.39
STP-054	Burdekin Shire Council	Ayr	21,717,534	30,654,265	80,284,779	2.19
STP-162	Townsville City Council	Henry Lawson	4,862,881	6,951,415	18,249,800	0.42
STP-165	Townsville City Council	Condon	88,914,185	126,420,886	332,148,537	9.13
STP-178	Gladstone Regional Council	Agnes	8,773,949	12,545,381	32,856,320	0.82
STP-186	Bundaberg Regional Council	Bundaberg North	154,606,499	224,741,138	596,386,852	24.91
STP-187	Bundaberg Regional Council	East Wastewater Treatment Plant	9,786,816	14,007,452	36,785,634	1.37
STP-191	Bundaberg Regional Council	Millbank	115,202,021	169,047,870	445,644,906	12.41
STP-188	Bundaberg Regional Council	Childers	11,696,449	16,730,629	43,913,523	1.10
STP-193	Bundaberg Regional Council	Woodgate	10,298,663	14,695,069	38,553,184	8.22
STP-190	Bundaberg Regional Council	Gin Gin	3,934,161	5,651,803	14,868,871	0.54
STP-175	Gladstone Regional Council	Boyne Island	32,690,959	46,264,531	121,594,294	4.39
STP-176	Gladstone Regional Council	South Trees	21,573,867	30,654,265	80,404,215	2.19
STP-172	Gladstone Regional Council	Yarwun	3,674,576	5,271,069	13,838,676	0.32
STP-179	Gladstone Regional Council	Gladstone	170,531,004	246,968,284	654,530,173	18.25
STP-504	Rockhampton Regional Council	North Rockhampton	122,200,468	177,500,263	469,133,613	16.19
STP-505	Rockhampton Regional Council	South Rockhampton	57,140,385	81,878,686	215,192,107	5.89
STP-066	Whitsunday Regional Council	Jubilee Pocket	6,582,747	9,369,298	24,655,114	0.57
STP-057	Hinchinbrook Shire Council	Lucinda	5,256,501	7,555,886	19,894,941	2.85
STP-058	Hinchinbrook Shire Council	Ingham	104,540,011	150,138,800	398,401,816	10.95

STP-116	Palm Island Aboriginal Council	Palm Island	18,620,720	26,682,171	70,147,815	1.83
STP-199	Douglas Shire Council	Mossman	20,688,415	29,452,055	76,727,740	2.10

The most likely cost-effectiveness for each STP upgrade included in the tool in shown in Figure 2.

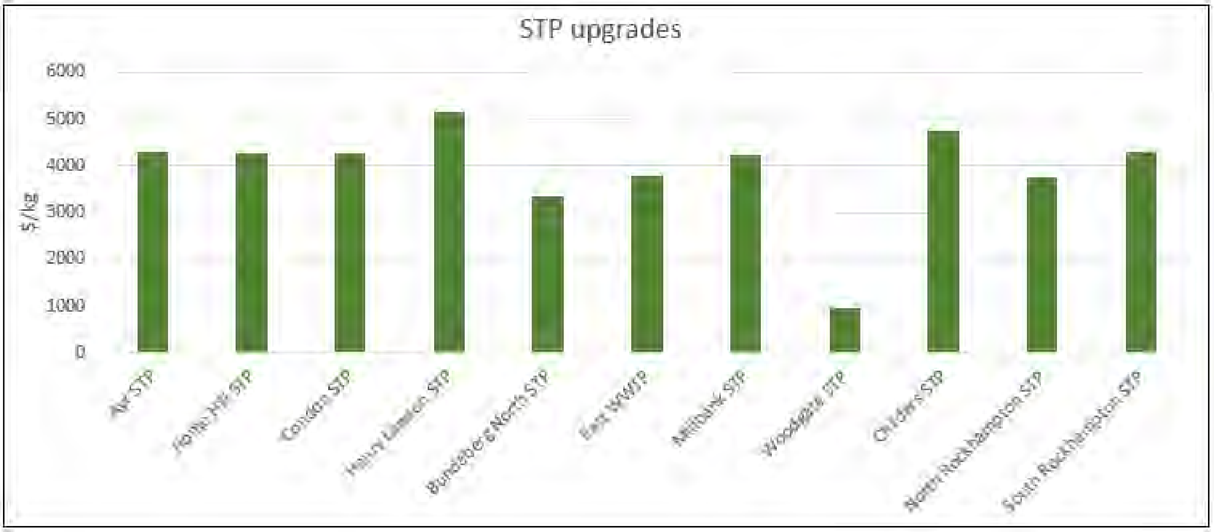

Figure 2. *Cost-effectiveness (most likely cost and efficacy) for each STP upgrade*

2.2 Assumptions and limitations

This analysis was constrained by the limited data available on which to assess the performance of individual and collective performance of STPs in GBR catchments. A significant number of STPs in the GBR region are already at tertiary treatment and hence upgrades were not considered for these.

Insufficient data was available to assess Cape York STPs, and so the region was not assessed. This seemed reasonable given the relatively very small populations and total TN load emitted from the region.

A caveat: While these equations were developed from the best data available, qldwater noted that further data was needed to fully characterise the relationship of unit costs with STP size. Therefore, whilst noting that although a Monte Carlo analysis generally captures the likely variability of results successfully, it is also acknowledged that a revised equation (changing inputs into the Monte Carlo analysis) could significantly affect output results and so impact subsequent analyses and decisions.

For some treatment plants there were discrepancies between the loads reported in the Paddock to Reef modelling and that reported to DES through licence assessments. There may be a number of reasons for this, including the loads in the model being attributed to DIN and that being reported to DES as total nitrogen. Where reductions in DIN load were possible through upgrading of treatment plants from secondary to tertiary treatment, adjustments were made to scale both the loads and upgrade costs to be consistent with the values reported in the P2R modelling. It should be noted then that where a particular upgrade is reported as being cost-effective, the magnitude of total cost of upgrade and the performance of the upgrade is likely to be greater than represented in the results reported here.

The findings of this analysis should be treated with caution.

3 References

DES (2018) Information sheet. Environmentally relevant activities. Summary of fees for environmentally relevant activities (ERAs), Department of Environment and Science, Queensland Government

DES (2017) Great Barrier Reef Point Source Metadata Collection Project, Department of Environment and Science

GBRMPA (2005), Policy—Sewage discharges from marine outfalls to the Great Barrier Reef marine park, Great Barrier Reef Marine Park Authority. Queensland. Accessed via: http://www.gbrmpa.gov.au/__data/assets/pdf_file/0015/3912/sewage_policy2005.pdf

Productivity Commission (2003), Industries, land use and water quality in the Great Barrier Reef catchment, Research Report, Canberra.

Qldwater (2017). Sewage treatment plants in Great Barrier Reef catchments, Industry Discussion Paper. Accessed via https://www.qldwater.com.au/_literature_224653/STPs_in_GBR_Catchments

Solution Statement 10: Land use change

1 Scenario description and context

In many major Australian agri-environmental programs, the predominant methods used for encouraging change in farm management are extension and small, temporary incentive payments, reflecting Australia's usual reliance on low-cost voluntary approaches (Pannell and Roberts 2015). Although considerable investment in changing agricultural management has occurred, it is becoming increasingly well recognised that voluntary approaches will be insufficient (Craig and Roberts 2015), particularly in the context of the substantial water quality targets which need to be achieved to protect the Great Barrier Reef.

Changing agricultural land-use affects the mix of benefits produced with inevitable trade-offs (DeFries *et al.* 2004). Such changes may be controversial (Kim & Dale 2011), due to the impact on competing resource uses (Gordon *et al.* 2010), and agriculture and biodiversity conservation (Barraquand and Martinet, 2011). Although historically politically unpopular, there is some recent interest in assessing the need for land retirement of some agricultural land, defined as the process of taking agricultural land out of production or converting it to a less intensive and (potentially) less polluting land use.

Several factors are required for land retirement programs to be successful. These are:

- Clear objectives
- Mechanisms for targeting land for retirement based on environmental benefit (e.g. use of metrics such as an Environmental Benefits Index)
- Cost of retirement.

Some of the key issues of land retirement are the calculation of the compensation for changing land use and where the land retirement should occur. In addition, the forgone production of taking the land out of productive use also needs to be considered.

Land retirement can be voluntary or compulsory (which would be more politically difficult and would also be likely to require higher compensation for unwilling participants). For the purposes of this study it is assumed that land retirement is voluntary and targeted to areas of high environmental benefit (significant pollutant impact into the Great Barrier Reef). It may also be that the land to be retired is that of marginal productive benefit. Whether these are mutually exclusive or related is open for debate.

This scenario explores land use change in five ways:

1. Converting areas of cane to open grazing, reducing the quantity of DIN and pesticides, but potentially increasing the quantity of sediment
2. Converting areas of cane to conservation, reducing the quantity of DIN and pesticides, with some change in sediment
3. Converting areas of open grazing to forested/closed grazing, reducing the quantity of sediment
4. Converting areas of open grazing to conservation, resulting in some change
5. Converting areas of forested/closed grazing to conservation.

2 Approach

2.1 Costs

2.1.1 Data

The costs estimated for practice change were mostly based on updated data from Alluvium (2016). The following three cost categories were estimated for sugarcane practice changes: (1) capital – on ground direct costs of purchasing and installing capital equipment; (2) operating and maintenance – costs associated with on farm operations and maintenance after the practice change; and (3) program – these are the costs to cover overhead expenses, extension, monitoring and evaluation. Additional costs of fencing for some actions were included, while a more sophisticated approach was used to incorporate opportunity cost of production. Thus, changes in operating margins were accounted for in the estimation of life-cycle costs. The Department of Agriculture's Farm Economic Analysis Toot (FEAT) was used to estimate the sugarcane opportunity cost of lost farm production for actions requiring land use change from a cane farm. FEAT scenarios for the Burdekin, Mackay and Tully regions were used to estimate operating margins. The operating margins for shifts to/from grazing were based on NCE (2017, 2018). Table 1 shows the values used to estimate value of lost production for different regions and land-use changes.

Table 1. Annual production impact ($/ha)

Region	Land use change	Lost	Gained	Impact
Bowen	Grazing open to conservation	-41	0	-41
Burdekin	Cane to conservation	-901	0	-901
	Cane to open grazing	-901	41	-860
	Grazing open to conservation	-41	0	-41
Mackay Whitsunday	Cane to conservation	-697	0	-697
	Cane to open grazing	-697	41	-656
Fitzroy	Grazing open to conservation	-41	0	-41
Wet Tropics	Cane to conservation	-563	0	-563
	Cane to open grazing	-563	41	-522

Marsden Jacobs (2013) estimated that the cost of fencing a farm ranges from $1,350 to $6,175 per kilometre, with a most likely value of $2,810. This cost was used to estimate the per ha cost of fencing for cane to grazing land use change.

All costs values were adjusted to 2018-dollar values. In all cases a range of values for the different costs were modelled to establish the most likely, 5th percentile and 95th percentile using a Monte-Carlo analysis with 20,000 iterations. The Monte Carlo analysis provides two key insights, the variability of costs and the drivers of variability in the life cycle costs for each action type.

2.1.2 Results

After careful consideration of the changes relevant to land use changes in different regions, costs were estimated for each practice change. Table 2 provides a summary of the estimated initial cash costs over a 5-year period. A 2.5% inflation rate was used to adjust the estimated year 1 costs over subsequent years (year 1 to 5). The 5-year cash costs are the estimated funds to support land use change over the initial 5 years. For example, in the Burdekin region, it is estimated that the most likely cost of shifting land use from a cane cropping to conservation requires capital costs of $6,920, no fencing cost, operating and maintenance costs of $21 in year 1 and program costs of $234 in year 1.

Table 2. Most likely cash costs by practice change and region over a 5-year period (2018 AUD)

Practice Change	Region	Capital	Fencing	Operating and maintenance					Program				
	Year	*1*	*1*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
	Region												
Cane to conservation	Burdekin	6,920		21	21	22	22	23	234	240	246	252	259
	Mackay Whitsunday	2,893		21	21	22	22	23	199	204	209	214	220
	Wet Tropics	4,285		21	21	22	22	23	166	170	174	179	183
Cane to open grazing	Burdekin	31,873	86	166	170	174	179	183	117	120	123	126	129
	Mackay Whitsunday	29,800	86	166	170	174	179	183	100	102	105	107	110
	Wet Tropics	29,800	86	166	170	174	179	183	83	85	87	89	92
Grazing open to conservation	Bowen	446		21	21	22	22	23	1	1	1	1	1
	Burdekin	7,389		21	21	22	22	23	1	1	1	1	1
	Fitzroy	1,379		21	21	22	22	23	2	2	2	2	2

Life cycle costs (2018AUD per ha) were estimated using a 7% discount rate over a 30-year appraisal period. Life cycle costs are the estimated costs per ha over a 30-year period in 2018 Australian dollar values. It should be noted that there is significant variability in the range of input data and assumptions used in the modelling. Thus, data on low (best), most likely and high (worst) costs was included in our modelling to capture this variability. Table 3 shows the estimated most likely costs (annual $ per ha) and the 90% prediction interval from a Monte Carlo simulation with 20,000 iterations. The best and worst values represent the 5th and 95th percentile for each reported cost estimate. These results indicate that the most likely life cycle costs for a land use change in the Burdekin from cane to conservation is $19,510 per ha over 30 years and the 90% prediction interval ranges from $12,771 to $25,566 per ha.

It is intuitive to assess how much of an impact each of the different costs have on the bottom line estimates of lifecycle costs (LCCs). For a land use shift from cane to conservation the Burdekin, our Monte Carlo estimations indicate that the loss in cane income has the greatest contribution to variance in the 30-year LCCs at 99.5%, followed by capital costs at 0.48%, and the remaining costs types have minimal contribution variance in the estimated LCCs. This contribution to variance is a result of the variability and/or confidence in the input parameter values.

Table 3. Estimate costs of practice change and the contribution to variance in the life cycle costs

Practice change		30 Year life cycle costs			Contribution to variance					
	Region	Best	Most Likely	Worst	Capital	Operating & maintenance	Program	Lost cane margin	Lost grazing margin	Fencing
Cane to open grazing	Wet Tropics	28,760	39,189	51,451	87.94%	0.49%	0.00%	11.56%	0.00%	0.00%
	Burdekin	34,902	45,826	58,492	70.98%	0.46%	0.00%	28.56%	0.00%	0.00%
	Mackay Whitsunday	30,275	41,003	53,561	83.40%	0.47%	0.00%	16.13%	0.00%	0.00%
Cane to conservation	Wet Tropics	8,091	12,277	16,198	9.92%	0.03%	0.00%	90.05%		
	Burdekin	12,771	19,510	25,566	0.48%	0.01%	0.00%	99.50%		
	Mackay Whitsunday	7,619	12,716	17,172	2.45%	0.02%	0.00%	97.52%		
Grazing open to conservation	Burdekin	7,338	8,221	9,177	99.00%	0.62%	0.00%		0.38%	
	Bowen	1,210	1,277	1,497	60.29%	24.67%	0.00%		15.05%	
	Fitzroy	1,861	2,211	2,463	90.89%	5.64%	0.00%		3.47%	

2.2 Efficacy

2.2.1 Data

Consistent with the approach used in the Reef Costings (Alluvium 2016), the Paddock to Reef (P2R) Source modelling results have been used to estimate the efficacy of changing from one land use to another by investigating the change in pollutant loading rates from one land use to another.

The areal loading rate (kg/ha) for each constituent (DIN, fine sediment, pesticides) was calculated for each relevant land use (cane, grazing open, grazing forested and conservation) for each of the 46 basins and used to calculate the efficacy values for each constituent for each basin.

The average results across each NRM region are shown in Table 4 and Table 5 for DIN and fine sediment.

For DIN, the consistency in efficacy when transitioning land away from cane suggests that it is highly likely that there will be a significant reduction in nutrient loads when moving to a less intensive land use. Conversely, there was a high level of variability in the efficacy values for transitioning grazing lands. An increase in DIN generated on forested grazing and conservation areas would not be unexpected compared with open grazing, due to the increased organic matter and potentially soil nutrients, however the variability in values does not provide sufficient confidence for these values to be applied. Given that DIN loads from grazing are relatively low compared with cane, it was decided to not attribute any change in DIN when transitioning from open or forested grazing to conservation.

Table 4. Average efficacy (percentage reduction) for DIN removal for land use change management actions

Management action	Cape York	Wet Tropics	Burdekin	Mackay Whitsunday	Fitzroy	Burnett Mary
Cane to grazing open	n/a	92%	96%	91%	87%	97%
Cane to conservation	n/a	91%	94%	94%	81%	99%
Grazing open to grazing forested	59%	3%	10%	5%	11%	48%
Grazing open to conservation	61%	-37%	-43%	32%	6%	66%
Grazing forested to conservation	-4%	-40%	-53%	64%	-7%	35%

For fine sediment, it would be expected that sediment loads would decrease when transitioning to land uses with increased ground and canopy cover, such as moving from open grazing to forested grazing or conservation, however some basins showed an increase in sediment loads when land uses were changed to a less intensive use.

Analysis of the results at a finer spatial level suggests that this is likely due to the topographical distribution of different land uses. Open grazing is generally located in flatter floodplain areas, while conservation and forested grazing is generally located on hillier areas where relatively larger sediment loads may be generated due to runoff response and potentially different soil conditions. For land use changes away from grazing, it was therefore concluded that efficacy would only be calculated on areas where a reduction in loads was determined and assumed to be zero where results indicated an increase in sediment loads.

For transitioning from cane to open grazing, it would be expected that sediment loads would increase, due to reduced land cover, land and animal disturbance in grazing lands. However, this was not consistently demonstrated in the analysis of the P2R data. Given that where an increase in loads was observed, it was in the order of 200%, it has been assumed that cane to open grazing will result in at least a 50% increase in sediment loads as a conservative estimate. For cane to conservation, there is no robust physical explanation for an increase or decrease in sediment loads, and this will be assumed to be zero for this study. While conservation areas are likely to have lower disturbance, sugarcane sediment loads in the modelling are already of the same magnitude, so any changes in pollutant loads indicated by the modelling results are likely to be attributed to topographic parameters (soils, slope etc.) rather than associated with the land use change. In discussions with the P2R researchers, this issue has also been identified in their workings and is currently being investigated to better understand the drivers for these observations.

Table 5. Average efficacy (percentage reduction) for fine sediment removal for land use change management actions

Management action	Cape York	Wet Tropics	Burdekin	Mackay Whitsunday	Fitzroy	Burnett Mary
Cane to grazing open	n/a	20%	-200%	15%	66%	-261%
Cane to conservation	n/a	58%	-185%	54%	54%	-341%
Grazing open to grazing forested	-59%	-8%	-26%	-48%	-58%	-14%
Grazing open to conservation	-74%	-37%	-43%	44%	6%	66%
Grazing forested to conservation	-4%	42%	-22%	64%	8%	3%

For pesticides, efficacy was assumed to be 100% removal when transitioning away from cane.

Given these results, the scenarios of land use change were revised to no longer consider change of open grazing to forested grazing, or forested grazing to conservation, simply because the results do not indicate that these are beneficial. It does highlight uncertainty in the way that land use change is modelled, and it does not imply that changing from open to forested grazing or forested grazing to conservation may not be beneficial. Adopted final efficacies for the revised land use change scenarios for DIN and fine sediment are shown below in Table 6 and Table 7.

Table 6. Average efficacy (percentage reduction) for DIN removal for land use change management actions

Management action	Cape York	Wet Tropics	Burdekin	Mackay Whitsunday	Fitzroy	Burnett Mary
Cane to grazing open	n/a	92%	96%	91%	87%	97%
Cane to conservation	n/a	91%	94%	94%	81%	99%
Grazing open to conservation	0%	0%	0%	0%	0%	0%

Table 7. Average efficacy (percentage reduction) for fine sediment removal for land use change management actions

Management action	Cape York	Wet Tropics	Burdekin	Mackay Whitsunday	Fitzroy	Burnett Mary
Cane to grazing open	n/a	-50%	-50%	-50%	-50%	-50%
Cane to conservation	n/a	0%	0%	0%	0%	0%
Grazing open to conservation	0%	0%	0%	44%	6%	66%

The above results indicate a high uncertainty around the likely reductions to be achieved from conversion of one land use to another and further work on this would be highly desirable to improve confidence in the results likely to be achieved. Even so, it is likely that a move from poor cover to high cover such as moving from grazing to conservation land would result in much lower runoff (simply through the hydrologic characteristics) and as fully vegetated areas are less active than grazing lands, lower pollutant generation is also likely. As such, it is considered reasonable to attribute a load reduction to that land use change where one is indicated by the modelling, but the magnitude of that change should viewed with a degree of caution.

3 Results

3.1 Cost-effectiveness

The available area and fine sediment load from grazing for each NRM region is shown in Figure 1. The cost-effectiveness of each grazing practice change step based on the most likely efficacy (percentage reduction) and cost ($/ha) is shown in Table 8 to Table 10. This is only the area available for change where improvement was predicted from the modelling. There are obviously significant areas of grazing lands in Cape York and the Burdekin, but the modelling provided conflicting results regarding potential improvements from shifting grazing lands to conservation. This is largely a function of the spatial variability of conservation and grazing lands (e.g. grazing lands are on flatter terrain and produce lower unit loads in tonnes per hectare than conservation lands which are typically on steeper terrain – it is highly likely that if converted to conservation with resultant increases in vegetation cover that loads would reduce, but there is no quantification of that available at this stage).

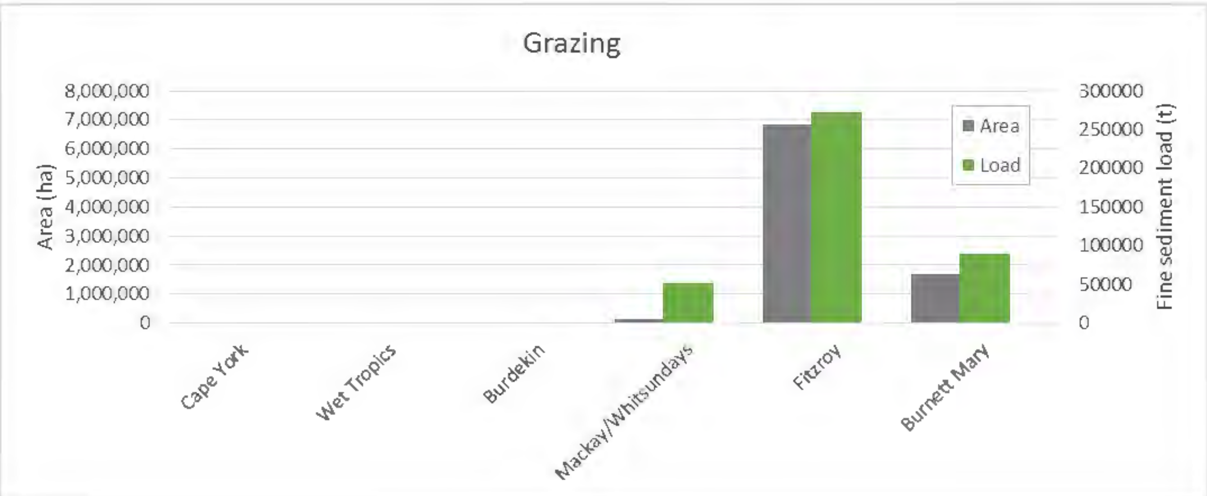

Figure 1. *Areas and loads from grazing for each NRM region*

The following tables show preliminary estimates of cost-effectiveness based on the most likely cost per hectare (Table 2) and the stated efficacy (Table 4). For each region (e.g. Wet Tropics) there are a number of basins that each have a different delivery ratio to the end of catchment as well as a different load per hectare. This has an impact on cost-effectiveness at the end of the catchment. The range of cost-effectiveness estimates presented for each region below shows the range of end of catchment costs (minimum through to 75th percentile of the basins modelled, with values above 75th percentile considered to be too expensive to warrant investment and statistical outliers).

Table 8. Estimated cost-effectiveness and treatable area and load for cane to open grazing

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Cape York	0	0	-	-	-	-
Wet Tropics	179,986	3,062	$1,894	$1,924	$2,145	$2,575
Burdekin	104,759	876	$3,230	$5,006	$6,050	$8,293
Mackay/Whitsundays	167,717	833	$8,192	$8,223	$8,509	$9,132
Fitzroy	332	0	$73,149	$73,149	$73,149	$73,149
Burnett Mary	86,389	505	$4,863	$7,506	$8,408	$8,763

Table 9. Estimated cost-effectiveness and treatable area and load for cane to conservation

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Cape York	0	0	-	-	-	-
Wet Tropics	179,986	3,062	$600	$609	-	$816
Burdekin	104,759	876	$1,405	$2,177	$2,631	$3,606
Mackay/Whitsundays	167,717	833	$2,459	$2,469	$2,555	$2,742
Fitzroy	332	0	$27,746	$27,746	$27,746	$27,746
Burnett Mary	86,389	505	$1,683	$2,597	$2,909	$3,032

Table 10. Estimated cost-effectiveness and treatable area and load for open grazing to conservation

			Cost-effectiveness ($/kg)			
	Area (ha)	Load (t)	Min	25th percentile	Median	75th percentile
Cape York	0	0	-	-	-	-
Wet Tropics	0	0	-	-	-	-
Burdekin	0	0	-	-	-	-
Mackay/Whitsundays	140,809	52,315	$20.8	$23.5	$32.0	$42.9
Fitzroy	6,858,009	271,830	$225.9	$299.9	$829.2	$1,379.2
Burnett Mary	1,696,236	89,138	$39.1	$74.3	$121.4	$139.8

The range of cost-effectiveness for each practice change, according to region, is visually represented in Figure 2 to Figure 4.

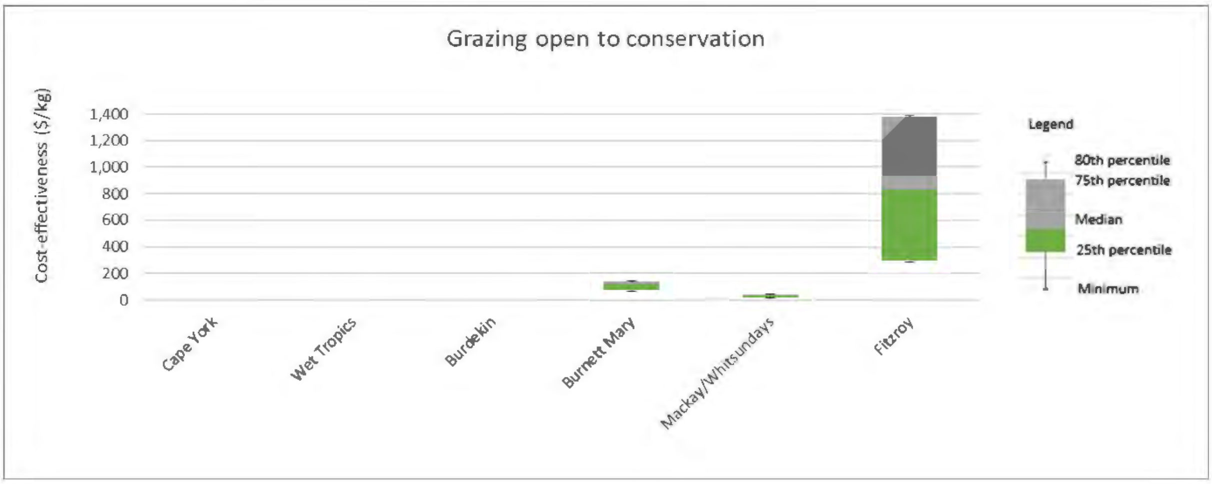

Figure 2. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for open to conservation land use change grazing*

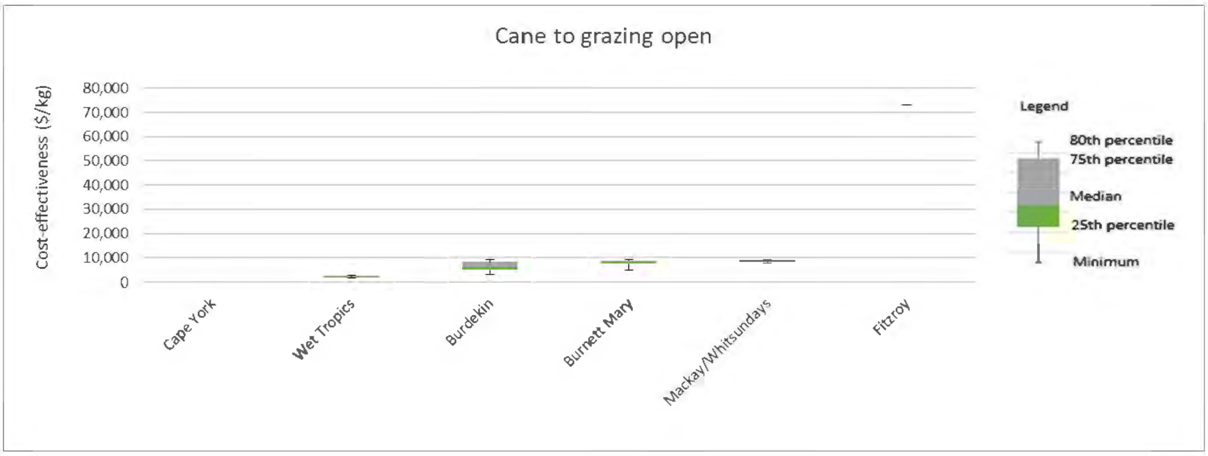

Figure 3. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for cane to grazing open land use change*

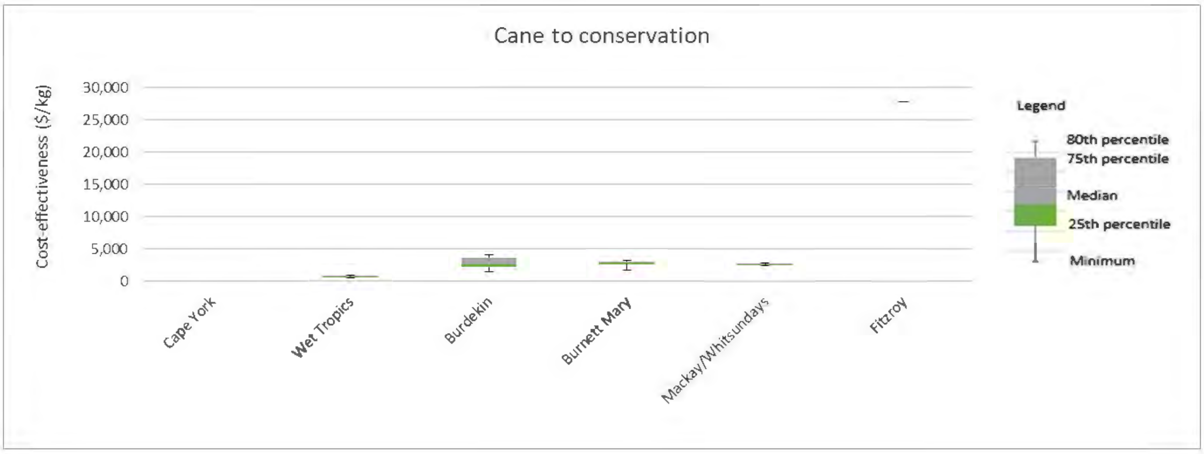

Figure 4. *Cost-effectiveness range (most likely cost and efficacy) for each NRM region for cane to conservation land use change*

3.2 Assumptions and limitations

There were number of assumptions and limitations noted in the discussions and have not been further reproduced here.

4 Contributors

Cost information was obtained and processed by the project team to generate the results presented here.

5 References

Alluvium (2016). 'Costs of achieving the water quality targets for the Great Barrier Reef'. Report to the Department of Environment and Heritage Protection. Brisbane, Queensland.

Barraquand, F. and Martinet, V., (2011). Biological conservation in dynamic agricultural landscapes: Effectiveness of public policies and trade-offs with agricultural production. Ecological Economics70(1) 910- 920.

Craig, R.K. & Roberts, A.M. (2015). 'When will governments regulate nonpoint source pollution? A comparative perspective'. Boston College Environmental Affairs Law Review 42(1), 1-64.

DAF (2016) Farm Economic Analysis Tool (FEAT) for Regional Scenarios. *Queensland Department of Agriculture.*

DeFries, R., Foley, J. and Asner G.P. (2004). Landuse choices: balancing human needs and ecosystem function. Frontiers in Ecology and the Environment 2:249–257.

Gordon, L.J., Finlayson, C. M. and Falkenmark M. 2010. Managing water in agriculture for food production and other ecosystem services. Agricultural Water Management, 97: 512–519.

Hone, P., Edwards, G. and Fraser, I. (1999). 'Agricultural land retirement and biodiversity policy'. Agenda vol. 6, no. 3, pp.211-224.

Kim, S., Dale, B.E., (2011). Indirect landuse change for biofuels: testing predictions and improving analytical methodologies. Biomass Bioenergy, Vol 35, No., 7, pp. 3235-3240

Marsden Jacobs (2013). Draft report on the economic and social impacts of protecting environmental values in Great Barrier Reef catchment waterways and the Reef Lagoon. Report to Queensland Department of Environment and Heritage protection.

NCE (2018). Burdekin Coastal Hazard Assessment Strategy, Report to the Burdekin Shire Council.

NCE (2017). Analysis of rural lot sizes for Isaac Regional Council, Report to the Isaac Regional Council.

Pannell, D., and Roberts, A. (2015), 'Public goods and externalities: agri-environmental policy measures in Australia'. *OECD Food, Agriculture and Fisheries Papers.* No. 80, OECD Publishing, Paris. http://dx.doi.org/10.1787/5js08hx1btlw-en