

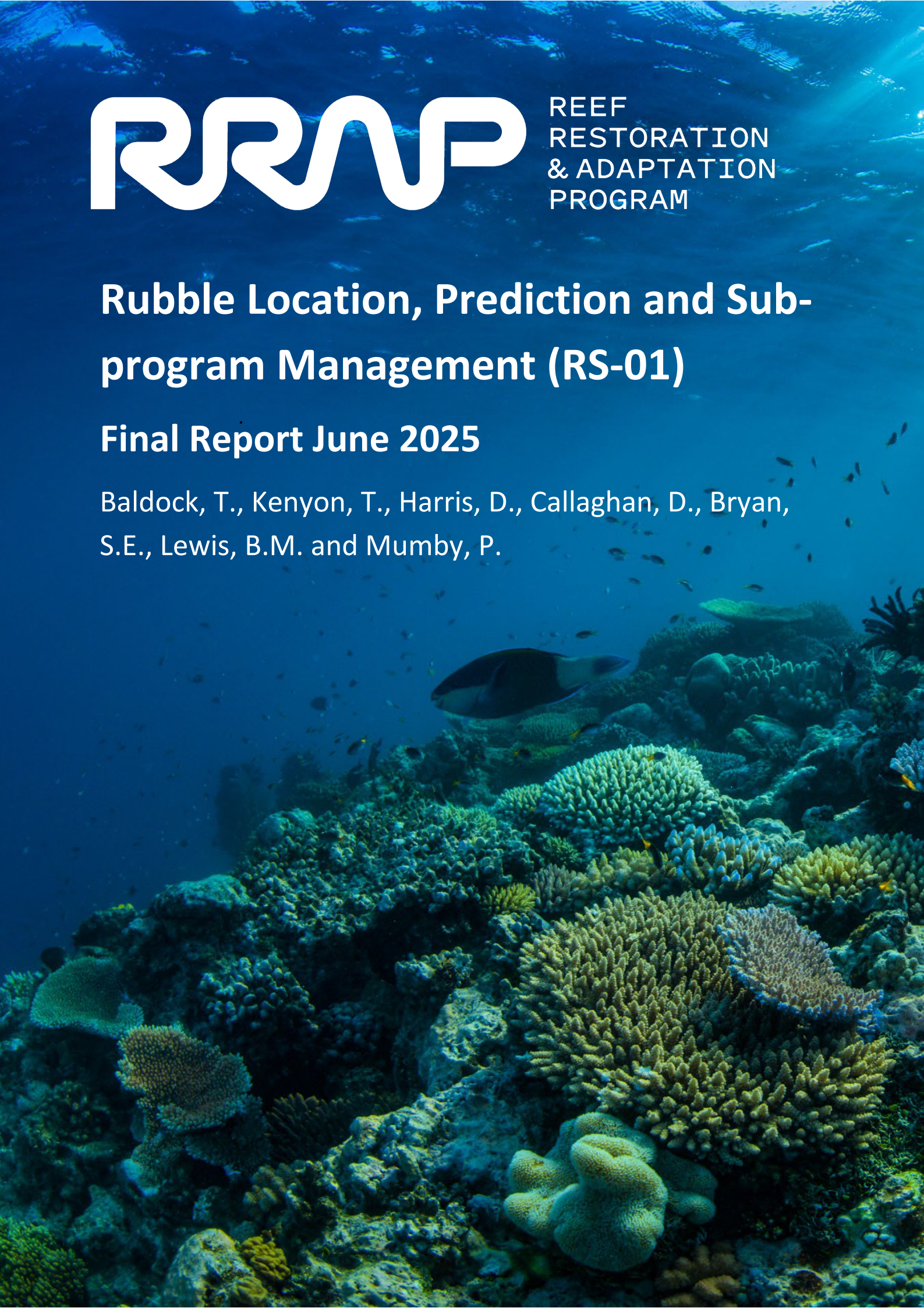


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PROGRAM

Rubble Location, Prediction and Sub-program Management (RS-01)

Final Report June 2025

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RRAP Rubble Location, Prediction and Sub-program Management (RS-01) Final Report June 2025

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This report summarises work undertaken under *Rubble Location, Prediction and Sub-program Management (RS-01)* in accordance with the Reef Restoration and Adaptation Program's *Rubble Stabilisation Project Agreements*. It provides a summarised, point-in-time synopsis of activities, methods, findings and outcomes completed in accordance with the approved project scope up to 30 June 2025.

All information reflects project scope and outcomes as of May-June 2025. Subsequent updates, analyses, or scientific developments are not included. This report should be read alongside any associated and publicly available technical reports, datasets, and publications for full detail. This report does not provide scientific inferences, policy guidance or operational instructions beyond the project's defined scope and duration.

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The RRAP partners acknowledge Aboriginal and Torres Strait Islander Peoples as the first marine scientists and carers of Country. We acknowledge the Traditional Owners of the places where RRAP works, both on land and in sea Country. We pay our respects to elders; past, present, and future; and their continuing culture, knowledge, beliefs, and spiritual connections to land and sea Country.

We specifically acknowledge and thank the following Traditional Owners of sea Country that this report relates to:

Location	Traditional Owner Group
Bundaberg to Gladstone	PCCC Trust and Gidarjil Rangers (PCCC represents the First Nations Bailai, Gurang, Gooreng Gooreng and Taribelang Bunda Peoples)
Keppel Island Group	Woppaburra
Hayman Island, Whitsundays	Ngaro
Moore Reef, Cairns	Gunggandji

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1 Executive Summary

Disturbance-generated coral rubble can pose a substantial barrier to reef recovery when it remains loose and unstable over time. Predictions of an increasing number, intensity and reduced return periods of disturbance events in the future due to climate change will result in increased rubble generation on reefs, a wider occurrence of rubble and less substrate availability for restoration. Rubble stabilisation interventions can help respond to this growing problem and support reef resilience across the Great Barrier Reef (GBR). Understanding rubble dynamics, in terms of rubble generation, movement, stabilisation rates and recovery potential, are imperative to guide best practices in rubble stabilisation and reef restoration.

The four main objectives in the RRAP Project, Rubble Location, Prediction and Sub-program Management (RS-01) were: (1) *rubble generation rates*: assess breakage of live and dead coral colonies; (2) *rates and causes of rubble binding*: assess binding rates and strengths at inshore and offshore reefs and how this i) leads to varying rubble bed types, and ii) impacts coral recruitment and recovery; (3) hydrodynamic measurement, modelling and *rubble movement*: assess rubble mobility probabilities according to rubble size and shape and across the GBR wave climate; and (4) *vulnerability and risk mapping* of rubble generation on the GBR: assess where on the GBR rubble is most likely to be generated and remain persistent as a result of combined disturbances.

Key activities included extended periods of time in the field (564 days between the University of Queensland (UQ) and QUT), to collect colony samples, track rubble movement, measure hydrodynamics, assess binding rates and strengths, and investigate coral recruitment in rubble beds. Additionally, significant time was spent conducting experiments in the UQ wave flume.

The main outputs include (1) high-resolution pdf and databases for end-users to access rubble movement model results across the GBR (*rubble movement*); (2) Reef-Risk model for end-users to visualise the risk of rubble breakage and movement across the GBR (*rubble generation rates*); (3) inputs to the RRAP Project, Approaches to stabilisation (RS-02) and the RRAP Project, Synthesis, intervention tool and guidelines (RS-03) (binding rates and strengths; rubble movement thresholds) (*rates and causes of rubble binding*); (4) Vulnerability Index and maps developed at GBR-, natural resource management- and down to individual reef-scales to visualise and identify key areas to monitor for signs of reef damage and substrate deterioration ; (*vulnerability and risk mapping*) (5) two Traditional Owner ranger engagement workshops to train the use of Rapid Rubble Assessment to identify rubble bed types and predict rubble bed recovery risk;.

This work has contributed greatly to our understanding of the current state of rubble dynamics across the GBR, in the context of present-day rubble extents, generation, movement, classification, binding, and coral recruitment. Strong collaborations have been formed with tourism (Cairns, Southern GBR, Whitsundays), Reef managers (Great Barrier Reef Marine Park Authority (GBRMPA)) and industry (Mars Incorporated, BMT Consulting) with respect to workshops, manuscripts and field research.

Future research could focus on: expanding rubble generation (breakage) and movement models; continuing conversations with the GBRMPA ship grounding team to develop a protocol using our rubble movement maps and assessment tools, tailored to their needs; building on Traditional Owner ranger relationships and continuing training in rubble bed assessment and restoration (potentially in collaboration with Mars Incorporated); linking findings with respect to rubble classification with digital guidance systems being developed to assess substrate suitability for RRAP Coral Aquaculture and Deployment device deployment; and extending the reef vulnerability and rubble persistence mapping to northern and Western Australian reefs.

2 Background and Justification for the Research

This Project aimed to determine where rubble will be a persistent problem on the GBR, hindering recovery of the reef after storms, bleaching or crown-of-thorns starfish (COTS) predation, and was focused on the prediction of rubble generation, location and mobility. Overall, the project integrates laboratory and field measurements into a predictive approach for estimating coral rubble stability through multi-scale computational fluid dynamics (CFD) modelling from coral structure (a few centimetres), habitat (a few metres) and reef form (10s of metres to kilometres). The coral stability models are linked with large-scale wave predictions for mapping coral rubble stability, to enable assessing where stabilising coral rubble within reef resilience action plans may provide benefit and links to the RRAP Modelling and Decision Support (M&DS) Sub-program through enhancements to the ecological model ReefMod. There are four sub-projects within the RRAP Rubble Location, Prediction and Sub-program Management (RS-01) Project. Previous research was limited to estimating breakage of individual corals and forces on specific coral species, without generalisation to different morphologies or a link to reef-wide wave climates. Prior work on thresholds of motion for coral rubble was limited to PhD research by Kenyon (2021).

Sub-project 1.1 Rubble Generation Rates

This sub-project provides data and modelling to estimate the rate of dead coral converting to rubble as a function of the physical environment. Field and laboratory measurements were performed to assess the hydrodynamic forces required for damage, breakage and motion for different types of corals, both live and dead, developing structural models for different coral species. Coral samples were collected during fieldwork to obtain a selection of live and dead coral samples and rubble of different age and degrees of bioerosion to determine mechanical properties. The strength of specimens that have naturally bound in field conditions has also been assessed. Results were to be fed back into ecological models (ReefMod) and benefit the RRAP Modelling and Decision Support (M&DS) Sub-program.

Sub-project 1.2 Rates and Causes of Rubble Binding

Different aspects of rubble binding were investigated at both inshore and offshore settings, including the efficacy of binding by live fragments and stabilisation leading to coral recruitment and reef recovery in dynamic environments. These experiments also establish timelines for fragment attachment in both fast- and slow-growing species and if coral is a viable binder under different conditions. The data elucidates when fragment recovery is not expected and when stabilisation intervention is needed.

Sub-project 1.3 Hydrodynamic Measurement, Modelling and Rubble Movement

This sub-project provides new hydrodynamic modelling of rubble motion, and verification data in both laboratory and field settings, enabling assessment of rubble motion at local and reef scales. Field and laboratory work was conducted with rubble of different types and sizes to calibrate and verify hydrodynamic and force models across different environments. The fieldwork investigated the hydrodynamic processes that drive rubble movement in natural settings. Modelled rubble dynamic motions and coral breakage were used to generate maps indicating reefs where rubble motion is likely and incorporated in a Web portal (Reef-Risk) to allow end users access to estimate spatial information to assess if there is benefit from intervention compared with natural processes.

Sub-project 1.4 Vulnerability and Risk Mapping of Rubble Generation on the GBR

The project utilises spatial data on the drivers of rubble generation so that the current state and future scale of rubble generation on the GBR can be understood to develop rubble vulnerability maps for the GBR. The project integrates several different historical datasets on drivers of rubble generation and recent benthic mapping to develop *vulnerability and rubble persistence maps* at individual reef to local reef group scales and identifies zones with a persistent problem and unlikely to recover naturally, for both rubble generation and

rubble persistence and areas where specific interventions (e.g. out-planting of corals with enhanced heat tolerance) can be undone by other causes of reef damage.

Sub-project 1.5 Rubble Stabilisation Sub-program Management

The day-to-day management and administration, including fieldwork planning, RRAP project meetings, supervisory meetings with post-doctoral fellows and PhD students, data management, communication activities, liaison with other RRAP Sub-programs such as Stakeholder and Traditional Owner Engagement, Traditional Owner consents and permitting, as well as reporting of outputs and financial expenditure to RRAP were completed. Traditional Owner engagement and communication activities were continuous throughout the duration of the sub-project. Liaising with the RRAP M&DS Sub-program provided some deliverables from the RRAP Rubble Stabilisation Sub-program that were used to assist with the parameterisation of the modelling of the rubble processes in ReefMod via improved accuracy and resolution of the fraction of coral that is vulnerable to breakage, via enhanced hydrodynamic modelling and risk mapping, and improved quantification of the time required for rubble stabilisation, via better quantification of binding strength, binding rates, the forces required to mobilise rubble, and expected intervals between mobilisation events. Upscaling to GBR scales is achieved through integrating the new physical models with GBR scale wave climates (cyclones, everyday waves and future wave climates).

Key overarching research aims are:

- Development of a generic modelling framework to assess the fraction of coral breakage as a function of species, morphology, degree of bioerosion, location and wave climate; development of a new empirical method to determine thresholds of motion for coral rubble in the field and without wave flume testing.
- Development of a physical model for determining the threshold of motion for coral rubble to determine the probability of rubble instability and upscaling this for current and future wave climates at GBR scales.
- In situ measurement and modelling of rubble mobility across multiple coral reefs and coral reef habitat zones, and categorisation of rubble according to multiple size and shape dimensions.
- Investigation into why rubble limits coral recruitment and a comparison of the impacts of different types of rubble on coral recruitment.
- Understanding the complex interactions that cause coral bleaching across the GBR, identifying refugia from cyclones and quantifying impacts of climate change on coral reef connectivity.
- Using satellite data to estimate the percentage of rubble cover across the GBR and re-training a photo dataset to better detect rubble; investigating rubble binding processes following rubble stabilisation at a site in the northern Great Barrier Reef.
- Using Blue Pearl Bay (Hayman, Island, Whitsundays) to assess the cyclonic impacts on a fringing reef by developing detailed bathymetry and benthic maps to define the current state of the reef, reef zonation and the state and stores of coral rubble generated by Severe Tropical Cyclone (STC) Debbie in 2017.

3 Research Objectives and Key Findings

A current list of project outputs are listed on the RRAP website: gbrrestoration.org. Key research objectives and findings are detailed below.

Table 1: Key findings of the Project aligned to the overarching and specific research questions for each sub-project.

Objective	Key Findings and/or Outcomes
1.1 Rubble Generation Rates	
<p>1.1 (a) Measure the rate of dead coral converting to rubble as a function of the physical environment.</p>	<p>In the field and in the wave flume, dead coral colonies were break-tested, to ascertain how breakage of dead colonies compares to live colonies, including an assessment of the strength of samples with biofouling. The location and extent of the biofouling has a significant impact on the structural strength and in colonies with biofouling this will govern the wave-induced breakdown of coral colonies into rubble.</p> <p>To investigate the breakdown of colonies over time accurately, a bleaching-related mortality event is required that affects areas varying in exposure (sheltered and exposed), but in the same location or reef. A bleaching event did not impact the main field sites used in the rubble stabilisation program at Heron, Keppels, Whitsundays and Moore Reef from 2021 to 2023, when extensive field work was being conducted. A bleaching event did affect Heron Reef at the beginning of 2024, however, the last trip to Heron was in June of that year. There were no plans to return and track coral breakdown, so no corals were tagged in June. While the time of death is unknown, a small-scale study was conducted in the Keppels whereby 92 dead apical branches were tagged across four branching coral colonies in November 2021, and resurveyed in April 2023 (17 months). Within the 17-month period, 35% of the tagged branches were missing (32), 26% were broken and shorter as a result (24), and 39% were intact (36). However, of those intact branches, 50% were on main branches that had themselves broken off. Of the main branches, 30% were missing, 34% were broken, and 36% were intact. Thus, two thirds (64%) of the main branches had broken off the colony over the 17 months. A study by Morais et al. (2022) found that dead coral colonies had a half-life of about 40 months, and that wave exposure had little impact. They found that, regardless of the location, after five years, between 60.8 and 83.3% of all dead coral colonies were completely eroded.</p>
<p>1.1 (b) Assess the hydrodynamic drag and shear forces required for damage, breakage and motion for different types of corals, both live and dead and rubble of different age and degree of bioerosion, using field and laboratory measurements.</p>	<p>Field studies, laboratory experiments and numerical modelling were conducted to determine coral morphology, material properties, size distributions and characteristic material strengths. Measurements or estimates of bioerosion were made when present.</p>

Objective		Key Findings and/or Outcomes
		Thresholds of motion, breakage models and drag and shear forces were determined to provide coefficients for analytical and numerical modelling.
1.1 (c)	Structural and hydrodynamic testing of specimens to determine mechanical properties and force coefficients using experiments in wave flumes	<p>Coral samples obtained in the field were prepared and tested for material strength in traditional bending tests and mimicking in-situ field tests.</p> <p>An extensive set of laboratory experiments was conducted in wave flumes to determine drag coefficients, effects of coral morphology and the influence of sheltering on the hydrodynamic forces affecting coral colonies.</p>
1.1 (d)	Quantify parameters for hydrodynamic-structural modelling of large reef areas and map the rates of rubble generation incorporating possible regeneration of dynamic rubble based on the strength of specimens that have naturally bound in field conditions.	Models were developed to predict probabilities of breakage and coral rubble motion at reef and GBR scales under typical waves (everyday wave conditions), cyclonic conditions and current and future wave climates. Influences of bioerosion on breakage are included. Data is presented in map form via pdf, database and will be available via a dynamic user-driven Web portal.
1.1 (e)	Combine 3D mapping by EcoRRAP (an RRAP sub-program) with additional small-scale field measurements to parameterise and evaluate ecological models.	The EcoRRAP 3D mapping was not suitable for hydrodynamic modelling of branching corals due to difficulties in scaling images but this did not impact the project deliverables.

1.2 Rates and Causes of Rubble Binding

1.2 (a)	At both inshore and offshore locations, compare binding mechanisms and rates for rubble pieces that are physically held together in a frame to binding rates for those that remain mobile (loose versus interlocked rubble).	Binding incidence was assessed at both inshore and offshore locations, at different levels of exposure (sheltered vs exposed) and in rubble beds of different types (loose vs interlocked), to identify predictors of rubble bed recovery potential. Rubble size and rubble bed thickness were identified as key metrics in predicting binding potential and the natural recovery potential of a rubble bed. Compared to small, loose rubble, larger rubble in thicker rubble beds is more likely to be stable, through interlocking or part burial, and thus more likely to be bound, and provide a stable substrate for coral recruitment.
1.2 (b)	Test fragment attachment across multiple coral taxa to identify inhibitors that prevent reattachment, binding and stabilisation. Establish timelines for fragment attachment in both fast- and slow-growing species and whether live coral is a viable binder under certain conditions	In 2021, we collected corals in the Keppels from multiple taxa, including those that were found to be binding between rubble fragments. Coral fragment attachment rates were measured in aquaria at QUT for both fast and slow growing species. Some species (<i>Acropora</i> , <i>Montipora</i>) are more efficient in terms of their attachment base than others (e.g. <i>Pocillopora</i>) which were more susceptible to detachment from water velocities. While the previously modelled three-step attachment process was broadly conserved across taxa, we observed taxonomically distinct variations at each stage in immune response, behaviour, tissue development, and skeletal microstructure at each phase, which likely accounts for the observed disparities in attachment rates, robustness, and efficacy among species. Due to the precise and slow nature

Objective		Key Findings and/or Outcomes
		<p>of tissue and skeletal development for attachment minor movements in either substrate or coral fragment of less than 2 mm can inhibit the biological process at the attachment interface resetting the biological attachment process, and in some cases, completely stop it altogether. This demonstrates how rubble-dominated substrates remain a major limiter to natural reattachment and recruitment in most species, and why rubble remains a dead zone for coral recovery.</p> <p>The results from the binding surveys, and binding rates and strengths experiment, conducted in the field at Heron and Keppels, showed that live coral can be a viable binder of rubble fragments. Hard corals were found to begin binding between rubble fragments as early as four months after deployment (i.e. four-month period of stability) at exposed sites, and were found binding from 18 months post-deployment in sheltered sites.</p>
1.2 (c)	Field studies to investigate binding in high-energy and highly mobile seabed settings to identify the successful binding species and mechanisms of binding.	We investigated rubble binding in inshore and offshore locations, across exposures, depths and reef zones. In highly mobile areas (e.g. depositional areas like grooves in spur and groove systems), the probability of binding was extremely low (~5%) and only turf algae were successful in binding quickly enough during small stability windows. In exposed reef slope sites where conditions are also rough, but rubble <i>was</i> able to stabilise (whether through interlocking or part burial), binding was achieved primarily by sponges, followed by macroalgae, and calcareous algae like Crustose coralline algae (CCA) and Peyssonnelia.
1.2 (d)	Strength testing of fragment grafting to establish what hydrodynamic conditions may inhibit fragment attachment, regrowth and survival.	Aquaria and field experiments showed that there were differences in attachment strength between <i>Pocillopora</i> and both <i>Acropora</i> and <i>Millepora</i> . Mean forces measured indicated the latter taxa had securely attached to the substrate was able to resist modelled ambient hydrodynamic forces caused by 0.1-0.5 m/s flows at 30 days compared to <i>Pocillopora</i> which took 45 days. In addition, the field trials showed that <i>A. millepora</i> withstood cyclone-level forces (>5m/s) by 70 days and <i>Montipora</i> after 90 days. In contrast, <i>Pocillopora</i> did not meet this threshold during the experimental period. As such, <i>Pocillopora</i> is more susceptible to dislodgement by water velocities for much longer. We suggest an eco-evolutionary approach to reef restoration—one that selects out-plant species based on key taxonomic traits such as attachment efficacy and environmental compatibility to help form timelines for out-planting and monitoring.
1.2 (e)	Using material bound over different timescales, measure the force required to break the binding (and thus the strength of rubble binding as a function of time).	At inshore and offshore locations, binding rates and strengths were assessed for stabilised rubble over time, at 4, 8, 12, and 18 months. These time periods represent periods of stability, i.e. binding rates and strengths on pairs collected at four months reflect that which could be expected in a rubble bed if there were no movement in the four-month period. At every time point, the amount of binding, and the strength of binding, was lower at inshore, sheltered sites, compared to inshore exposed sites, and compared to offshore sites (of any exposure).

Objective		Key Findings and/or Outcomes
		Given an 18-month stability window, bound rubble at inshore sheltered sites reaches a strength that will break at a velocity of 3N, equivalent to a flow of ~1.4 m/s. At inshore exposed sites and at offshore sites, rubble is more strongly bound and will only break at approximately 3 m/s. The binding community is a key driver of habitat differences in bind strength over time. Inshore, sheltered rubble were bound largely by weak macroalgae, while stronger binders like tunicates, oysters, vermetid snails and hard coral themselves, were more highly represented at exposed and offshore sites.
1.3 Hydrodynamic Measurement, Modelling and Rubble Movement		
1.3 (a)	New hydrodynamic modelling of rubble motion to enable assessment of rubble motion at local and reef scales.	Models were developed to predict probabilities of breakage and coral rubble motion at reef and GBR scales under typical waves (everyday wave conditions), cyclonic conditions and current and future wave climates. Influences of bioerosion on breakage are included. Data is presented in map form via pdf, database and via a dynamic user-driven Web portal.
1.3 (b)	Use field and laboratory data from hydrodynamic sensors and tagged rubble of different types and sizes, with associated local hydrodynamic and shear measurements, to calibrate and test hydrodynamic and force models. Sensors include Acoustic Doppler Velocimeter (ADV), high frequency pressure transducers, accelerometers and digital positioning systems.	An extensive set of laboratory experiments was conducted in wave flumes to determine drag coefficients, effects of coral morphology, influence of sheltering, and utilised to calibrate the reef and GBR hydrodynamic and force models. Field data on the movement of tagged rubble pieces, tracked while monitoring the hydrodynamic environment, was used to calibrate and test hydrodynamic models that predicted rubble motion across the GBR.
1.3 (c)	Fieldwork to identify motion and forcing stratified across the environment at sites with relevant geomorphology, including direct measurement of forces required to initiate rubble motion at selected sites.	In the field, rubble movement was tracked, together with measurements of the hydrodynamic environment, to determine mobilisation thresholds for rubble pieces of varying size and shape parameters, e.g. circularity. Movement was tracked every 24 hours over three-day periods at three sites at Keppels, 10 sites at Heron, and three sites at One Tree Reef. The hydrodynamic environment was measured with ADVs, pressure transducers, accelerometers and current meters.
1.3 (d)	Wave and flume experiments to assess rubble dynamics of different species on different substrates as a function of hydrodynamic environments.	An extensive set of laboratory experiments was conducted in wave flumes to determine drag coefficients, effects of coral morphology, influence of sheltering, and utilised to calibrate the reef and GBR hydrodynamic and force models.
1.3 (e)	Develop and test model for coral breakage and rubble dynamics using coral-scale hydrodynamic modelling (e.g. using the SWASH (Simulating WAVes till SHore) wave phase resolving model and	Models were developed to predict breakage and motion at reef and GBR scales under typical waves, cyclonic conditions and current and future wave climates. Phase resolving models and phase averaging were used at reef scales, and analytical models used at GBR scales.

Objective	Key Findings and/or Outcomes
Computational Fluid Dynamics coupled with structural models of different coral species.	
1.3 (f) Use modelled rubble dynamic motions alongside field and laboratory data to generate maps indicating reefs where rubble motion is likely to hinder recruitment. Map between coral rubble states (stable—unstable and levels between) with a range of local Hs/Tp/tidal range/wind speed (forcing parameters).	Data is presented in map form via pdf, database and via a dynamic user driven Web portal. The portal allows end-users to select appropriate wave conditions for any given location or use wave climate information for that location. Maps of stability across the GBR are available for present and future wave climates for branching corals. Future work will seek to expand this range of coral sizes.
1.3 (g) Investigate how the hydrodynamic models developed, or the derived results, could be incorporated within the eReefs framework for broader application.	The hydrodynamic models use Fenton's theory to estimate near-bed velocity and pressure gradients, key to predicting rubble instability. Validated with lab data, they generate spatial maps of instability probability across reefs. These outputs are scalable and data-driven. They can be integrated into the eReefs framework to support reef-wide restoration planning.
1.3 (h) Develop reef-scale models for both cyclonic waves (10-20 m grids depending on bathymetric resolution) and everyday waves and map risk and probability of breakage and rubble motion within a Bayesian Belief Network (BBN) tool or Web portal.	Models were developed to predict breakage and motion at reef and GBR scales under typical waves, cyclonic conditions and current and future wave climates. Data is presented in map form via pdf, database and via a dynamic user driven Web portal.
1.3 (i) Use fluid/structure modelling of coral rubble in conjunction with the laboratory and field experiments to determine thresholds of motion for rocking and displacement to identify functional relationships between rubble characterisation and forcing parameters.	Laboratory experiments were conducted in wave flumes to determine thresholds of motion and were used to calibrate the functional relationships used in the modelling. Given the need for very time-consuming and expensive wave flume testing, which is not universally available, a technique to determine thresholds of rubble motion without wave flume testing was developed. This can be applied in any setting, in air, and is likely valid for a larger range of substrates and corals than that tested in this work.
1.3 (j) Link regional wave cyclone and non-cyclonic waves statistics to on-reef hydrodynamics. This requires establishing hydrodynamic models of a range of reef shapes and sizes and using historical forcing.	This study uses 32.1 years of regional wave data to link non-cyclonic wave statistics to on-reef hydrodynamics via Fenton's wave theory. Field-measured 412 rubble samples were used, and hydrodynamic forces were estimated using the Morison equation. The model translates regional wave conditions into local forces acting on rubble. Cyclonic wave forcing can be added using the same framework. Machine learning was then applied to extend predictions to the GBR scale and assess coral rubble stability over the next 70 years.
1.3 (k) Apply the set of hydrodynamic models at various scales to identify locations that have short periods of stationary rubble or rocking motion during non-cyclonic conditions that are potential intervention sites for active coral rubble stabilisation projects in future.	Data is presented in map form via pdf, database and via a dynamic user driven Web portal. The portal allows end-users to select appropriate wave conditions for any given location or use wave climate information for that location. Maps of stability at individual reefs and across the GBR are available for present and future wave climates for branching corals. Future work will

Objective	Key Findings and/or Outcomes
	seek to expand this range of coral sizes. These provide locations where active rubble stabilisation projects may succeed.
1.4 Vulnerability and Risk Mapping of Rubble Generation on the GBR	
1.4 (a) Collate and integrate historical datasets on drivers of rubble generation: cyclones, COTS invasions, bleaching events and hydrodynamic data, reef structure, and recent benthic mapping to develop <i>vulnerability maps</i> for individual reef.	Five different drivers were identified and utilised to define a vulnerability index for the GBR – cyclones, storm waves and tsunamis, ship groundings, bleaching and COTS invasions. Cyclonic data was further subdivided into cyclone-generated winds, waves, and bottom currents. Cyclonic wind exposure is represented by a new measure - accumulated time in hours for which the wind intensity is that of a tropical cyclone category one in the Australian scale (> 17 m s ⁻¹); this measure also incorporates cyclone frequency or return period which is important cause for breaking rubble binding and resetting the rubble 'binding clock'. Each driver was synthesised separately for the entire GBR and at a consistent spatial resolution of 0.05° x 0.05°. Seven separate map layers were generated for each driver, which were then combined to create a Vulnerability Index both for individual drivers of reef damage and rubble generation and then summed and rescaled to a 0-1 scale to define overall vulnerability. Key findings include: 1) the GBR has a moderate risk profile to future damage and rubble generation in the next 10-20 years under current climate conditions; 2) Risk to reef damage broadly increases towards the central GBR; lowest risk occurs at northern and southern ends of GBR with the Cape York Natural Resource Management Zone having the lowest overall vulnerability score due to lack of direct cyclone impacts at these low latitudes. 3) Almost all of the Burdekin Natural Resource Management Zone has high vulnerability and includes more localised hotspots than other zones; and 4) the Mackay-Whitsunday Natural Resource Management Zone is at risk from the widest range of reef damage and rubble generation drivers.
1.4 (b) Extend rubble vulnerability maps to local reef groups on the GBR, and to represent both rubble generation and rubble persistence.	Four localised areas of high vulnerability to cumulative damage and rubble generation were identified with the Lizard Island and Swains Reefs being most at risk. These results are consistent with recent reported damage and coral loss on the GBR where the Cooktown-Lizard Island sector was significantly impacted from bleaching and two cyclones (AIMS LTMP 2024 report) An interactive map version is available at: https://seacatkim.github.io/test_rubble_index/ .
1.4 (c) Identify locations where hydrodynamic forcing can maintain mobility of sufficient severity and duration/recurrence that prevents natural recovery.	Key factors promoting rubble persistence are: 1) cyclone frequency; and 2) hydrodynamic forcing from storm and ambient wave climate and ocean bottom currents. These collectively

Objective		Key Findings and/or Outcomes
		<p>reset the rubble 'binding clock'. This work was benchmarked to the rubble motion thresholds determined under Objective 1.1 and 1.3 (see also Kenyon et al. 2023).</p> <p>In terms of where ambient conditions are most conducive to keeping rubble mobilised and unconsolidated, reefs within the Burdekin Natural Resource Management Zone were found to be most at risk. This connects with the vulnerability index analysis which found this region also had the highest vulnerability to rubble generation. The Mackay-Whitsunday and Wet Tropics Natural Resource Management Zones have more localised risk areas where rubble can persist once formed.</p>
1.4 (d)	Undertake field studies to constrain how different disturbance events (e.g. cyclones, bleaching) create different rubble volumes and characteristics that might influence rubble mobility and binding.	Field studies were completed at Blue Pearl Bay (Hayman Island, Whitsundays) to assess at a more local scale the effects of a cyclone on generating rubble. The field studies formed part of a MPhil project at QUT led by Carlos Botana Gomez. STC Debbie caused substantial damage and coral loss (<5% hard coral cover after the cyclone). The cyclone resulted in selective damage and coral loss - the reef crest dominated by branching and plate corals was entirely removed, but the Porites fore reef and microatoll zone on the reef flat mostly survived. A >6,000 m ² and up to two metre thick rubble field was deposited on the reef flat in the southern bay and has partially concealed the Porites microatoll zone. The rubble field has migrated over the last eight years demonstrating it has remained mobile and unbound. Most rubble volume was transported to deeper waters (>20 m).

1.5 Sub-project 1.5 Sub-program Management

1.5 (a)	Facilitation of quarterly reporting, including the curation of metadata and document records	Completed except for final corrected/amended theses.
1.5 (b)	Sub-program plans for Traditional Owner and other stakeholder engagement, data management, collaboration and communication	These were completed throughout the sub-program.
1.5 (c)	Sub-program fieldwork coordination and Workplace Health and Safety	Fieldwork coordination was orchestrated as per the research plans.
1.5 (d)	Liaison with other sub-programs, particularly with M&DS due to dependencies	Completed
1.5 (e)	Annual engagement, communication and collaboration activities	Completed

Adjustments to key research objectives

Table 2: Variation in the Project over time.

Initial Research Question	Explain when, how and why the research question changed
No adjustments to report	

4 Future Research Recommendations

Rubble Generation Rates

Results from the rubble generation (breakage) models in this RRAP Project, Rubble Location, Prediction and Sub-program Management (RS-01) highlight that plating corals will not break at the stem even at extremely high velocities of 7 m/s, leading researchers to deduce that plating corals will only generate rubble through: i) breakage induced by bioerosion commonly present in the stem; ii) breakage from the impact from flying debris generated during a storm (rather than from the flow velocity itself); or iii) dislodge from the attachment point between the colony and relatively softer substrate, rather than breaking at the stem itself.

The threshold for plates to break from bioerosion, or to dislodge, is unknown owing to the vast possible variation in substrate strength and the level of bioerosion. The degree of breakage through impact on a reef is also a varied and unpredictable process, depending on the surrounding coral colony's abundances, sizes and morphologies, and which ones break off or detach to become debris during a storm event.

Improvements to the breakage models could be made by more thoroughly and extensively investigating levels of bioerosion at the stems of colonies and the substrate across varied locations across the GBR. Investigations into debris loading and how it may affect breakage of coral colonies could also help to improve the breakage model and explain how plates commonly flip during storms.

Finally, improvements to the breakage model could be made by break-testing a greater number of coral species and more varied morphologies. Currently, only branching and plating corals have been considered, with data on the coral morphology from a single reef. The model is generic to enable input of any morphology once known.

Rates and Causes of Rubble Binding

Investigating binding strength in additional habitats (e.g. deeper inshore sites, not investigated in RS-01) and intermediate exposure areas, could improve binding predictions at a wider variety of habitats when it comes to scaling predictions across the GBR. Additionally, there are several limitations with our study that could be improved upon with future research. These are that: a) the binding rates and strengths are based on solidly stabilised rubble only; and b) the binding model assumes that binding is reset to 'zero' after a bound pair is broken apart. While the binding experiments under RS-01 were conducted with solidly stabilised rubble for important logistical and experimental reasons, there will be a combination of solidly stable rubble fragments (e.g. interlocked) and loose fragments (easily shifted) in an actual rubble bed. A pilot study conducted under RS-01 revealed that bind abundance and strength between loose fragments will be slightly lower than between solidly stabilised fragments. Thus, modelled estimations of binding potential may be partially inflated. However, this may be offset by the fact that the binding rate is likely to be underestimated after every breakage event (i.e. where the wave velocity goes above the binding break velocity and breaks apart a bound rubble pair). The binding experiment conducted under RS-01 used bleached, bare rubble fragments to standardise the starting point and represent rubble that had been formed immediately following a disturbance that has smashed up the coral and killed it (e.g. storm, dynamite fishing, ship grounding). Thus, the resulting function of binding strength over time begins with bare rubble. This is what is applied in the model when rubble is: i) first stable; and ii) just after a breakage event. In reality, bound rubble that has been broken apart will *not* be bare, and existing encrusting and binding organisms may be able to more rapidly rebind. These accelerated binding rates have not been investigated over long-time scales, but if conducted in future could be incorporated into the recovery potential modelling.

To investigate these gaps, the pilot experiment run in RS-01 could be expanded to be carried out in three shallow and three deep sites on exposed and sheltered reef slopes at Heron Reef, totalling 12 sites. At each of the sites, three grids could be deployed, each with 20 pairs. The number of pairs should be increased, as there will be a much higher risk of pairs being lost if loosely stabilised. For this reason, the experiment should also be run over a shorter period of time, perhaps only over eight months, with collections at four and eight months. Furthermore, a third of the pairs should be processed while still in water (although, force testing underwater is problematic without an underwater digital force gauge), and then re-paired. Thus, the rate of

binding from zero to four months (starting from 'zero' with bleached rubble) could be compared to the rate of binding from four to eight months (when they are already encrusted with binding organisms when repaired).

Hydrodynamic Measurement, Modelling and Rubble Movement

The current threshold velocity for rubble motion is based on empirical data from Kenyon (2021), Deng et al. (2024) and Liu et al. (2024). This assumes rubble is orientated parallel to the wave crests and fully exposed to the flow. Deng (PhD thesis) provides some initial estimates of the influence of sheltering by adjacent rubble and the change to thresholds of motion for different orientation. Consequently, the current thresholds are conservative from a modelling perspective. Further experimental work is required to generalise these effects to include this complexity in the modelling. Similar work could be conducted with the RRAP Sub-program Coral Aquaculture and Deployment (CAD) devices combined with coral regrowth to assess the longer-term stability of that restoration technique. The end-user mapping models also require deployment onto the appropriate servers for end-user access and maintenance and upgrades as new data comes on stream from future studies.

Improvements to the model could be made through the extension of the range of sizes and shapes for modelled rubble. Currently, modelled rubble comprises rubble (from branching coral colonies with typical branch diameter of 1.5 centimetres), with rubble piece length varying from 3 to 27 cm. In conversations with GBRMPA's ship grounding response team, we have learned that they would like to incorporate the following size ranges and shapes into our rubble movement modelling:

1. Cube shaped rubble of side length 1.5 cm, 3 cm, 9 cm and 27 cm
2. Rectangular shaped rubble of:
 - a. 3 x 3 x 15 cm
 - b. 9 x 9 x 25 cm
 - c. 15 x 50 x 50 cm
 - d. 27 x 27 x 50cm
 - e. 15 x 50 x 100 cm
 - f. 15 x 100 x 100 cm; and
 - g. 75 x 100 x 150 cm

The ship grounding team communicated that the currently modelled rubble (3 to 27 cm, 1.5 cm branch diameter) are typical of strikes that they see by vessels <15 m, while the cube-shaped rubble of the sizes mentioned above it more common for vessels 15-50 m. Models of larger rubble (a to f) is planned to be incorporated into the model in future. Vessels >20m commonly cause rubble fragments of these larger size classes, due to the fracturing of *Porites* bommies for instance.

Vulnerability and Risk Mapping of Rubble Generation on the GBR

Maps of variations in drivers of reef damage and rubble generation can be used to help manage reefs for climate change. The reef damage vulnerability index developed under Objective 1.4 has utilised the most up-to-date data of the main drivers that have caused damage to the GBR, and which are likely to be the main causes of future damage. By evaluating each driver separately and collectively across the whole Great Barrier Reef Marine Park (GBRMP), this vulnerability mapping is a useful tool that can now be used by managers to monitor and prioritise management actions in both the short and medium-term. This work helps connect core components of RS-01 by connecting regions of likely reef damage, rubble generation, movement and persistence (e.g. the Reef-Risk model), and long-term accumulation in ecologically important reef zones (Leung and Mumby, 2024).

The approach undertaken here can be applied to any reef system globally. In Kim et al. (in review) we identified a comprehensive global list of drivers that lead to reef damage and rubble generation, such as blast fishing which is a practice absent from the GBR but continues today in the Coral Triangle. The

vulnerability analysis and mapping can be undertaken for the northern Australian and Western Australian reefs. Our analysis found that the northwestern Australian coast has the highest cyclone return period or frequency of any region in Australia. Vulnerability analysis could also be undertaken using different future climate scenarios. More detailed analysis placing weightings on the different drivers of rubble generation will provide improved resolution on critical areas of vulnerability on the GBR.

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