COTS Control Innovation Program

TECHNICAL REPORT

Empirical Decision Support: using Control Program data to make real-word decisions about crown-of-thorns starfish (COTS) management

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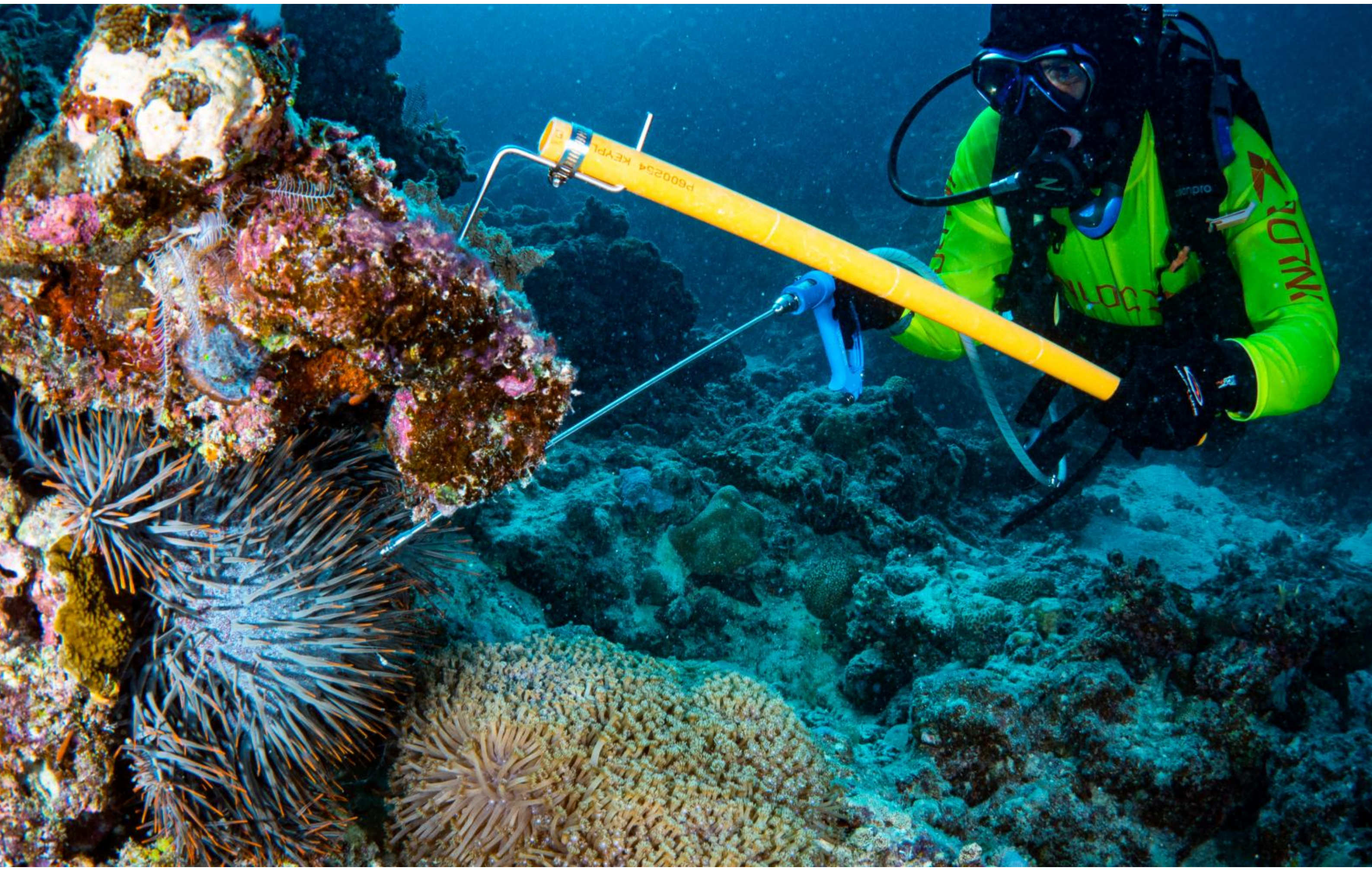

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Empirical Decision Support: using Control Program data to make real-world decisions about crown-of-thorns starfish (COTS) management

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COTS Control Innovation Program | A research and development partnership to better predict, detect and respond to crown-of-thorns starfish outbreaks

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Traditional Owner Acknowledgement

The COTS Control Innovation Program extends its deepest respect and recognition to all Traditional Owners of the Great Barrier Reef and its Catchments, as First Nations Peoples holding the hopes, dreams, traditions and cultures of the Reef.

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Acronyms and Abbreviations

AIC	Akaike Information Criterion
AIMS	Australian Institute of Marine Science
API	Application Programming Interface
CCIP	Crown-of-thorns starfish Control Innovation Program
COTS	Crown-of-thorns starfish
CPUE	Catch-Per-Unit-Effort
CSIRO	Commonwealth Scientific and Industrial Research Organisation
eDNA	Environmental DNA
EotR	Eye on the Reef
EWS	Early Warning System
GBR	Great Barrier Reef
GLM	Generalised Linear Model
GLMM	Generalised Linear Mixed Model
IaC	Infrastructure-as-Code
IDE	Integrated Development Environment
IPM	Integrated Pest Management
IS	Information System
JCU	James Cook University
JSON	JavaScript Object Notation
KML	Keyhole Markup Language
LTMP	Long-Term Monitoring Program
PWA	Progressive Web Application
Reef Authority	Great Barrier Reef Marine Park Authority
RHIS	Reef Health Impact Survey
RIMReP	Reef 2050 Integrated Monitoring and Reporting Program
RJFMP	Reef Joint Field Management Program
RRAP	Reef Restoration and Adaptation Program
SALAD	Scooter Assisted Large Area Diver-based survey

EXECUTIVE SUMMARY

Crown-of-thorns starfish (COTS) are one of the major threats to coral on the Great Barrier Reef (GBR). Unlike other threats, COTS can be managed through direct culling to provide immediate protection of coral on the GBR. In 2018, the COTS Control Program was redesigned based on an ecological understanding of the interaction of COTS populations and management efforts. The COTS Control Program was designed to use data collected during control activities to guide effective ecologically-informed decision-making immediately, and to gradually refine the Program through adaptive management over time.

Since 2018, the COTS Control Program has been shown to be effective in managing COTS at site, reef and regional scales. As the Control Program has matured and the volume of data collected has increased, new opportunities have emerged to refine and improve the effectiveness and efficiency of decision support for COTS control. This project, CCIP-R-02 (Empirical Decision Support) of the COTS Control Innovation Program (CCIP), was designed to progress four key areas of innovation in the way data is used to improve the efficiency and effectiveness of decision-making in the COTS Control Program. These four areas of innovation were: 1) Reusable Digital Workflows to automate and standardise the preparation of Control Program data for research and decision making; 2) Empirical Analyses to adaptively refine key Control Program management parameters using accumulated field data; 3) Manager Dashboards to translate and deliver CCIP research outputs to managers at the time and place decisions need to be made; and 4) an On-Water Decision Support System to guide day-to-day operational decisions by on-water contractors.

Quality, availability, and consistency of data are crucial to inform the research and models used to guide management decision recommendations. Every day, across a fleet of vessels, the COTS Control Program collects a significant amount of data at precisely the locations where COTS management decisions need to be made. However, this data requires consistent preparation, analysis and interpretation to be used appropriately in models and to inform decision making. In the past, this preparation has been a periodic manual process completed only several times a year, slowing the availability of data for research and management decision making and introducing the risk of inconsistency across datasets. This project (CCIP-R-02 Empirical Decision Support) has established Reusable Digital Workflows that can automatically run processing algorithms every time new data is uploaded to the CCIP Information System (developed in a linked project CCIP-R-01 Information Infrastructure). This speeds up the availability of consistent data and amplifies innovation through code and data reuse across projects.

The COTS Control Program makes good use of data to inform decision making, but to be efficient and effective, the right data must be collected at the right frequency and used to inform the right decisions. When the Control Program was re-designed in 2018, several key management parameters had to be estimated from the limited data available at the time. Project CCIP-R-02 used more recent data collected from the Control Program to review and refine several of these management parameters. As an example, manta tow surveillance that has played a crucial role in the COTS Control Program could be undertaken less frequently than the current standard while maintaining the same quality of decisions around site cull

order. This refinement could potentially allow a greater proportion of vessel time to be invested in culling and increase efficiency.

Project CCIP-R-02 also demonstrated a model to estimate the effort required to complete management actions at a reef (e.g. COTS culling), which enables the early identification of outlier or “effort sink” reefs. This allows managers to improve effectiveness by changing strategy or redirecting resources. Finally, as part of the empirical analysis component, project CCIP-R-02 examined the conditions under which manta tow data most effectively inform decision-making. A key finding was that when only feeding scars were detected, COTS density was already below the Ecological Threshold approximately three out of four times, indicating that scars alone are not a reliable criterion for deploying cull divers, and supporting a recommended change to this element of the operational decision process.

Research makes a difference in the real world when it informs decisions made by managers. The innovations driven by CCIP-R-02 have helped drive real-world impact for research across CCIP by interpreting and digitally delivering research outputs from CCIP projects to managers at the Great Barrier Reef Marine Park Authority (Reef Authority) through the development of Manager Dashboards. Using outputs from other CCIP projects, six digital Dashboards were built and tested in close collaboration with managers to address their needs using the outputs of CCIP research. This included using a novel larval dispersal ensemble model to develop two Larval Dispersal Dashboards that allow managers to visualise networks of highly connected reefs and understand the implications for reef prioritisation. Another two Dashboards were developed to allow managers to dynamically explore how different management strategies will drive coral trajectories over the coming decades across the entire GBR, in terms of both ecological and economic metrics. An Effort Sink Reef Dashboard was also developed to help managers identify reefs that require a disproportionate or unexpected amount of resources to control. Finally, an Early Warning System (EWS) was developed that provides early and actionable insights regarding the initial build-up of COTS outbreaks, based on data aggregated across CCIP and beyond. The Early Warning Dashboard demonstrated direct management impact during the 2024/25 planning cycle, providing early detection of an emerging primary outbreak near Lizard Island and Cape Grenville that informed decisions to reallocate control resources to the Far North region, a concrete example of CCIP research driving management action.

Effective decisions also need to be made on-water during the day-to-day operations. The COTS Control Centre On-Water Decision Support System was designed and built to help the on-water contractors interpret cull and manta tow data to decide which sites to deploy cull divers, in what order sites should be assessed, and when management action at a site or reef can be considered complete. This on-water decision support system was implemented using a modern Progressive Web App architecture accessible across multiple device platforms and compatible with the Reef Authority’s on-water data collection tools, leveraging a hybrid architecture allowing both cloud sync for data sharing across the fleet, and local operation when vessels are out of internet connection.

Together, this suite of innovations around the way data from the COTS Control Program is used to guide more effective decision making will increase the efficiency, effectiveness and impact of research and management. Importantly, in each case, the research outputs produced as part of this project (CCIP-R-02) not only provide immediate efficiency gains but also create digital platforms and workflows that provide a foundation for future innovation.

1. INTRODUCTION

Along with bleaching (Hoegh-Guldberg 1999; Claar et al. 2018) and cyclone damage (Gardner et al. 2003; Pratchett et al. 2014), crown-of-thorns starfish (COTS) outbreaks are one of the primary threats to coral on the Great Barrier Reef (GBR) and across the Indo-Pacific (Pearson 1981; Yamaguchi 1986; Bruno and Selig 2007; De'ath et al. 2012; Pratchett et al. 2014). Indeed, COTS have been estimated to be responsible for 42% of all coral lost on the GBR between 1985 and 2012 (De'ath et al. 2012). However, unlike bleaching and cyclone damage, COTS can be managed through direct culling to provide immediate protection of coral on the GBR (Fletcher et al. 2020; Westcott et al. 2020; Matthews et al. 2024).

As a result, there have been efforts to cull COTS on the GBR since the 1960s (Gladstone 1993; Pratchett et al. 2014; Westcott and Fletcher 2018). In 2012, a coordinated program was established to manually cull COTS to protect coral at high value tourism sites on the GBR (Fletcher et al. 2020). In 2018, following recognition that COTS control provided a feasible on-water action to enhance the resilience of the GBR (GBRPMA 2017; Price 2018), the Control Program was significantly scaled up, and objectives expanded to include protection of ecologically important reefs. This expanded Control Program was designed to be structured based on an ecological understanding of the interaction of COTS populations and management efforts (Fletcher et al. 2020), in terms of day-to-day decisions, annual decisions, and over the longer term through adaptive management using Control Program data.

Under this program, decisions are guided by an Integrated Pest Management (IPM) framework that combines multiple data sources and decision criteria to plan and assess control activities. Data are collected at multiple scales, including manta tow surveys that provide relative measures of COTS abundance and outbreak status, and diver-based cull site surveys within defined polygons to quantify local densities and target aggregations for control. Manta tow is used in four roles in the COTS Control Program: 1) to assign reef outbreak status; 2) to gather reef intelligence upon first arrival at a reef to guide initial dive plans; 3) during ongoing management at a reef to sequence the order in which sites are culled; and 4) on completion of a reef to verify that ecological threshold conditions have been achieved. A reef is considered "closed" (i.e. active control completed) when COTS densities are reduced below an Ecological Threshold, defined as the density at which coral growth can outpace consumption by COTS (Fletcher et al. 2020). The frequency of manta tows and the sequence of cull site visits are planned based on ongoing data streams, ensuring control efforts are effective and efficient while highlighting opportunities to further optimise monitoring frequency, site selection, and closure decisions.

The COTS Control Program is strongly data-driven, integrating operational data with information from other GBR programs, research, and ecosystem models to inform day-to-day operations, annual planning, and longer-term adaptive management. While this richness creates strong opportunities to guide real-time management decisions and support ongoing learning and program refinement, it also poses significant challenges. The volume, complexity and operational tempo of the data require systematic, consistent, and timely processing and interpretation to ensure they can be effectively integrated into models and decision support systems. Addressing this challenge is a central objective of the innovations delivered through this project (CCIP-R-02 Empirical Decision Support) as part of the COTS Control Innovation Program (CCIP). To support the growing scale and complexity of this data-driven approach, project CCIP-R-01 (Information Infrastructure, Fletcher and Rezvani 2026) concurrently developed the COTS Information System, providing a centralised platform for storing, integrating and distributing Control Program data across research and management applications.

Project CCIP-R-02 was designed to progress four key areas of innovation in the way data is used to improve the efficiency and effectiveness of decision making in the COTS Control Program:

1. **Reusable Digital Workflows:** Standardised and automated preparation of empirical data for improved research, decision making, and innovation amplification.
2. **Empirical Analysis for Adaptive Management:** Refinement of key Control Program management parameters through empirical analysis of Control Program data.
3. **Manager Dashboards:** Better supporting management decision making by interpreting and delivering research at the time and place managers need to make decisions.
4. **On-Water Decision Support with the COTS Control Centre:** Improved support for on-water decision making with Control Program data using digital decision support.

This report details the innovations developed as part of CCIP-R-02 under these four sub-projects.

Reusable Digital Workflows: High-quality, consistently prepared data are essential for research, modelling, and the management decisions that depend on them. Through its daily operations across multiple vessels, the COTS Control Program collects large volumes of spatially explicit data, including approximately 35,000 manta tow observations and 3,500 cull site observations each year. These data are collected in targeted areas of active management and are central to fine-scale operational and strategic decision making.

To be useful for analysis and decision support, however, raw operational datasets require systematic preparation and interpretation. In particular, spatially linking manta tow observations to cull sites is non-trivial and can be approached in multiple valid ways, each with implications for how data are used in models and management decisions. Without repeatable workflows, data preparation can become fragmented and difficult to reproduce, slowing the translation of research into operational outcomes.

Reusable Digital Workflows were developed in CCIP-R-02 to address this challenge by formalising and automating common data processing steps. By encoding scientific and operational logic in shared, version-controlled workflows, raw Control Program datasets can be consistently transformed into analysis-ready products as new data become available. This improves efficiency, transparency and reusability, and enables methodological innovations developed in one project to be readily applied in others.

This approach is enabled by the CCIP-R-01 COTS Information System (Fletcher and Rezvani 2026) which provides centralised infrastructure for storing, integrating and distributing Control Program data. Together, the Information System and Reusable Digital Workflows provide foundational capability for adaptive management by ensuring that expanding volumes of operational data can be reliably converted into robust, decision-ready information at the pace required by the Control Program.

Empirical Analysis for Adaptive Management: Empirical analysis plays a central role in adaptive management by enabling key decision points to be evaluated and refined as new information becomes available. When the expanded Control Program was designed in 2018, several key management parameters had to be estimated from the limited data available and were explicitly flagged as candidates for refinement as the program matured. The accumulation of operational data across reefs, sites, and years now provides the opportunity to empirically evaluate and improve these assumptions, with the aim of enhancing both effectiveness and efficiency.

Key questions that can be addressed through empirical analysis include how frequently surveillance data need to be updated to reliably inform operational decisions, how control effort requirements vary among reefs, and under what conditions different data streams provide sufficient guidance for management actions. Addressing these questions empirically supports evidence-based refinement of control strategies and helps close the adaptive management loop by linking observed Program performance back to future decision making.

Manager Dashboards: Research influences management outcomes when its outputs reach decision-makers in a usable form, at the time and place decisions are made. Within the COTS Control Program, digital dashboards have become a central mechanism for monitoring performance, evaluating management outcomes, and supporting communication between managers and on-water operators. Such platforms provide an opportunity to directly integrate research outputs, Program data, and model results into management workflows, allowing scientific advances to be considered alongside operational information in real time. Manager dashboards can be designed to address different decision contexts, from strategic planning and prioritisation to operational surveillance and early warning, using outputs drawn from multiple research and monitoring streams.

By aggregating and synthesising information across CCIP projects and complementary monitoring programs, dashboards can support more comprehensive and transparent decision making. Integrating diverse data types such as surveillance, modelling outputs and early-warning indications into a single decision support environment reduces the cognitive burden for managers and increases the likelihood that researchers will meaningfully influence management actions.

On-Water Decision Support with the COTS Control Centre: Effective decisions also need to be made on-water during the day-to-day operations. During on-water operations, decisions must be made dynamically about which sites to target, the sequence in which sites are visited, and when control objectives at a site or reef have been achieved. These decisions are made in operationally challenging environments, often across multiple vessels and devices and under constraints such as limited connectivity, weather and time. Without fit-for-purpose digital decisions support, this can lead to increased operator workload, variability in decision quality and inefficient use of vessel time.

Effective on-water decision support requires systems that are accessible across devices, robust to intermittent connectivity, and capable of integrating historical information with data collected during ongoing operations. Such systems must integrate data ingestion, decision logic, and user interaction in a way that supports real-time operational use while remaining consistent with broader Program objectives and decision frameworks. Embedding the IPM framework directly within on-water decision support helps to ensure that operational decisions are informed by both historical Program data and current observations and remain aligned with agreed management strategies. Presenting this information in a clear and context-aware manner enables operators to interpret recommendations, apply professional judgement, and adapt decisions to local conditions encountered during control activities.

1.1 CCIP Project Logic

Project CCIP-R-02 drives real world impact through its direct connection to decision makers in the COTS Control Program. There are three paths to impact: via direct consultation with managers, via decision support provided to managers via the Power BI Dashboards, and via decision support for on-water operators via the COTS Control Centre decision support tool. These pathways deliver both research results from the empirical analysis within CCIP-R-02 itself, but also innovations from projects across CCIP via the decision support platforms.

Figure 1 illustrates this path to impact, and where project CCIP-R-02 fits within the CCIP Program Logic. What is not captured in the diagram are cross-connections to many other CCIP projects. These include project CCIP-R-01 (Information Infrastructure (Fletcher and Rezvani 2026), which provides the Information System that connects project data to the decision support tools in CCIP-R-02, as discussed in the companion final technical report for that project; CCIP-R-04 (Regional modelling, Skinner et al. 2025) and CCIP-R-06 (Cost effectiveness of Control, Scheufele et al. 2025), which deliver GBR modelled management scenarios to a Power BI Dashboard, as discussed in section 3.3.2; CCIP-R-05 (COTS dispersal ensemble modelling, Choukroun et al. 2026), which provides larval dispersal modelling as discussed in section 3.3.1; and projects CCIP-P-04 (Pre-outbreak monitoring, Pratchett et al. 2025) and CCIP-D-03 (Operationalising eDNA monitoring, Uthicke et al. 2025), which provide Scooter Assisted Large-Area Diver-based (SALAD) survey and eDNA data, respectively, to the Early Warning Dashboard described in section 3.3.4.

1.2 Project Aims

Project CCIP-R-02 aimed to provide a series of innovations to decision support for the COTS Control Program, from automation of common data processing needs to empirical analysis to inform adaptive refinement of the Control Program structure, to the development of manager-focused Dashboards and on-water operator decision support tools.

The specific aims of project CCIP-R-02 were to:

- Develop Automated Digital Workflows to automate the common processing needs for Control Program data to speed up the distribution of data necessary for research and management decision making;
- Complete empirical analyses to underpin adaptive management refinement of key Control Program parameters;
- Develop management dashboards to translate and focus CCIP research to the specific information required by managers to guide effective decision making, and;
- Develop an on-water Decision Support System to help guide on-water decision making.

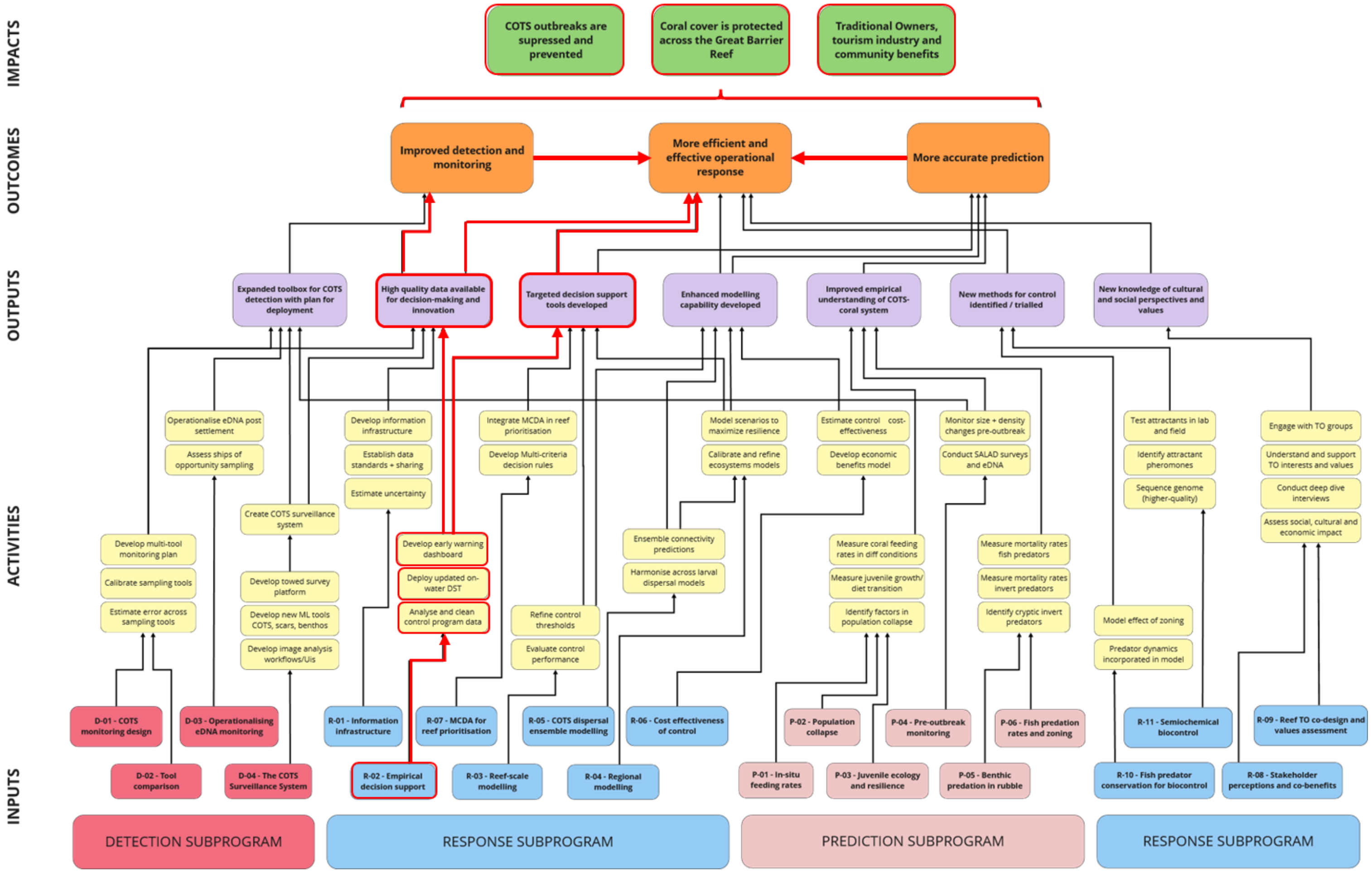

Figure 1. CCIP Program Logic. Project CCIP-R-02 and the path through Activities, Outputs, Outcomes, and Impacts are highlighted in red. Not shown are the cross-project connections, which are extremely important in the case of project CCIP-R-02 due to its core role enabling impact from CCIP research outputs direct to decision makers via decision support tools.

2. METHODS

Project CCIP-R-02 employed a range of methods, all focused on innovation and design, development and testing of practical tools to support effective decision making in the COTS Control Program. Below, the methods used for each of the four key innovations are detailed. First, the design approach used to enable the Reusable Digital Workflows is briefly outlined, before the development and testing is detailed in section 3.1. A more detailed outline of methods underpinning three separate Empirical Analyses, around re-tow frequency, effort sink reefs, and the conversion of manta tow to cull density, is provided in section 2.2. Brief outlines of the design philosophy for the Reef Authority Dashboards and the on-water decision support tool are then provided in sections 2.3 and 2.4.

2.1 Reusable Digital Workflows

Reusable Digital Workflows are both vital for efficient data sharing, and central to the innovation multiplier of science translation and code reuse across CCIP. The design of the CCIP Information System as part of project CCIP-R-01 (Fletcher and Rezvani 2026), and its tight integration with automated digital reusable workflows as part of this project (CCIP-R-02), represent a significant opportunity for digital transformation in the way data can be shared between COTS managers and researchers, between researchers and other researchers, and the way that research outputs can be delivered back to managers to inform decision making. Using Reusable Digital Workflows means that intermediate data generated from primary field datasets, like the cull data collected by the Control Program, can be automatically processed and uploaded to the CCIP Information System, which increases the efficiency and standardisation of data flows. Writing code to be open and shared via the CCIP Information System means that innovations in one research project can inform new approaches in others, multiplying innovation.

Two primary reusable digital workflows were developed and tested as part of CCIP. This included a workflow for processing Control Program data including manta tow surveillance, culling records, and Reef Health Impact Surveys (RHIS) datasets, as well as a workflow to assign manta tow observations to cull sites. These workflows standardise notations, formats, and conventions, ensuring comparability across time and between different datasets. Additionally, they generate intermediate data, such as COTS density estimates, in a standardised manner, improving consistency and reliability among researchers and management staff. The central principles used to guide the development of Reusable Digital Workflows in project CCIP-R-02 were transparency, robustness, and reusability. These principles informed both high-level architectural decisions and detailed implementation choices, ensuring that workflows could be reliably automated in an operational environment while remaining auditable and extensible for research use. The project was developed with R, a widely adopted and open-source programming language within the scientific community. Development with R allows the reuse of popular data and spatial analysis packages professionally maintained by the community. Custom functions were housed in a dedicated source file for repeated use in several applications to automate sub-processes, while application-specific main files were developed that can be automated by external processes. Algorithm and code packages were stored on GitHub, enabling connection to the CCIP Information System to enhance findability and reusability.

Automating the workflows required professionally implemented data processing code, robust to both minor data anomalies and larger deviations such as inconsistent input data structure. Given the volume, velocity and operational origin of Control Program data, workflows were required to accommodate variability in data content, structure and quality without manual intervention. Advanced generalised approaches to robust data processing algorithms were employed, using fuzzy matching techniques and data type checking compared against data formats specified in template JavaScript Object Notation (JSON) files. Advanced error catching mechanisms were designed to test alternative data processing methods when errors occur, while custom control data checking functions were developed to assess, identify and make corrective actions to rectify deviations from established data standards essential for research applications. Each time a workflow runs, a structured JSON output is autonomously generated, documenting any deviations identified, assumptions applied, or alternative processing pathways selected. This ensures full transparency of automated decisions and supports auditability, reproducibility and professional reuse of derived datasets while ensuring reporting is both human- and machine-readable.

Similar design philosophies were adopted in the automated workflow used for assigning ecological observations from manta tow to cull site polygons. Additionally, this workflow employed a modular approach to enable the testing and substitution of alternative algorithms. This design pattern is critical in a mixed research and operational system, where innovation and testing of decision-support algorithms must be balanced against the need for stability, consistency and risk management in operational decision making. This approach was tested with multiple algorithms for assigning manta tows to COTS Control Program cull sites, allowing comparison between algorithms. The primary difference between the algorithms was how underlying geospatial distance calculations were performed between polygons and lines, and how this information was used to map manta tows to cull sites. The results are discussed further in section 3.1.2.

2.2 Empirical Analyses

In this part of project CCIP-R-02, we used empirical analysis of Control Program data to estimate the optimal re-manta tow frequency and identify effort sink reefs. We also explored the relationship between manta tow and cull density data within the Control Program data. This is vital because information gathered from manta tow surveillance is frequently used to inform decision-making and underpins many operational decisions. The empirical analyses are based on a number of metrics that are defined in **Table 1**.

Table 1. Key metrics and parameters used in the empirical analyses of COTS Control Program data.

Metric	Definition	Unit
Manta tow COTS density	Number of COTS observed per 2-minute manta tow.	COTS per tow
Manta tow scars density	Number of scars observed per 2-minute manta tow.	COTS scars per tow
Cull density (Catch-per-unit-effort, CPUE)	COTS removed per unit dive time during culling – a proxy for COTS density at a site.	COTS per dive minute
Ecological threshold	The cull density below which coral growth can outpace COTS consumption; used to define when a cull site can be closed.	COTS per dive minute

2.2.1 Re-tow frequency

Manta tow surveillance plays a crucial role in the COTS Control Program (Fletcher et al. 2020; GBRMPA 2020). Manta tow surveillance data is used to inform a number of decisions, such as the COTS outbreak status at a reef (GBRMPA 2020), and which order sites at a reef should be culled (Fletcher et al. 2020; GBRMPA 2020). Once active control begins at a reef, it is manta towed every fourth voyage or roughly every six weeks to update planned control actions in response to changes in COTS densities as culling progresses (Fletcher et al. 2020). In the initial design of the expanded COTS Control Program in 2018, the six-week interval was based on expert estimates of the maximum acceptable surveillance interval, and the parameter was flagged for future refinement as part of the adaptive management framework (Fletcher et al. 2020). Our goal here was to review the six-week re-tow interval, and provide an empirical estimate of effective re-manta tow frequency.

One of the key roles of manta tow is to provide intelligence to the Control team on the location and density of COTS to guide decisions about which sites to dive at first once control begins at a specific reef. Manta tow can cover large areas efficiently to provide representative statistics at the reef scale, but it is relatively insensitive to small changes in COTS density. For example, recent field data showed that at sites with reported manta tow densities of 0.9–1.2 COTS per 200 m tow, subsequent actual reported cull density varied from 0.007 to 2.08 COTS per dive minute when the time between tow and cull was within three days. This level of uncertainty implies that manta tow is not able to reliably resolve small differences in cull density (**Figure 2**Error! Reference source not found.). This is not a problem when manta tow is used to detect high density aggregations of COTS when control first begins at a reef. However, as control actions at a reef reduce density differences between sites below the level that can be resolved by manta tow, more frequent towing will add little value. To maximise efficiency, the re-manta tow frequency should be high enough to inform decision making, but no higher.

One way to identify the optimal re-tow frequency is through data currency, specifically determining how often data should be collected to correctly inform a change in management decision. In the COTS Control Program, the relevant change is when an initial manta tow that recommends that “no culling is required” at a site is followed by a subsequent manta tow that instead recommends that “culling is required” at the site (hereafter, No-Yes). This happens either: 1) when no scars or COTS were observed across the manta tows at a site during an initial voyage, but scars or COTS were then detected during a tow in a subsequent voyage; or 2) when a site was culled below the Ecological Threshold but scars or COTS were observed in subsequent tows. Here, we defined the optimal re-tow frequency as the expected duration to detect such changes. We used ‘No-Yes’ to indicate the transition from no culling required to culling required for a site, and ‘No-No’ indicates no culling required in two consecutive tows.

Because Control Program data is collected for operational purposes, not statistical analysis, we implemented the following inclusion criteria to mitigate artifacts and noise. First, we only included data from reefs south of 16°S and north of 23°S, excluding data from the Swains reefs where different population dynamics can influence trends. Second, to control for recruitment effects, we only considered data where the duration between consecutive tows was less than 365 days. Because we have nearly three times more observations of No-No than No-Yes, we down-sampled the No-No data and repeated the analyses 100 times to ensure the model had both high sensitivity and specificity. Only data from reefs that were regularly controlled were included in the analyses. Data used for this study spanned from November 2018 to August 2023. Given that many reefs were only manta-towed a couple of times during this period, and many did not experience any COTS outbreak, only data from reefs that were manta-towed and culled at least three times within a 365-day period were included.

Transitions occur at a site level, but the Control Program conducts manta tows around entire reefs. The optimal re-tow frequency is complicated by the heterogeneity of COTS activity within a reef, as not all sites at a reef have significant COTS densities at the same time. This is further complicated by operational considerations, such as weather, resources and accessibility, which can lead to variable intervals between tows. Therefore, instead of providing estimates of a single optimal re-tow frequency, the model examines how the probability of transitioning from no culling required to culling required (No-Yes) at a site change with time.

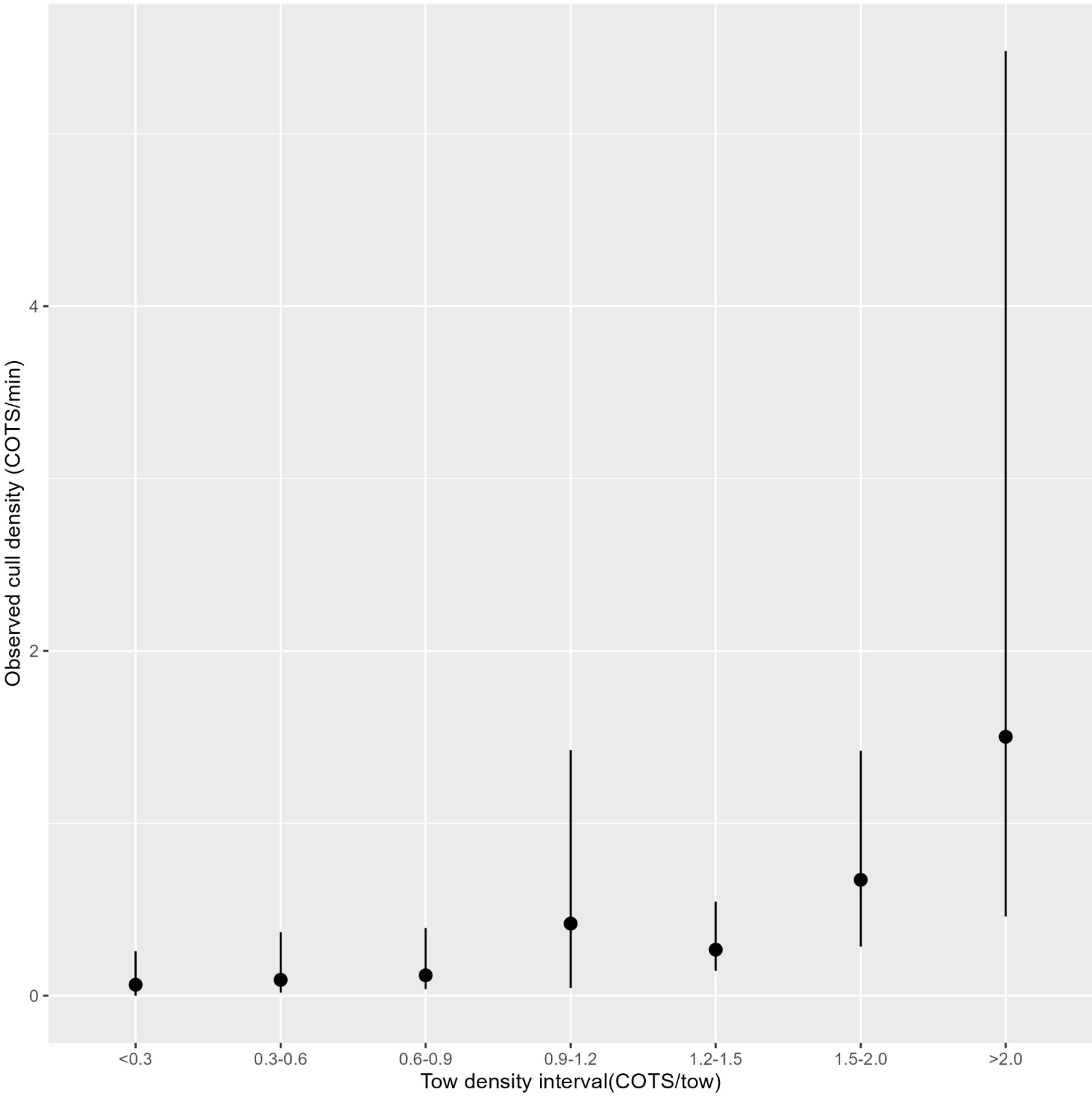

Figure 2. The 95% quantile of the recorded cull density for each manta tow density interval. This figure shows that manta tow is not sensitive in detecting changes in cull density, therefore towing too frequently is unlikely to add significant value to the control operation.

The control activities at the reef between two consecutive tows can potentially affect the time it takes for a site to transition from No-Yes. We tested model fits against the following variables: 1) site culled between tows?; 2) adjacent sites culled between tows?; 3) proportion of sites at reef culled between the tows; 4) cull density if the site was culled; 5) whether the site was recurrent (had been culled recently), and; 6) proportion of hard coral cover at the site. We tested various models and found that a generalised linear mixed model (GLMM) with binomial distribution and log-link function had the lowest Akaike Information Criterion (AIC). Estimations at site level were then aggregated to the reef level to support decision making. The time was treated differently for sites that were culled and sites that were not culled between two consecutive tows. For the sites culled, we used number of days between the time the site was culled below Ecological Threshold to the next tow day. For the non-culled sites, the time was the number of days between two tow days.

2.2.2 Identifying outlier or "effort sink" reefs

Effort sink reefs can be defined in various ways. In this project, we consider reefs that, when controlling to the Ecological Threshold, require an investment of effort greater than that expected based on comparison with other similar reefs. This analysis can be approached in several ways. The most direct method for identifying effort sink reefs involves specifying a maximum acceptable level of effort, then comparing the effort required to reduce cull density below the Ecological Threshold at a given reef against this acceptable effort. Reefs requiring effort above the acceptable effort are classified as an effort sink reef.

Using manta tow and cull data from November 2018 to August 2023 provided by the Control Program, we modelled the amount of dive bottom time required to bring entire reefs to below the Ecological Threshold density, a Catch-Per-Unit-Effort (CPUE) of 0.04 COTS / min (Rogers et al. 2017). The start and end dates of control at a reef were provided by the Reef Authority, and used to filter detailed Control Program dive data to determine the amount of effort put into bringing the reef down to the specified Ecological Threshold. To aggregate cull dive data to the site level, the cull numbers and bottom time of all dives conducted at a given site during a given voyage were summed to create a single record per culled site per voyage. To obtain reef scale data, aggregated site records were grouped by reef and voyage. In addition, the first aggregated cull record across the first voyage at a reef, and the maximum aggregated cull record across the first voyage at a reef were extracted.

Similar to the cull data, the manta tow data was grouped by Reef IDs and date of tows. The data was then summarised to give the total number of unique sites towed, the number of sites slated for culling, the total number of COTS counted in the tows, the density of COTS per tow, the highest number of COTS counted at each reef in a single tow, the total number of sites that showed evidence of scarring from COTS feeding, the proportion of sites that had scarring, and if scarring was present at each reef.

Both manta tow and cull data were then combined to make a single large dataset by Reef ID. The manta tow that corresponded to the reef level cull data was taken to be the manta tow that happened just before the first cull date, with a 30-day cut off. If manta tow data was not available for the reef in the cull dataset or was not within 30 days before the first cull date, the reef was not included in the subsequent analyses. As a result, 57 reefs remained in the dataset, which was then combined with habitat data obtained via the Allen Coral Atlas. The Allan Coral Atlas was also used to quantify the size of various reef features, such as back reef slopes, lagoons, and overall area of the reef (Allen Coral Atlas 2022).

A Generalised Linear Model (GLM) with a Gamma distribution and log link was used to estimate the cumulative bottom time that would be required to close a reef. Various combinations of variables were tested to find the equation of optimal fit. This process involved a stepwise method of including variables one by one and testing for any interactions to improve the AIC of the model. The final equation used is shown in the Results section below.

2.2.3 Manta tow to cull density using Control Program data

The COTS Control Program makes good use of data to inform decision making, but to be efficient and effective, appropriate data must be used to inform decisions. Both manta tow and cull data are used to inform multiple decisions in the day-to-day operation of the Control Program, but they have different extent, frequency, accuracy and precision, provide different estimates of COTS density, and are reported in different units (

Table 1). To make the most effective use of this pool of data it is important to understand how the two measures correlate, and how they can best inform effective Control Program decisions.

At reefs under active control, the Control Program collects both manta tow and cull data, allowing a direct comparison of performance. Manta tows record the number of live COTS observed, coral cover, abundance of COTS scars and distance covered in a two-minute tow. Coral cover and scars are categorical variables, where coral cover is binned into 11 intervals, and scar count has three levels, absent, present (1–10 scars) and common (10+ scars). The tow distance mostly ranges from 162 m to 233 m, and outliers were omitted from the analysis. If one or more COTS and / or scars were observed at a site during a manta tow, the site was opened for culling. The sites with the highest COTS density estimated using manta tow at a reef were culled first. During culling, divers recorded information including the number of COTS of different size classes encountered and injected, and the total bottom time.

The data used in this study were collected between November 2018 and December 2023. The manta tow and culling data were recorded at different spatial resolutions, and for this study were aggregated to a site level. Each cull site is approximately 500 m x 200 m, and often it takes two to three 2-min tows to cover a site. We aggregated the scar data to site level, and used the proportion of tows without scar, the proportion of tows within the site with 1–10 scars and the proportion of tows with 10+ scars as predictors. To accommodate variations in tow distance we used the number of COTS per metre of tow, rather than number of COTS per tow, as the manta tow COTS density in this case.

We applied a number of inclusion criteria to ensure the data were relevant for the purpose of study. Data were included only if: 1) culling occurred within three days of the manta tow; 2) the reef was south of 16°S; 3) cull data reported density less than or equal to 1 COTS / min; and 4) manta tow data reported density less than or equal to 0.11 COTS / metre.

Due to the high proportion of zeros in the cull density records (~23% of cull density records were zero), we found a zero-inflated model was best to model the relationship between the cull density and information collected from manta tow. The probability of belonging to the zero component of the model was modelled using a Binomial distribution. The expected value of cull density and the likelihood of cull density being zero were modelled using the combination of proportion of tows without scar, proportion of tows with 1–10 scars, proportion of tows with 10+ scars, and tow density. Reef was included as a random effect in both the intercept and the coefficient of tow-density to account for the random variation among reefs.

2.3 Manager Dashboards

A cornerstone of an adaptive management program is the symbiotic relationship between managers and researchers. Consequently, research products produced by CCIP needed to be implemented into the COTS Control Program in a way that addressed managers' needs and maximised real-world impact. To ensure good coordination between research and management needs, a Research Translation Working Group was established, comprised of COTS Control Program managers, the CCIP Director and CCIP Subprogram Leads, and the CCIP Research Translation Lead. The Research Translation Working Group worked to identify the best platform for the integration of research outputs into the Reef Authority's digital systems, and prioritise research outputs for management translation.

Microsoft Power BI was selected as the research translation platform, due to its ability to generate dynamic and interactive visualisations capable of succinctly conveying research findings and how they related spatially to the GBR. Crucially, the Reef Authority staff are already adept with Power BI and utilise it within their current workplace practices, significantly reducing the time and resources required for adoption compared to other visualisation platforms or custom apps. Synergy with other Microsoft products enhances accessibility as data can be stored centrally within SharePoint, which is the platform on which the CCIP Information System is built, and be referenced by Power BI. Updates to the original data sources are reflected in Power BI, ensuring consistency for managers. Referencing a central data storage system with Power BI empowers the Reef Authority staff and managers to continuously develop and integrate features into other existing workflows as they identify value in the new research products.

In implementing the prioritised activities for Research Translation, a specific goal was to ensure each Dashboard would address a specific management-related question, rather than act as an exploratory tool for everything the underlying research had investigated. This philosophy led to mapping key management questions against available research outputs to indicate priority. High priority Dashboards were produced and iteratively refined with regular feedback from managers and researchers to ensure that visualisations were both scientifically rigorous and useful for industry.

Six priorities for research translation as Manager Dashboards were identified by the Working Group:

- Larval Dispersal Ensemble Exploration – informed by CCIP-R-05 (Choukroun et al. 2026)
- Larval Dispersal Decision Implications – informed by CCIP-R-05 (Choukroun et al. 2026)
- GBR scale management scenarios – ecological metrics – informed by CCIP-R-04 (Skinner et al. 2025)
- Economic cost effectiveness management scenarios – informed by CCIP-R-06 (Scheufele et al. 2025)
- Effort sink reefs – informed by CCIP-R-02 (this project)

- Early Warning Dashboard to display pre-outbreak monitoring data – SALAD / eDNA – informed by CCIP-P-04 (Pratchett et al. 2025) / CCIP-D-03 (Uthicke et al. 2025), as well as CCIP-R-05 (Choukroun et al. 2026) and CCIP-R-04 (Skinner et al. 2025)

2.4 On-Water Decision Support

The COTS Control Centre On-Water Decision Support System will help on-water contractors interpret cull and manta tow data to decide which site to drop cull divers, in what order sites should be assessed, and when a site or reef can be considered complete. To do this effectively across a fleet of vessels with intermittent network connectivity and a range of end-user device types required a solution with a focus on availability, capability and consistency. This newly developed approach provided a solution that enables the Decision Support System to be made robustly available on various devices when vessels are both online and offline, to synchronise data across boats, and to be capable of running ad-hoc data processing scripts written in R and other languages to process and interpret data based on the principles of the Control Program IPM decision process. **Figure 3** shows a high-level view of the architecture.

A multi-tiered architecture was developed, consisting of a sophisticated infrastructure architecture, and application architecture. The infrastructure architecture consists of: 1) an On-Water Server that is responsible for data transformation and storage when the boats are offline; 2) a Remote Server that is reachable when a boat has online connectivity and can receive updates from On-Boat Servers, and; 3) a multi-platform Progressive Web Application (PWA) that can be installed on laptops or mobile devices to provide a user interface for data interaction, to run data transformation processes, and to access decision recommendations.

The rationale behind this sophisticated architecture is to robustly manage complex connectivity requirements, while providing a computational framework capable of running the required data transformation processes when the boats are offline. The On-Water Server allows the fine-grained administration control and computational performance to effectively process datasets and run transformation pipelines. The PWA is used to create a cross-platform experience for interacting with the Decision Support System. The PWA enables the user to trigger the execution of reusable data transformation workflows, written in Python and R, leveraging the computational power of the On-Water Server. It also allows on-water decision makers to access and visualise key components of the dataset to better understand data trends to inform on-water decision making.

This advanced system was developed using professional software practices. Azure DevOps is used to store and version-manage the code, automatically deploy, and create infrastructure using Infrastructure-as-Code (IaC).

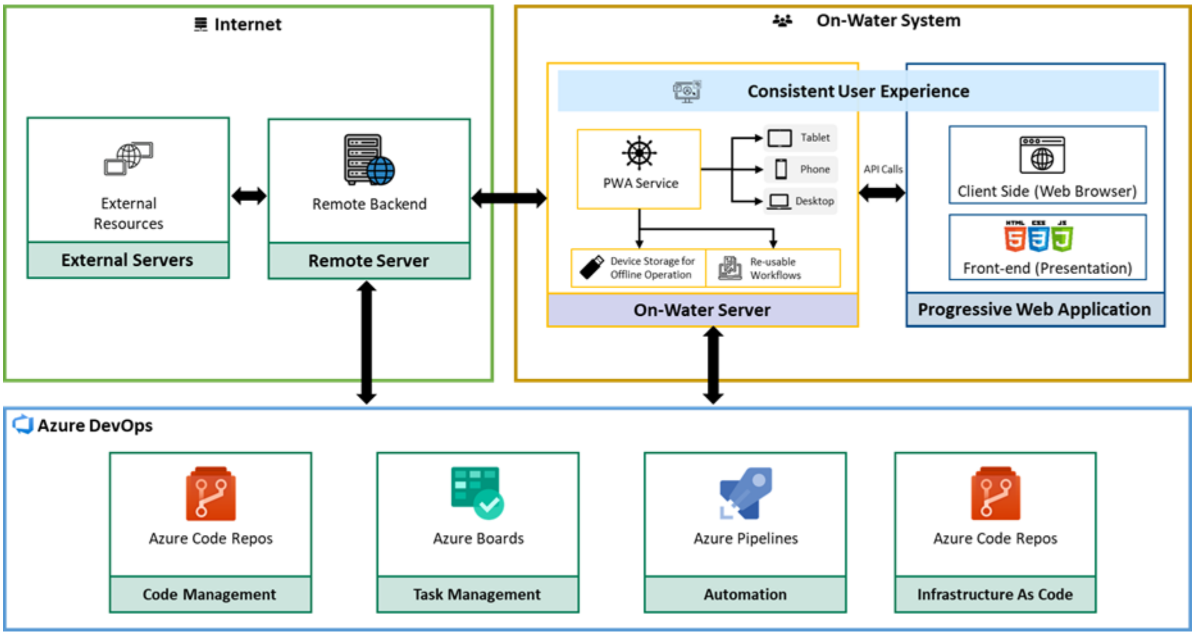

Figure 3. The on-water decision support tool architecture.

2.5 Stakeholder Engagement

Project CCIP-R-02 engaged extensively with key stakeholders across the four sub-projects. The most important of these interactions was the deep engagement of the Research Translation Lead, Ethan Waters, with researchers across CCIP projects and managers at the Reef Authority. In addition, one of the research team members, Sam Matthews, is also a key COTS Control Program manager, contributing time in kind to progress research questions important to future innovations in COTS control. Each sub-project also held small group meetings with key stakeholders at key points, and contributed to CCIP stakeholder workshops twice a year.

The Manager Dashboards developed as part of CCIP-R-02 were coordinated with and supported by a dedicated CCIP Research Translation activity. As part of this translation coordination, a Research Translation Working Group was established. The Working Group included representatives from the COTS Control Program management team, the CCIP Director and CCIP Subprogram Leads, and the CCIP Research Translation Lead. The Research Translation Working Group identified management questions that could be informed by CCIP research outputs, and prioritised areas for management translation. The Working Group met roughly fortnightly from December 2023 to June 2024.

Engagement was strongly supported by the Research Translation Lead, Ethan Waters, over the same period. The Lead was simultaneously appointed as a James Cook University (JCU) researcher, Commonwealth Scientific and Industrial Research Organisation (CSIRO) Visiting Scientist and Reef Authority intern, allowing access to organisational facilities and computer systems across researcher and management partners. The Lead attended CSIRO and the Reef Authority offices in Townsville one to two days a week to work directly with CCIP researchers to ensure research outputs were being appropriately interpreted, and COTS Control Program managers to ensure the Manager Dashboards provided the information required to address key management questions.

From 2021 to 2024, the project lead, Cameron Fletcher, and Sam Matthews attended bi-monthly COTS Action Group meetings with research leads, COTS Control Program managers, and on-water control staff. This included updates to participants on progress of CCIP-R-02 research, and in 2021 feedback was elicited from on-water operators about key needs for on-water decision support tools.

Early iterations of the Dashboards were used to inform some facets of the annual reef prioritisation process in March and November 2022, April and November 2023 and March 2024. Many of these were part of regular COTS Control Program operations rather than research components, but some innovations from CCIP-R-02, notably early iterations of the Early Warning Dashboard, contributed to reef prioritisation.

In addition to the six prioritisation workshops, the project team contributed to multiple project and CCIP-wide workshops, as well as national COTS conferences. On 18/11/2021, the team contributed to a CCIP-D-01 workshop. On 27/04/2023 the team gave a virtual seminar to the CCIP Seminar Series. The team made significant contributions to the three CCIP workshops on 07/10/2022, 15/05/2023 and 13/11/2023. The team has also presented work from CCIP-R-02 at two national conferences: the Australian Marine Sciences Association on 07/08/2022, and the Reef Resilience Symposium on 18/04/2024.

Finally, the team contributed to multiple coordination discussions across GBR research programs, including a workshop on 02/11/2022 around aligning the COTS Program, Reef Restoration & Adaptation Program (RRAP) and Reef 2050 Integrated Monitoring and Reporting Program (RIMReP) Data Management Systems, and workshops on 25/04/2023, 08/05/2023, 12/05/2023 and 23/11/2023 on integration opportunities across CCIP, RRAP and RIMReP.

3. RESULTS

Project CCIP-R-02 produced a series of innovations across the four key themes, each with one or more outputs. Below, three innovations around Automated Digital Workflows are detailed: the automated preparation of Control Program data for research reuse; testing the assignment of manta tows to Control Program cull sites; and the information infrastructure used to automatically run workflows when new files are uploaded to the CCIP Information System. The results from three empirical analyses around re-manta tow frequency, effort sink reefs, and manta tow and cull density comparisons are then presented. Six Manager Dashboards were developed, tested, and delivered in an operational state for use by Reef Authority staff in Power BI, to address specific management decision-support requirements using CCIP research. Finally, the implementation of the On-Water Decision Support System is described, which was developed and tested as a functional prototype. However, it requires formal onboarding and integration processes to be managed by the Reef Authority's technical team before full operational deployment.

3.1 Reusable Digital Workflows

For Reusable Digital Workflows to underpin efficient data sharing and act as an innovation multiplier by enabling the transfer of ideas and methods between projects, they must be open, robust, and reusable. Below, we detail how two Reusable Digital Workflows have been developed and tested with open design principles to ensure robust operation with modular and reusable code structures. The associated codebases are publicly available, and their execution has been automated within Azure.

3.1.1 Reusable Digital Workflow 1 – Control Program Data Preparation

Through its daily on-water activities across multiple vessels, the COTS Control Program collects a significant amount of data at precisely the locations where COTS management decisions need to be made. This data comes from multiple providers appointed by the Reef Authority and includes culling records, manta tow surveillance, and RHIS observations. However, it requires consistent preparation and careful interpretation to be used effectively in models and decision-making. Each dataset contains critical nuances that, if overlooked, can produce misleading outputs. Additionally, the data have been collected over many years, resulting in a wide range of notations, formats, and conventions. This variability complicates comparisons across datasets and time periods, making it challenging to develop a coherent overall understanding without effective preprocessing. In the past, this has been a periodic manual process completed several times a year. The first Reusable Digital Workflow significantly innovates this process to automatically generate standardised datasets for manta tow surveillance, cull, and RHIS data that can be ingested directly into research pipelines. This capability is particularly valuable because most research needs *intermediate data*, such as COTS density estimates, which must be generated from *primary field data*, such as cull rates recorded by the COTS Control Program.

The code was implemented in R version 4.2.1 and developed on a 64-bit Windows 11 machine, using the RStudio Integrated Development Environment (IDE). Version control and issue tracking were facilitated through GitHub, ensuring open-source transparency and accessibility. A specific project structure was adopted, with a .bat file developed to perform folder structure initialisation. Similarly, an R script and .bat file were provided to install the required dependencies for the project. A readme file provides context and information about the project, while configuration files are stored in a dedicated folder. It is recommended that configuration files are never edited or removed, instead an alternative should be developed and stored in the appropriate location. The file source ".R" contains all custom functions written for this project. Separate main files were developed for context specific applications of this code, including processing data for the COTS Control Centre app and Control Program data preparation. Application-specific main files can be executed via an IDE, through the command line or with an external automation process. An overview of the Control Program Data Preparation workflow is illustrated in **Figure 4**. The two primary outputs of this workflow are the processed dataset and the metadata report detailing what was done and any errors encountered, structured as a JSON file.

The first step in the Control Program Data Preparation workflow, as illustrated in **Figure 4**, is the program initialisation. The inputs required for this stage include the file storage location of the new data, the previous workflow output in the "legacy" data format, a configuration file, a KML file describing cull site geometries, and a Boolean variable indicating whether the output should be aggregated at a site level. The program programmatically acquires missing inputs by first checking the expected location of the metadata JSON file output produced by the workflow. This file records detailed information about the workflow execution, including processing steps, decisions made, changes applied, data used, errors and locations of other outputs, serving as a comprehensive log. The workflow identifies the most recent metadata file and uses it to locate the previous workflow's data outputs, the relevant configuration file, and the locations of previously used or new spatial files. Provided that no data have been removed or deleted, this process should successfully retrieve all required inputs. However, it is recommended that all inputs are provided where possible. Fuzzy matching extracts key words from the file naming conventions of the new data and determines the most appropriate configuration file, the most recent workflow output, and its associated metadata report.

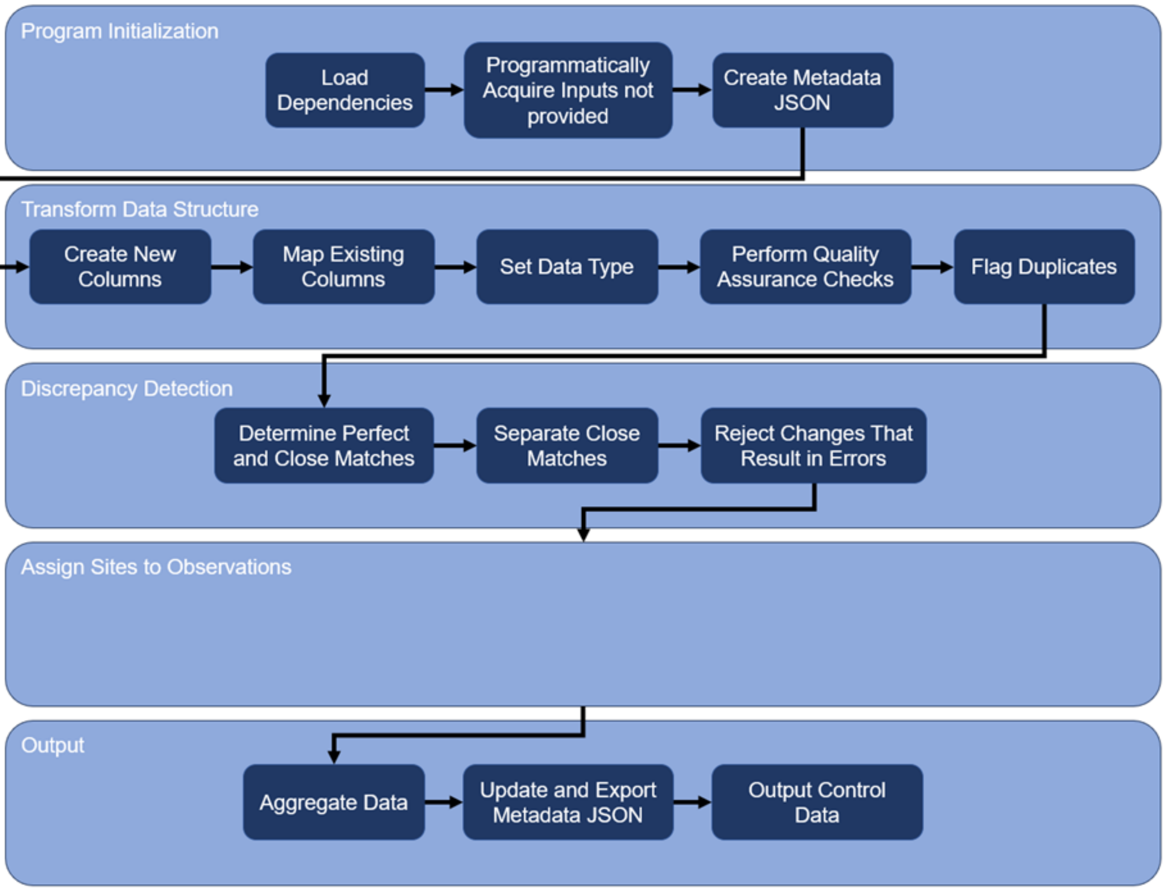

Figure 4. Control Program Data Preparation flow diagram.

The data structure transformation step ensures adherence to the required format and quality standards. The configuration file specifies columns to be created and contains strings of code that are executed to determine the columns value. Although the configuration file specifies mappings from legacy column names to expected input names, fuzzy matching is used to accommodate possible variations to the expected input column names. Column data types are defined in the configuration file and are set for consistency and compatibility. Custom functions perform quality assurance checks that flag and document errors, inconsistencies, or duplicates, to ensure the data is suitable for research purposes. An exhaustive list of checks is performed, and their approach is documented in the GitHub readme.

The discrepancy detection step aims to compare the previous output with the raw input data to identify and perform corrective actions if accidental errors were introduced into the data. Until an Application Programming Interface (API) is established to the Reef Authority database, there exists a potential for row IDs to be unintentionally altered, leading to code-breaking errors. Consequently, the codebase assumes a lack of unique identifiers as a fundamental constraint. Instead, to detect discrepancies, all rows from the new dataset are compared to the previous output with a series of vectorized operations to calculate distances between rows. These distances are then utilised to map rows from the original dataset to their counterparts in the current dataset. Mapped rows with an erroneous change are corrected. The output of this step is then passed to the assignment of manta tow sites workflow described in section 3.1.2. Subsequently, the data is aggregated and exported for further analysis and decision-making processes.

The constraint of not utilising an authoritative ID increases the computational complexity significantly. However, the vectorized implementation of these operations significantly reduces the processing time, rendering the computational overhead sufficiently small for the task at hand. The initial results from this workflow have already been used by several researchers, including the empirical analyses in this report.

3.1.2 Reusable Digital Workflow 2 – Assigning manta tows to cull sites

Another common data processing need for researchers and managers alike is assigning and aggregating line-based manta tow data to polygon-based cull site locations. This is a simply expressed but computationally complex problem with no objectively correct answer. There are several existing methods in use by researchers and managers, each with various strengths. This workflow was designed to provide a modular approach to allow different algorithms to be incorporated and tested while making it easy to generate data using existing methods to maintain consistent decision making. This design pattern will be important for other questions faced in the mixed research and operational system of COTS control innovation, where decision support algorithms must be innovated at the same time as operational decisions need to be reliably informed with stable algorithms.

This workflow is both a standalone workflow designed to test different site assignment algorithms, and a reusable subprocess called from the Control Program Data Preparation workflow. The high-level details regarding development and implementation are applicable to both workflows. An overview of the assigning manta tows to sites workflow is illustrated in **Figure 5**. The primary outputs generated are a dataset in the form of an R DataFrame and a serialised raster file.

To optimise computational efficiency, this workflow employs extensive measures to avoid redundant geospatial calculations, which are computationally expensive, by leveraging previously generated data where applicable. Initially, the workflow attempts to load the serialised raster file generated by this workflow in a previous iteration. Provided that the KML file utilised in the prior run is identical to the current KML file, the serialised raster is employed to assign sites, eliminating the need for redundant raster generation. However, if the files differ, the raster needs to be generated or updated to reflect the changes in site locations. In this case, every reef geometry collection is compared to determine which require new rasters. This will include all reefs if the workflow has not previously been executed.

A variation of the Ramer-Douglas-Peucker algorithm, specifically adapted for polygons, is employed to simplify the polygons, reducing computational complexity in subsequent steps. Blank rasters are generated for each reef with the same coordinate reference system as the input data. Every pixel within these rasters is assigned to the nearest site polygon in a geometry collection. This is performed with a process that calculates the Euclidean distance from the pixel centroid to the closest point on every polygon, including edges and areas formed by the polygon vertices. The resulting rasters are used to update the current raster list, which is serialised to minimise read/write times and saved for use in future workflow calls. The workflow then calculates the manta tow centroids as geometry points, to overlay and extract the corresponding site values from the rasters. The geometry is dropped and the resulting dataset, incorporating the site assignments, is returned. These approaches effectively minimise the use of computationally expensive geospatial calculations by strategically storing and reusing intermediate data from previous function calls.

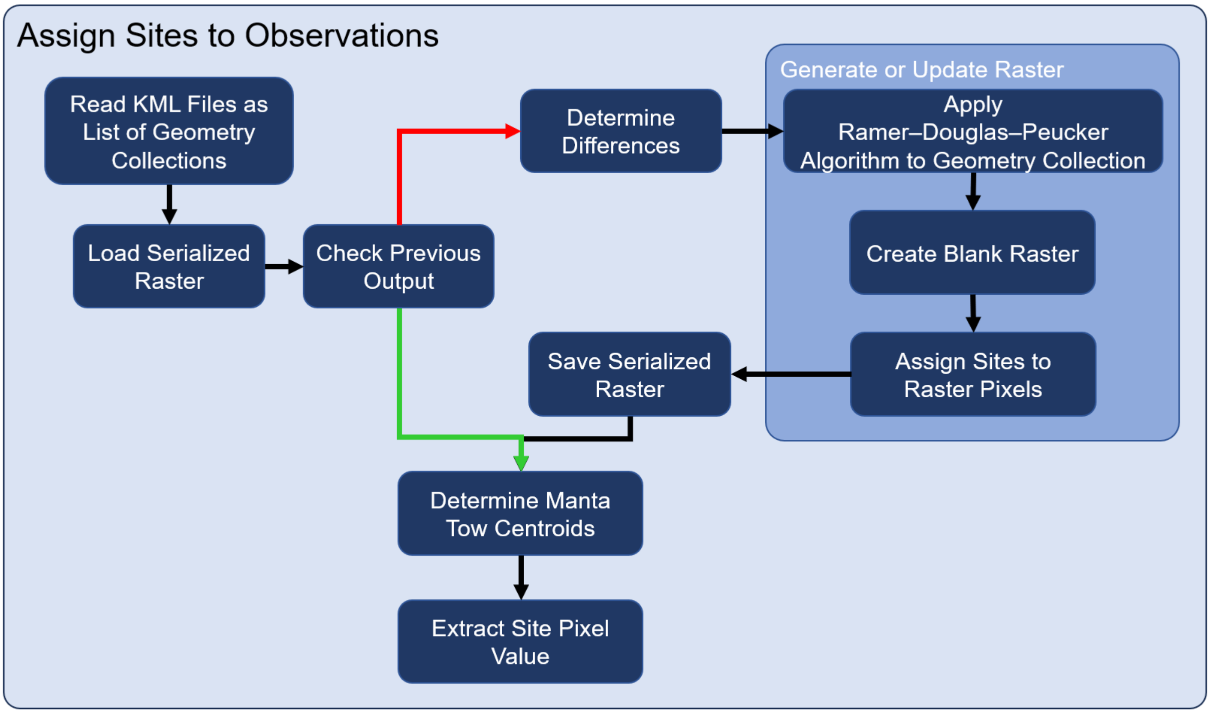

Figure 5. Assigning sites to manta tows flow diagram.

3.1.3 Automating the Reusable Digital Workflows

In today's data-driven world, the need for reliable, accessible, and up-to-date datasets is vital for both researchers and managers. Automating these two Reusable Digital Workflows ensures that researchers and managers can access accurate and up-to-date data. Previous implementations of this workflow produced consistent research datasets, but the code base was proprietary and relied on a periodic manual process completed at most several times a year, slowing down the transfer of data to researchers. CCIP-R-02 provides a robust, scalable solution using Azure Services to ensure the dataset is always up-to-date and easily accessible.

Microsoft Azure Synapse Analytics provides a cloud-based approach to perform data transformation without the need for managing infrastructure or platforms. It provides automated data integration workflows that have built-in integration with Microsoft OneDrive, Microsoft Storage Account / Data Lake and other storage platforms. Furthermore, it provides seamless integration with automation tools such as Microsoft Azure Logic Apps, Azure Functions, and Microsoft Power Automate. With advanced connections, this cloud-based platform can integrate with presentation layers such as Microsoft Power BI and SharePoint. **Figure 6** shows the high-level architecture of the proposed solution.

The automated workflows leverage automated data ingestion using Azure Pipelines, and store an intermediate dataset in the Azure Data Lake. The data can then be processed using the Apache Spark functionality built into the Azure Synapse platform, which is capable of running Python and R scripts. The data can be further enriched by linkage with existing datasets in the Azure Data Lake.

Microsoft Power BI is built on the Microsoft Azure Blobs storage, which is a subset of the Azure Storage Account, therefore integration with the Azure Storage Account is inherently embedded in Power BI. Once the datasets are transformed and enriched, they can be accessed within Microsoft Power BI for visualisation and presentation to stakeholders.

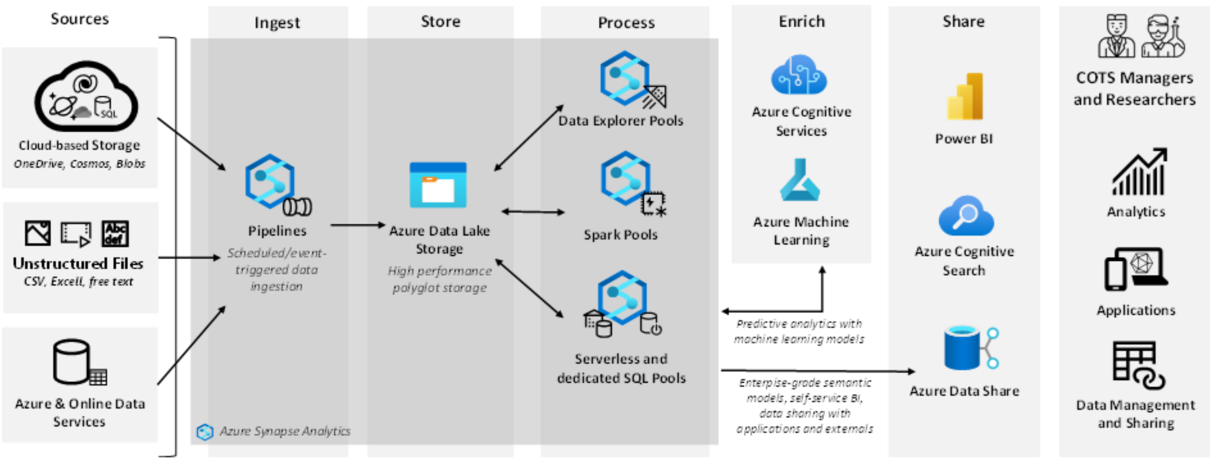

Figure 6. High-level architecture of the automated digital workflows that is designed based on the Azure well-architected framework.

3.2 Empirical Analyses

The COTS Control Program makes good use of data to inform decision making, but to be efficient and effective, the right data must be collected at the right frequency and used to inform the right decisions. In 2018, the expanded Control Program was designed using the principles of ecologically-informed management. The values of several key management parameters were set based on the limited data available at the time, but the Program also established data collection frameworks to enable adaptive refinement of these parameter values over time. Project CCIP-R-02 analysed data from the Control Program to recommend refinements to three key components that could improve the efficiency and effectiveness of the Control Program: re-manta tow frequency; effort sink reefs; and the appropriate use of manta tow and cull data to inform decision making.

3.2.1 Empirical Analysis - Re-manta tow frequency

Six-weekly manta tows are used by the Control Program to decide the order in which sites around a reef will be culled. In 2018, the six-week interval was selected based on expert input and identified as a parameter that could be adaptatively refined once data from the new Control Program was available. Manta tows need to be conducted frequently enough to inform the decision about whether and in which order sites should be culled. However, manta towing too frequently takes up vessel time that could be spent culling without improving the quality of decisions made. We analysed data from the Control Program to identify the instances in which the recommendation for whether a site needed to be culled changed from “No” to “Yes” from one manta tow to the next, a situation that would typically arise due to an incorrect decision being recommended by manta tow. Our analysis assessed how much time can elapse after a manta tow before the quality of the recommended decisions begins to decline.

At a site, when the days between the tows increased, the probability of the management recommendation transitioning from “No” (culling not required) to “Yes” (culling required) also increased. However, the rate of increase depended on whether the site was culled between the tows, the cull density of the site, whether the adjacent sites were culled, the proportion of the sites around the reef culled, and whether the site is a recurrent site. Coral cover did not have a significant association with the No-Yes transition.

Cull density and whether the adjacent sites were culled had the highest effect on transitioning from No to Yes. For a site with adjacent sites culled between the two tows, the odds of a transition from No to Yes were 1.75 times higher than sites where the adjacent sites were not culled over a given duration. Sites with high cull density also had higher marginal probability of transitioning from No to Yes. The proportion of reef culled between two tows however had a negative association with the probability of transitioning from No to Yes. Sites at reefs with a larger area culled between two tows had lower marginal probability of transitioning from No to Yes (Error! Reference source not found.**Figure 7**).

According to the model, the current recommendation, that reefs are re-manta towed every ~42 days (6 weeks), exhibits similar probabilities of detecting No-Yes transitions as re-towing every 100 days for most reefs. For instance, in frequently monitored control sites, the probabilities of a No-Yes transition with re-towing every 42 days and every 100 days were approximately 85% and 87%, respectively. However, at the reef scale only a small proportion, on average 20%, of sites require culling at a given point in time. As a result, the probability of detecting No-Yes transitions for re-towing the entire reef at 42 and 100 days were approximately 16% and 18%, respectively. The two-percent increase predicted by the model indicates very little gain from re-towing more frequently. However, care must be taken in interpreting these site-level results because manta tow is used to inform several different decisions, including when to open a site, the order in which sites should be culled, and when culling a site can be avoided. While the overall statistical distribution of the data is fixed, the statistical power of the data to inform each of these decisions varies.

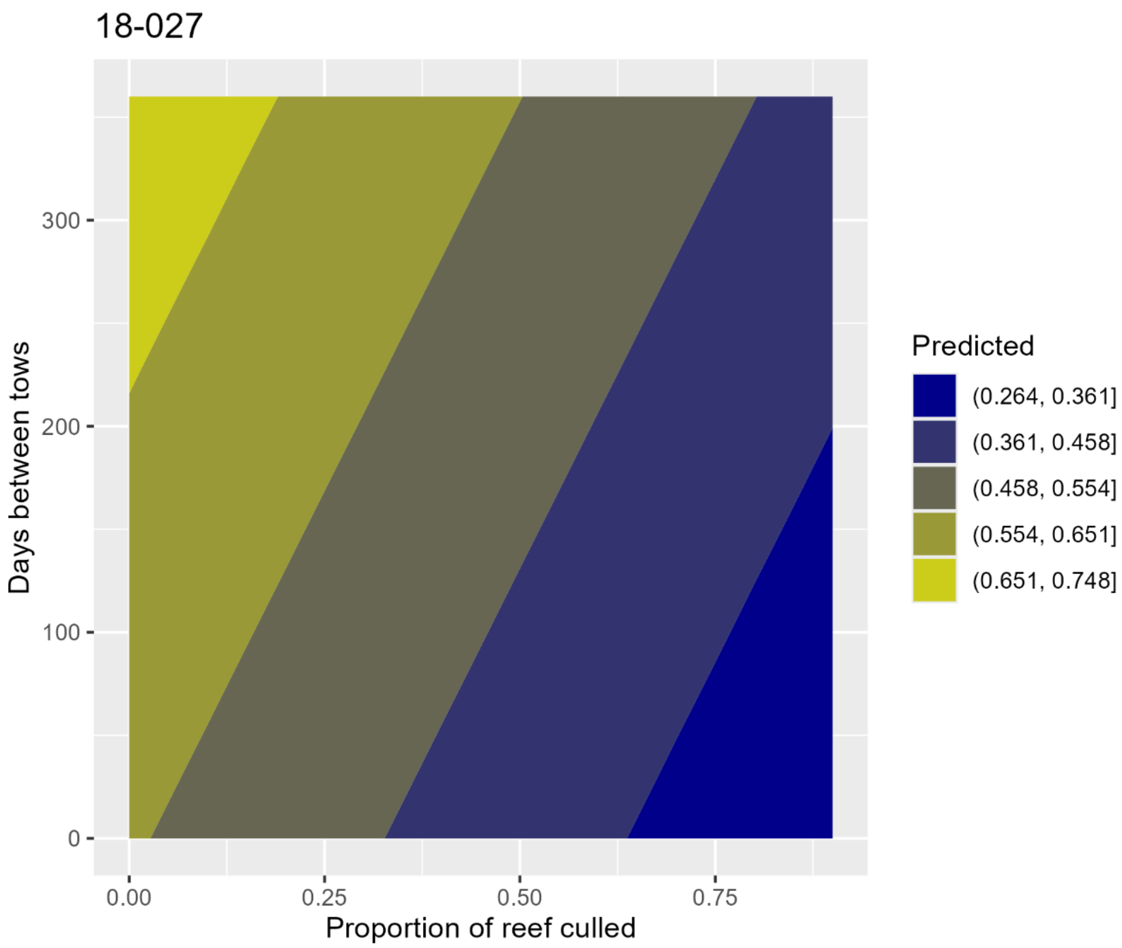

Figure 7. The estimated probability of a site transitioning from "No" to "Yes" cull required at Trunk Reef when varying the proportion of the sites at the reef culled and the number of days between tows.

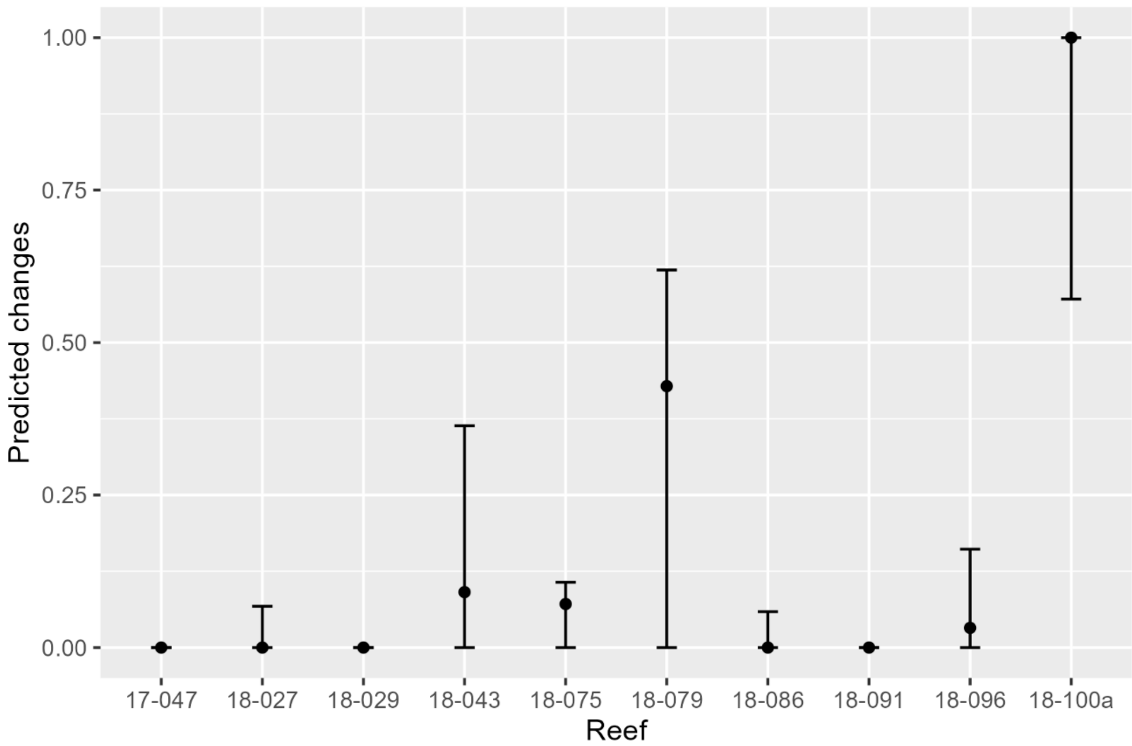

Figure 8. An example illustrating how the manta re-tow frequency model could be used to provide predictions at the reef level.

Importantly, the decision to re-tow is made at the reef level. Not all sites within the reef have the same COTS density or level of control, so the optimum frequency of re-tow varies and there is not a single fixed re-tow frequency for all sites or all reefs. To address this, we developed an algorithm to aggregate the prediction of optimal re-manta tow frequency to the reef level. When users provide the next voyage date, the model uses the previous control data to predict the probability of No-Yes transitions at each site at the reef. This information is then aggregated to the reef level which indicates the proportion of sites for which manta tow data is too old to provide reliable decisions about whether to cull, and thus potential urgency for a re-tow. For example, **Figure 8** shows the model-predicted changes for a number of reefs at a specific future voyage date. While most of the reefs in **Figure 8** show a relatively low level of predicted change, for a large proportion of sites in Reef 18-100a the most recent manta data may have low power to accurately inform decision making, so the control team may need to re-tow reef 18-100a during the next voyage.

To simplify interpretation and make these insights practically actionable by managers, we developed a user-interface to visualise the prediction spatially using recently collected Control Program data (**Figure 9**). Users input the date of voyage and the area of the GBR they intend to visit, then the model uses the previous voyage data to predict the probability of each site transitioning from No to Yes. This information is then aggregated to reef-level, and the urgency of re-manta towing each reef indicated with a colour code.

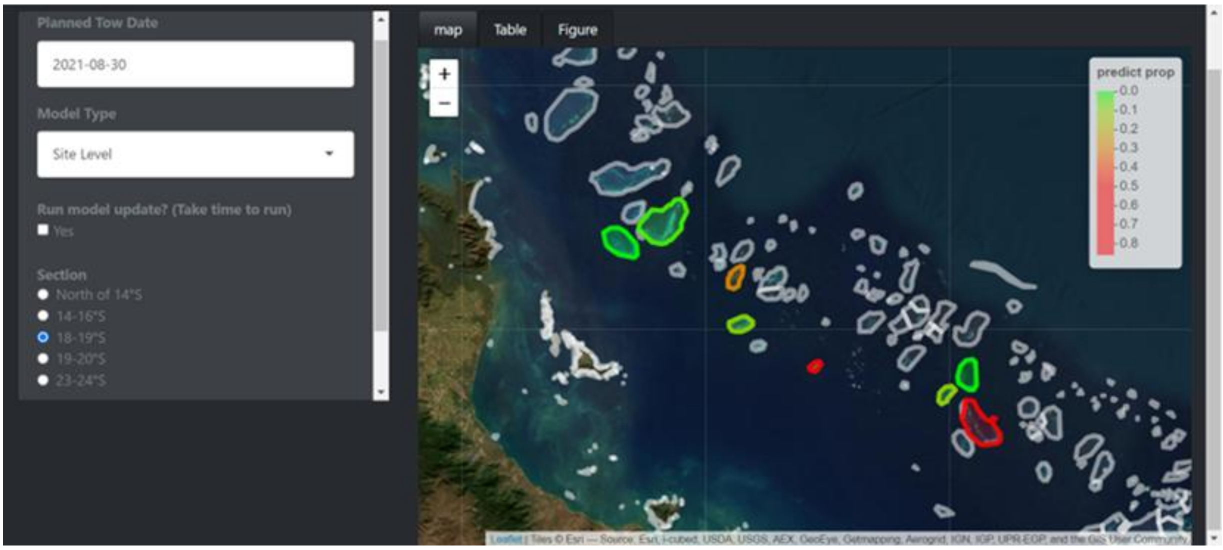

Figure 9. User-interface developed for the estimation of re-tow frequency.

3.2.2 Empirical Analysis – Effort sink reefs

Effort sink reefs can arise from a number of underlying causes, but regardless of what causes a reef to become an effort sink, a defining characteristic is that the reef is an outlier in terms of the amount of effort required to bring COTS densities at all sites of the reef to the Ecological Threshold. Often, however, it is only possible to identify that a reef was an effort sink in hindsight. Being able to identify these outlier reefs early, using the methods outlined below, will allow managers to change strategy or redirect resources efficiently.

The total dive time required to bring cull density of all sites at a reef to below the target Ecological Threshold is highly skewed. Between November 2018 and August 2023, data collected by the COTS Control Program exhibited a median total dive time to bring all sites at a reef to the Ecological Threshold of 4,940 minutes. However, this ranged from 450 minutes at Norman Reef, to 467,067 minutes at John Brewer Reef. Of the 91 reefs controlled, the majority (60%) of reefs had all sites successfully reduced to the Ecological Threshold within 10,000 minutes (**Figure 10**) while 78% reached the threshold by 100,000 minutes.

The results of the GLM model showed that the highest first cull density, the proportion of sites at the reef with scars, and the size of back reef slope all had a strong positive association with the time it took to bring a reef to below the Ecological Threshold. **Figure 10** shows the predicted versus actual total dive times at each reef, with the error bars representing the standard errors of the predicted dive times from the GLM. The majority of the actual cumulative dive times fell within the standard error of the GLM predictions.

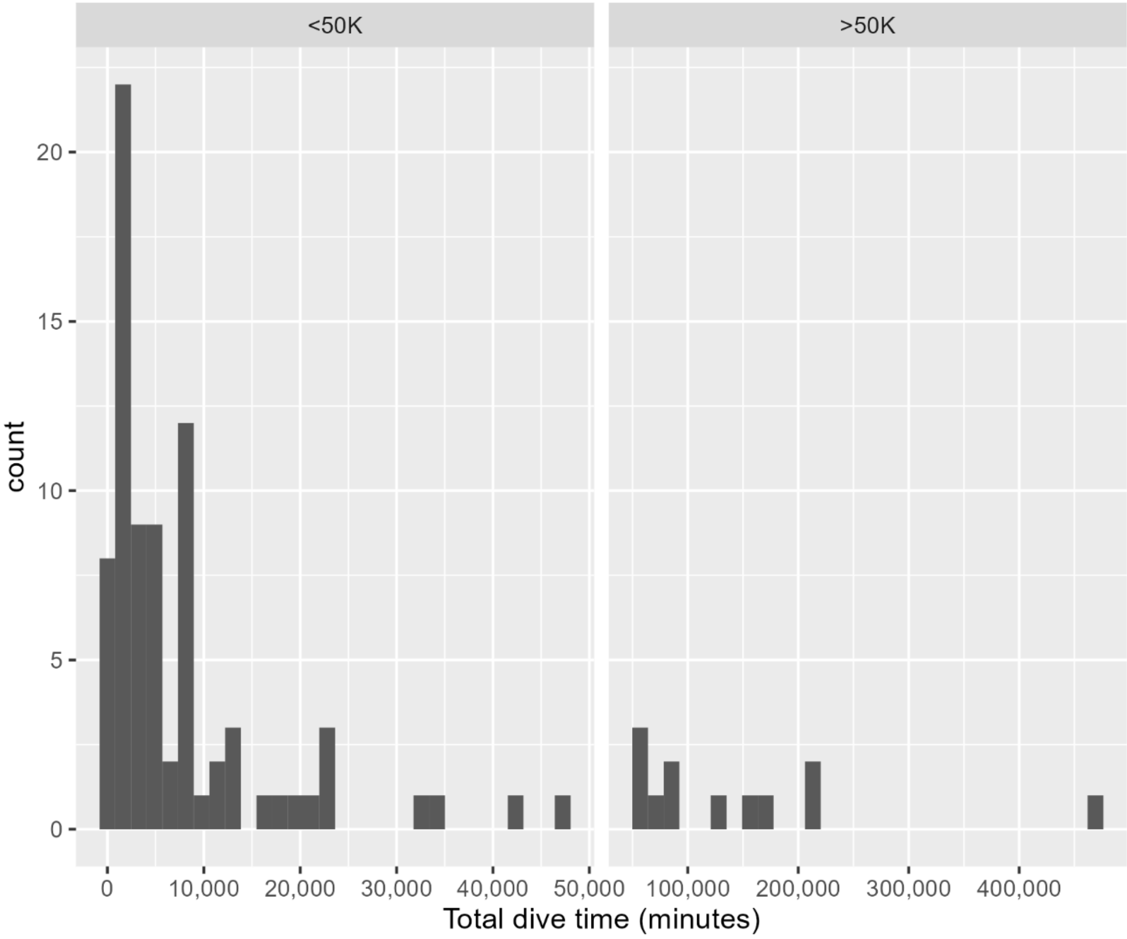

Figure 10. The empirical distribution of total dive time (minutes) used to bring the COTS density of all sites at a reef below the Ecological Threshold.

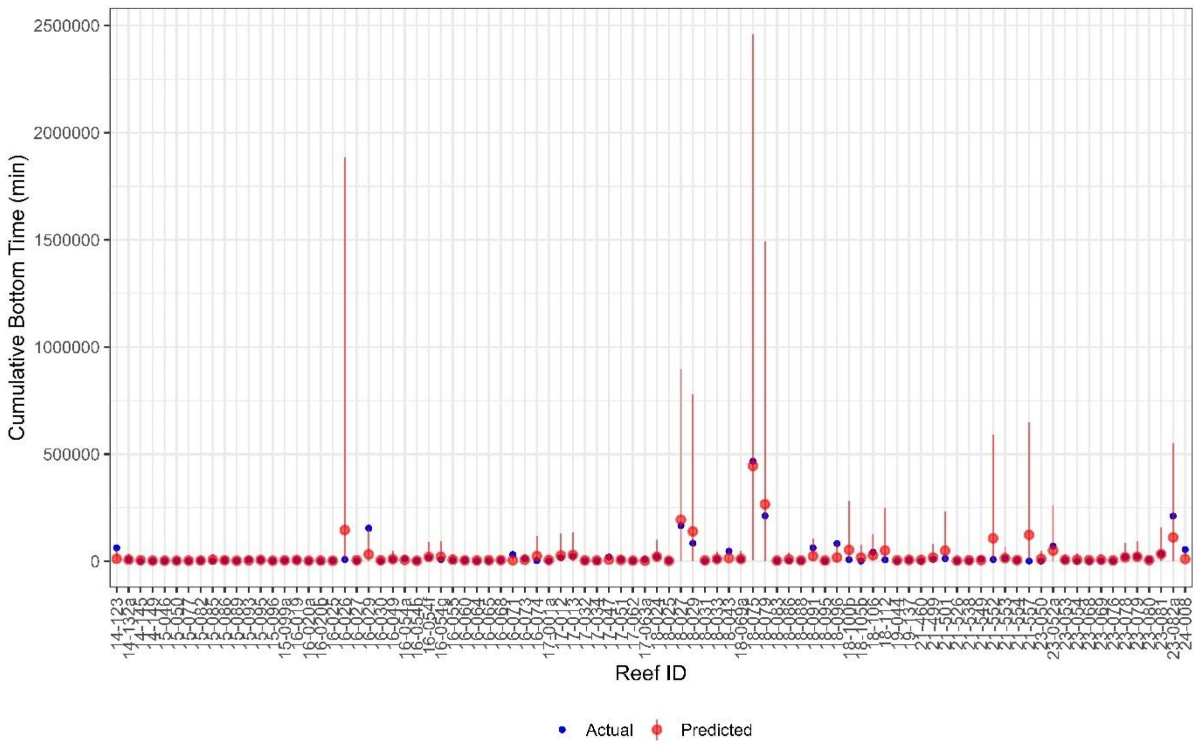

Figure 11. The actual (blue) vs predicted (red) cumulative bottom time in minutes to reduce COTS densities down to the Ecological Threshold, with the red error bars representing prediction interval. Reef 23-077 was excluded from this plot as an outlier.

However, the power of the model in identifying effort sink reefs depends on the threshold defined for the effort sink. If a reef requiring effort of over 100,000 dive minutes is defined as an effort sink reef, the model correctly identified all non-effort sink reefs, and misclassified two of the six effort sink reefs. If the threshold is set at 50,000 dive minutes, the misclassification of effort sink and non-effort sink reefs were 33% and 7%, respectively.

3.2.3 Empirical Analysis – Manta tow to cull density

Using data to inform decision making is at the centre of the ecologically-informed framework that underpins the design of the COTS Control Program. However, to be effective, the right data must be used to inform each decision. Both manta tow and cull data are used to inform multiple decisions in the day-to-day operation of the Control Program, but they provide different insights. To make the most effective use of these two datasets, it is important to understand how the two measures correlate, and which decisions they can best inform.

When the data associated with active outbreak periods was analysed, manta tow was three times more likely to find a scar at a site than it was to observe a live COTS. Of the times when a scar was observed from the manta tow, the cull density was zero approximately one in four times. If a scar was observed and the cull density was not zero, it varied from 0.0006 to 0.95 COTS/min. Although manta tow COTS density was more reliable than the presence of scars in identifying the presence / absence of COTS, there was great variation in the associated cull density (**Figure 12**).

The results of the modelling show that the probability of cull density at a site being zero was significantly associated with both the prevalence of scars and tow density. When scars were commonly observed at a site (i.e. for sites where most of the associated tows reported 10+ scars), the probability of cull density being zero was significantly lower than for sites where most tows detected no scars, or scars were present but not common. Interestingly, there was no difference in the probability of cull density being zero between sites where most tows had scars present (1–10 scars) and sites where most tows had no scars (p=0.410). This predictor was removed from the final model.

As the reported tow density increased, the probability of cull density being zero diminished, and the expected value of cull density increased. The results also found a strong between-reef variation in the association between tow density and the expected cull density, as well as the association between tow density and the probability of cull density being zero.

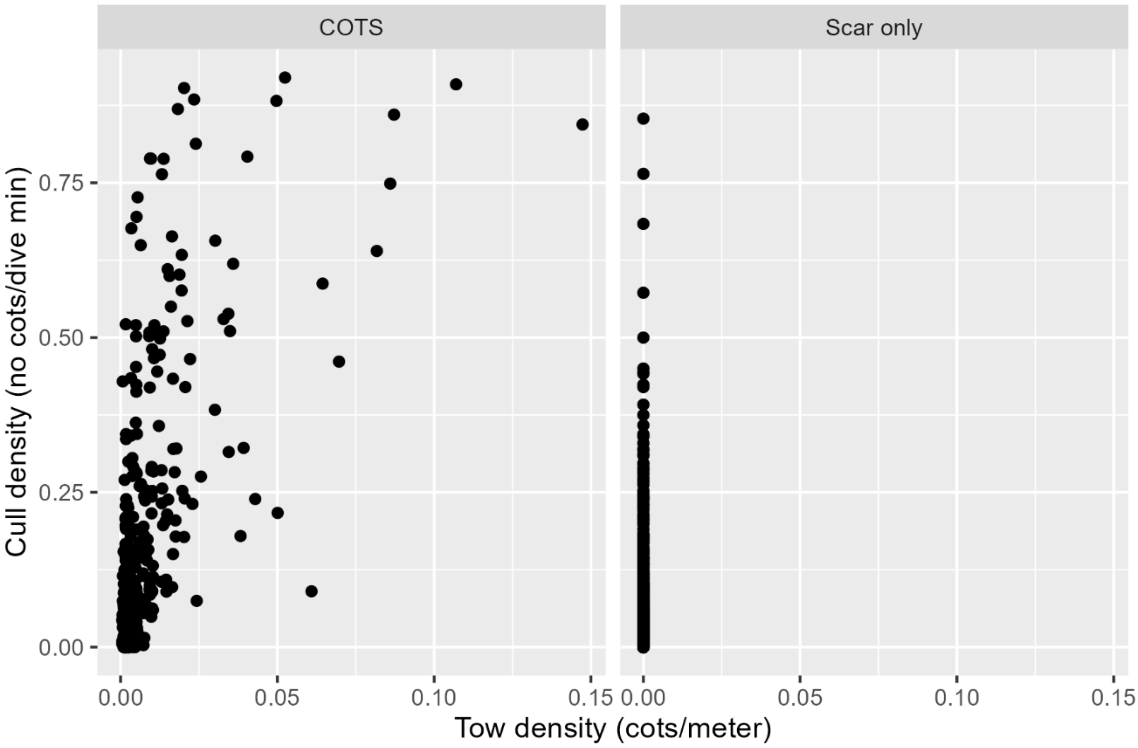

Figure 12. Tow density vs cull density when live COTS were observed during a tow.

Although the tow density and prevalence of scars were significantly associated with cull density, there was still a large level of uncertainty unexplained by the model. For example, **Figure 13** shows the predicted and observed cull density under different observed tow densities at the 16 reefs in the dataset with the most data. The prediction uncertainty increases as the tow density increases and the model did not perform well when the tow density was zero.

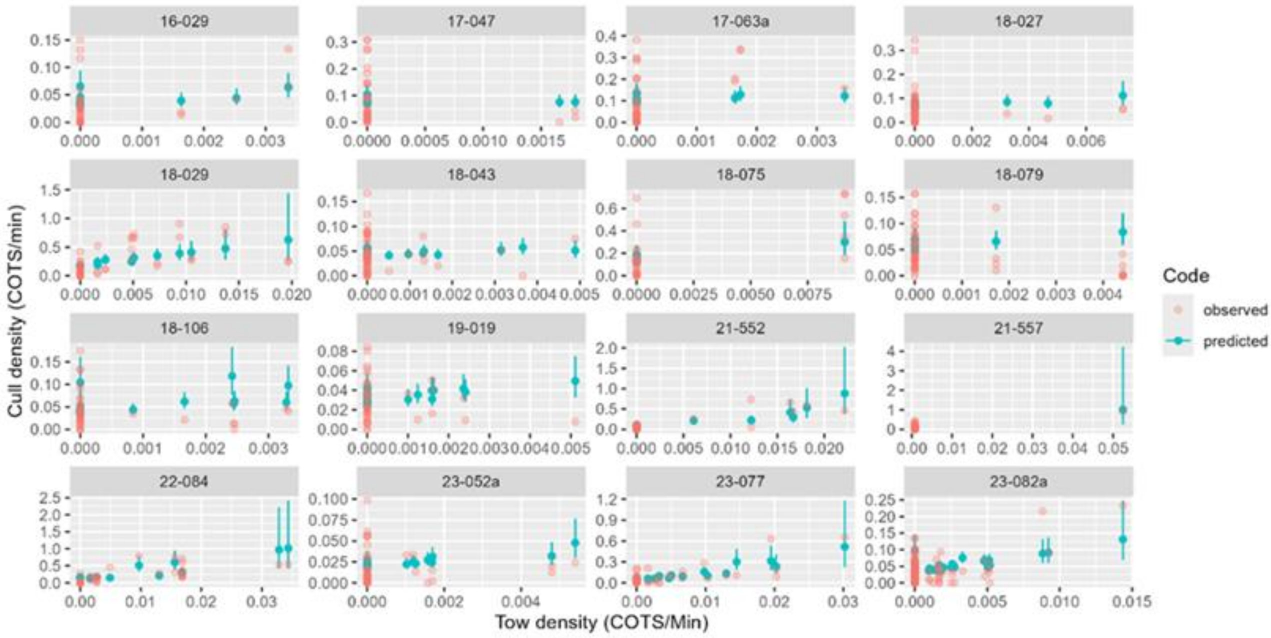

Figure 13. Observed vs predicted cull density of the 16 reefs with the most data.

The COTS Control Program uses manta tow density data to prioritise the order of sites for culling, with sites having high tow densities being prioritised for action over those with low tow densities. If tows associated with a site detect a COTS or scar, the site is identified as a cull site, and divers remove COTS until the cull density is below the Ecological Threshold. Sometimes, however, manta tow data recommends culling at a site that turns out to exhibit a catch rate already less than the Ecological Threshold, leading to a false positive recommendation, unnecessary dive time, and a reduction in program efficiency. **Figure 14** shows the rate at which manta tow generates false positives categorised by different manta tow density. When the tow density was <0.03 COTS / 200 m, the false-positive rate was around 70%. This was reduced to 45% when tow density was between 0.3 to 0.6 COTS / 200 m. When the tow density was one COTS per 200 m, the false positive rate was further reduced to 30%. When only scars were detected, approximately three out of four times the site already had cull density below the Ecological Threshold.

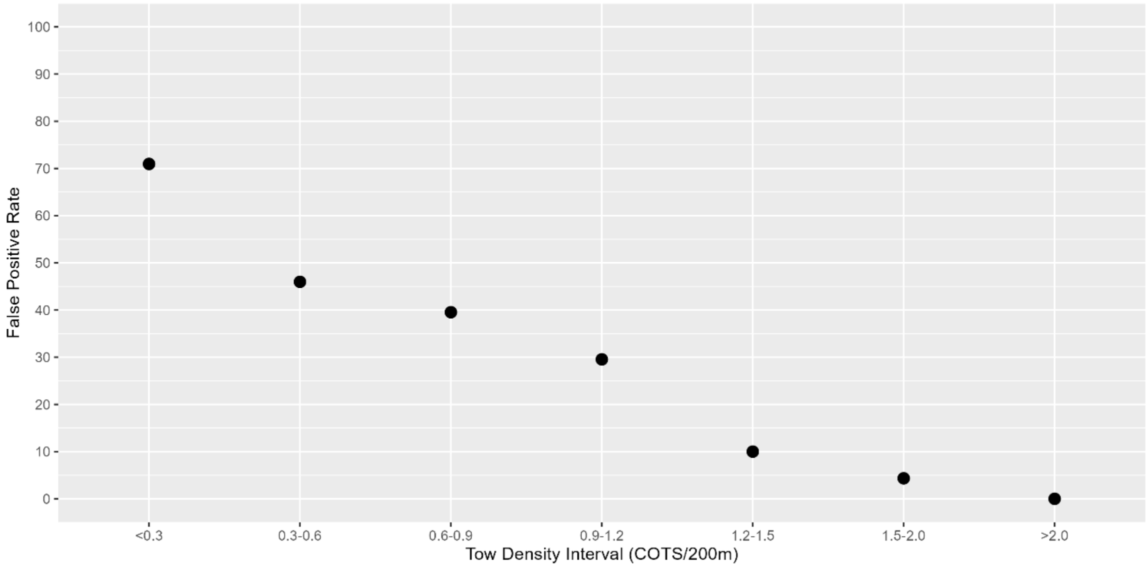

Figure 14. False positive rate vs manta tow density.

3.3 Manager Dashboards

For CCIP research to make a real difference to the way the COTS Control Program runs, detailed results need to be focused and interpreted to address the specific questions managers are seeking to answer, at the time and place they need to answer them. To address this need, CCIP-R-02 developed, tested and delivered six Manager Dashboards running alongside the Reef Authority's existing intelligence platform, to interpret and focus key CCIP results on specific questions identified by managers. Dashboards were refined over multiple iterations of user testing. Below, we outline the implementation of these six Dashboards.

3.3.1 Manager Dashboards – Larval Dispersal Dashboards

Larval dispersal is a critical ecological process driving the spread of COTS outbreaks across reefs in the GBR. Models of larval dispersal are integrated into several components of the COTS Control Program, most notably the annual process by which reefs are prioritised for control. A significant innovation provided by project CCIP-R-05 (Choukroun et al. 2026) was the development of novel COTS larval dispersal ensemble models. However, these models produced complex results with uncertain impacts for management decisions. In response, managers identified a need for research translation tools to better understand deviations from current models, and the subsequent impacts on existing decision-making processes for prioritising reefs. Researchers leading CCIP-R-05 provided the CCIP Research Translation Lead a matrix of average weightings from COTS larval dispersal ensemble models to indicate connectivity between every reef combination. Connectivity reflects the strength of the connection from a given reef to another, indicating the potential for COTS larvae and coral spawn to disperse between reefs. This information facilitated the development of two Power BI Dashboards to address managers' needs.

The first Dashboard is illustrated in **Figure 15**. The Dashboard employs an abstract network visualisation to highlight reefs with a significant number of connections, enabling the identification of critical nodes within the ecosystem. Complementing this, geospatial data is presented, with the size and colour of bubbles representing the number of connections and the strength of connectivity for each reef, respectively. This spatial representation allows for an intuitive understanding of the interconnectedness within the ecosystem. Additionally, the Dashboard includes a scatter plot depicting the relationship between CPUE and the average connectivity of a reef. An interactive matrix table is utilised, displaying the average weights of COTS into and out of each reef to provide a more detailed view.

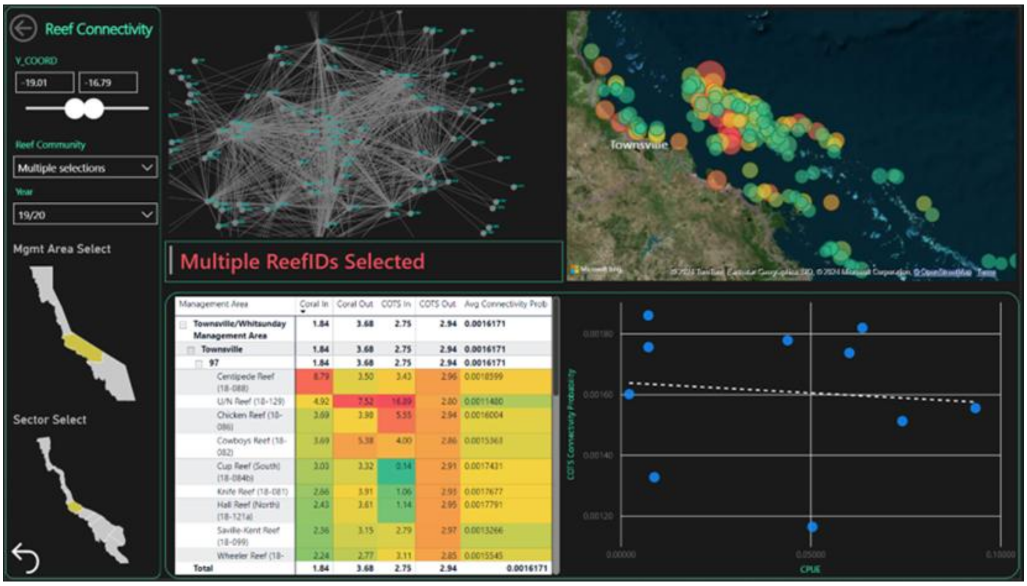

Figure 15. Connectivity ensemble model Power BI Dashboard.

The second Dashboard is illustrated in **Figure 16.** This Dashboard focused on a comparative analysis between the newly developed larval dispersal ensemble model and the models previously used to inform management decisions. The Dashboard features two side-by-side geospatial maps, employing colour to compare connectivity strengths of the models. Additionally, a scatter plot was implemented to compare the average connectivity strength of a reef in the new model against the previous model. The connectivity strengths are represented as percentiles of the management region or the Australian Institute of Marine Science (AIMS) sector they fall within.

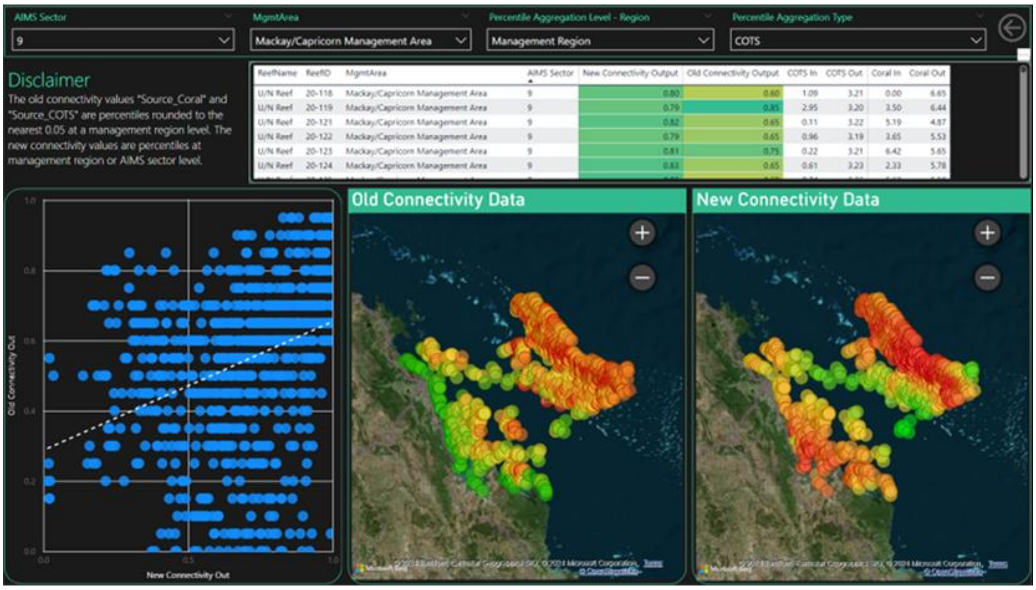

Figure 16. New COTS connectivity ensemble model compared with previous connectivity model Power BI Dashboard.

Together, these two Dashboards provide a set of visualisations allowing managers to thoroughly investigate the implications of the novel larval dispersal ensemble model developed in CCIP-R-05 (Choukroun et al. 2026), compare its outputs with the previous model, and make informed decisions regarding reef management and conservation strategies.

3.3.2 Manager Dashboards – GBR Scale and Economic Modelling

COTS populations at reefs across the GBR are connected by downstream dispersal of larvae. As a result, management actions to remove COTS at a reef provide both immediate protection of coral at that reef, and reductions in larvae arriving at downstream reefs in the region. Understanding the effects of management choices on these large-scale ecosystem interactions is complex and non-intuitive. Historically, researchers have used GBR-scale ecosystem models incorporating coral and COTS population dynamics, such as ReefMod-GBR, to understand these interactions and make recommendations to managers about the most effective Control Program strategies. Under project CCIP-R-04 (Regional modelling, Skinner et al. 2025), ReefMod-GBR was further innovated to test large-scale management practices on metrics such as coral cover, reef outbreaks, and COTS populations. Under project CCIP-R-06 (Cost effectiveness of COTS Control, Scheufele et al. 2025), these scenarios were assessed through the lens of cost-effectiveness. The Research Translation Working Group identified the potential for research translation tools to allow managers to dynamically interact with GBR-scale models of management scenarios to better inform the COTS Control Program strategy.

The Dashboard presented in **Figure 17** visualises the ecological impacts associated with different large-scale COTS management practices. The timeseries plot is dynamic, enabling comparisons between various management scenarios, reef types, or sectors within the specified region for a chosen ecological metric. Based on manager-suggested refinements, the distribution of residuals relative to the average management scenario is displayed. This visualisation required careful implementation to work within Power BI's 30,000 data point limitation, displaying data from a given management region over multiple years. In parallel, a time-independent coordinate plot was implemented to provide a comparative overview of performance of selected scenarios across all metrics. The Dashboard provides managers a mechanism to comprehensively compare the relative impact of different large-scale management scenarios for various metrics, over time and geospatially.

The Economic Analysis Dashboard, illustrated in **Figure 18**, provides a comparative assessment of the same large-scale management scenarios assessed in the GBR-scale management scenario Dashboard, visualised in terms of their performance across a number of economic metrics over time. Additionally, this comparison is facilitated with a time-invariant box plot representation. The visualisations dynamically adjust to incorporate different discount rates and different subsets of reefs. A scatter plot with dynamic axis functionality is employed to generate a Production Possibility Frontier, highlighting the most efficient management scenarios for the selected trade-off. Collectively, the Dashboard enables managers to evaluate trade-offs between management scenarios and the economic implications of a given scenario, both over time and cumulatively.

Figure 17. GBR-scale management practices Power BI Dashboard.

Figure 18. Economic Analysis Dashboard. The Dashboard visualises the performance of various management strategies against a number of economic metrics, such as cost-effectiveness.

3.3.3 Manager Dashboards – Identifying Effort Sinks

Although most reefs managed by the Control Program take a reasonable amount of time to bring all sites to the Ecological Threshold, some outlier, or "effort sink", reefs take more time than would be expected compared to other similar reefs. These reefs require a disproportionate share of resources, preventing efforts at other more easily controlled reefs. Managers identified a need to understand which reefs were likely to become effort sink reefs to allow them to know when to change management strategy, when to leave a reef, or when to avoid prioritising a reef that is likely to be an effort sink. Project CCIP-R-02 developed an empirical analysis to quantify which reefs were likely to become effort sinks, as described in this report in sections 2.2.2 and 3.2.2. The "Effort Sink" dashboard depicted in **Figure 19** was developed to allow managers insights into potential "Effort Sink" reefs to better manage available resources.

As part of CCIP-R-02, a linear mixed-effects model was developed to characterise the expected time required to bring a cull site under the ecological threshold. The fixed effects included the density of COTS observed with manta tow, prevalence of scars observed and the initial cull density. Reefs with adequate data had a random effect introduced to characterise this relationship more accurately. A tabular dataset was produced with the model for all reefs within the Control Program, indicating initial conditions, cumulative dive time and whether the site is under the Ecological Threshold.

The Effort Sink Dashboard incorporates COTS Control Program data to offer a point of comparison with the modelled results. This integration addresses a clear need articulated by management during the draft feedback stage. Time series control data is displayed with stacked column charts to differentiate cohort sizes, complemented by a geospatial mapping component that highlights high-density COTS locations within a reef. Line graphs depict the modelled cumulative time required to bring selected sites under the Ecological Threshold for specified initial conditions. The legend of these plots indicates the initial manta tow density, but it can be dynamically updated to display initial cull density. Furthermore, the Dashboard incorporates a color-coded matrix table, to facilitate comparison of effort requirements across different sites and initial conditions.

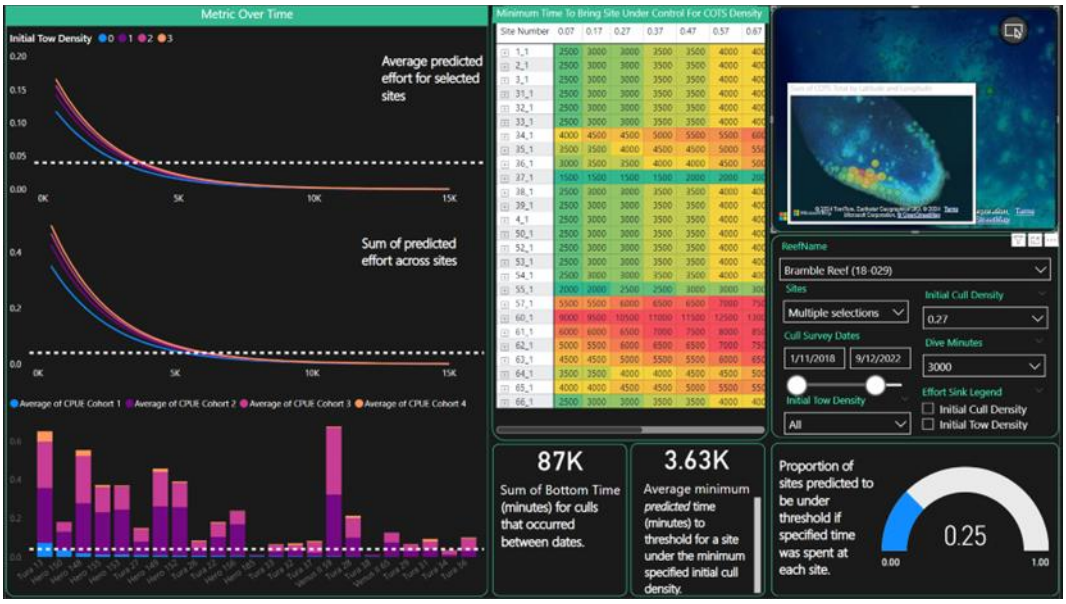

Figure 19. Effort sink Power BI dashboard.

3.3.4 Manager Dashboards – Early Warning System

The COTS Early Warning System (EWS) was designed to provide early insight to managers regarding the build-up of Primary and / or escalation of Secondary COTS outbreaks. The EWS is built upon data streams from the Control Program itself, partner monitoring programs, including the AIMS Long-Term Monitoring Program (LTMP), data from Queensland Parks and Wildlife Service's work under the Reef Joint Field Management Program (RJFMP), Eye on the Reef (EotR), as well as data from eReefs and research outputs from CCIP. The system was initially designed for two specific use cases: 1) to monitor the intersection of variables driving initiation of primary outbreaks and spread of secondary outbreaks, and; 2) to provide a "track and trace" interface to allow managers and operators to identify potential sources and sinks of observed COTS populations. Both of these use cases were developed based on an emerging need from managers to receive early intel on outbreaks, and they were designed to provide regional level guidance to the Reef Prioritisation Process by indicating the outbreak phase of management regions and sectors of the Marine Park.

The Early Warning System monitors the temporal and spatial intersection of 1) COTS adult densities (COTS Control Program data; SALAD data from project CCIP-P-04, Pratchett et al. 2025); 2) COTS DNA presence / absence (eDNA data from project CCIP-D-03, Uthicke et al.

2025); 3) fast growing coral cover (AIMS data; RJFMP data; COTS Control Program data; Regional Modelling data from project CCIP-R-04, Skinner et al. 2025); 4) modelled phytoplankton concentrations (eReefs data; larval survival data from literature); and 5) clustering metrics (connectivity data from project CCIP-R-05, Choukroun et al. 2026) to identify reefs / clusters that could be at risk of promoting a primary outbreak. The integration of these datasets included the creation of an eReefs extraction tool and data sharing between many CCIP projects. The tool focuses primarily on providing the ability to aggregate data from various indicators at reef cluster and sector levels (**Figure 20**). This provides managers an easy-to-interpret early indication of potential or emerging problem areas.

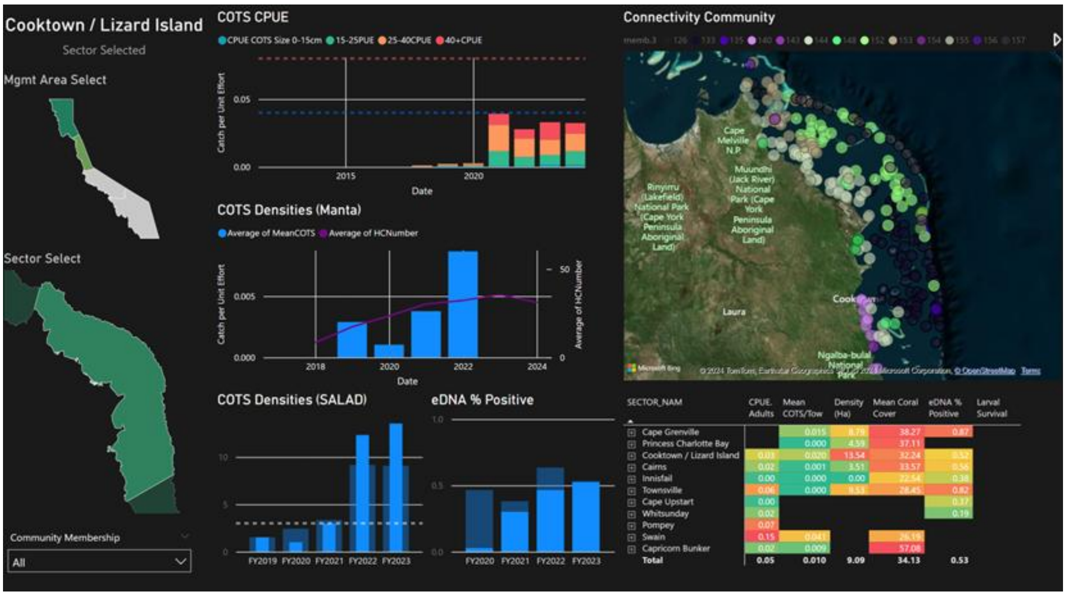

Figure 20. Main page of COTS Early Warning System. Provides a simplified view of the main data stream relevant to assessing risk of primary outbreaks.

The development of the Dashboard user interface built on previous the Reef Authority work and occurred in close collaboration with managers, going through multiple stages of refinement based on user feedback. Initial designs were focused on eDNA and SALAD data from CCIP projects CCIP-D-03 (Uthicke et al. 2025) and CCIP-P-04 (Pratchett et al. 2025) respectively. This version of the Dashboard provided insight into the emerging primary outbreak near Lizard Island (and Cape Grenville), facilitating management decisions to reallocate Control resources further north and to invest in control in the Far North region in the 2024/25 Annual Work Plan.

Based on feedback from managers, the initial Dashboard design was refined to include larval survival indicators (Chlorophyll *a*), temperature and salinity for each reef in the GBR. This created a larval survival metric that could be combined with adult density estimates to provide insights into the outbreak potential of a region. The refinement also included a prototype definition of COTS larval connectivity clusters that divide the GBR into smaller clusters of ~20–50 reefs to allow for the outbreak metrics to be viewed at the cluster level. In future, this component will incorporate larval connectivity modelling outputs from project CCIP-R-05 (Choukroun et al. 2026) to improve the definitions of reef clusters.

The main landing page of the Dashboard (**Figure 20**) tool provides the user with three levels of spatial aggregations by which the Dashboard can be filtered: Management Area, Sector, or Community Cluster. The middle panel displays annual time series charts for the selected spatial area including COTS CPUE, COTS per manta tow, hard coral cover, and COTS estimated from SALAD and eDNA sampling. These charts are aimed at identifying when critical thresholds for COTS densities have been breached to allow managers to assess the risk of escalating COTS outbreaks. Connectivity communities are displayed on the map and sector level summaries of each of the indicator variables are included in a matrix visual in the bottom left.

The second exploratory page of the EWS (**Figure 21**) offers deeper insight into the locations of eDNA and SALAD samples, as well as time series data related to COTS larval survival (Chlorophyll *a*, temperature and salinity). This time series is aimed at highlighting periods when critical thresholds for COTS larval survival are breached and when Chlorophyll *a* levels exceed 90th percentile for the region in question to provide insights into the increase in larval survival relative to the focal area.

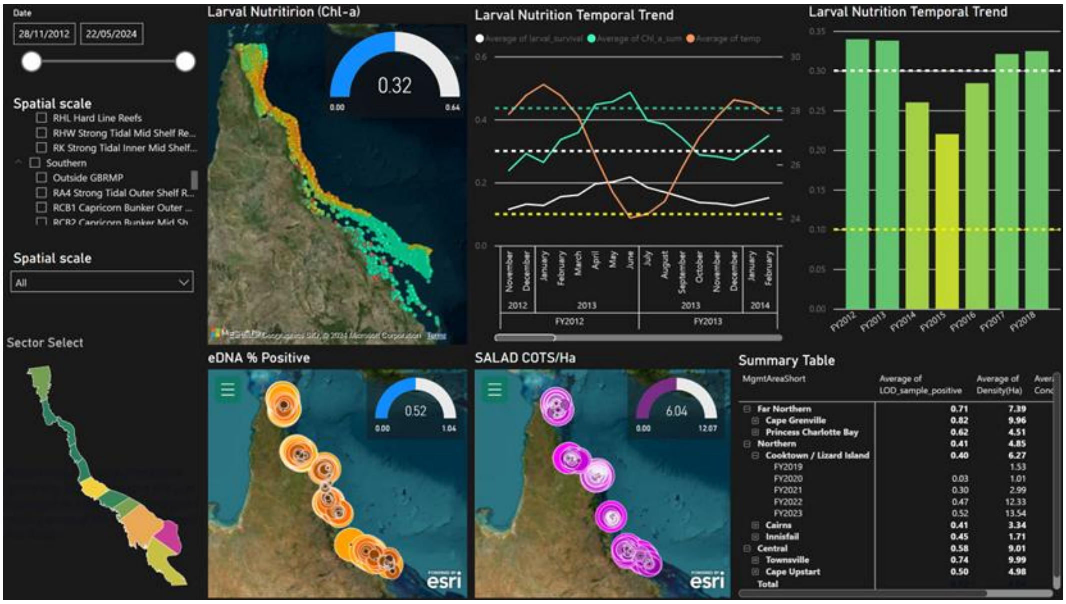

Figure 21. Secondary exploratory page of early warning system. Offers users the ability to spatially and temporally interrogate eDNA, SALAD and larval nutrition data.

3.4 On-Water Decision Support System

Effective decisions also need to be made on-water during day-to-day operations. The COTS Control Centre is an On-Water Decision Support System which aims to help on-water operators interpret cull and manta tow data to decide which site to deploy cull divers, in what order sites should be culled, and when a site or reef can be considered complete. To do this effectively, the Decision Support System needed to be robust, extensible, and flexible, capable of leveraging data and advanced processing to produce reliable decision recommendations across a fleet of vessels, both independently when network connectivity is not available, and in synchronisation when it is. While the high-level design and development approach for the system is outlined below, the use of standard web development frameworks, code comments and documentation throughout the process paves the way for long-term maintenance by an external entity.

The software system is composed of three distinct modules to separate responsibility and promote scalability. It employs a distributed server architecture, where each vessel is equipped with a small Linux-based server device. This configuration allows any number of clients to connect locally to the server on the vessel without requiring an internet connection. When an internet connection is re-established, a shore-based server hosted at CSIRO updates the databases stored on the distributed servers, ensuring data synchronisation across the system. This server could be replaced by any central server that is hosted in a public cloud or organisational data centre such as the Reef Authority. The backend module that handles client requests is an ASP.NET Core API, which connects to a MySQL database. The processing module comprises a subset of classes and functions from the .NET application, as well as several external scripts that the application can invoke. The front-end module is an Ionic React Progressive Web App, making it device-independent and accessible across various platforms. This ensures a consistent user experience that easily integrates with the backend API to facilitate processing and decision making.

3.4.1 On-Water Decision Support System – Backend Module

The backend of the On-Water Decision Support System is responsible for storage and retrieval of datasets, as well as running the reusable digital workflows (described in Section 3.1) both online and offline. The backend consists of two applications: one deployed on the On-Water Server, the second deployed in the cloud and remotely accessible by the On-Water Server. This hybrid on-vessel / cloud architecture ensures that the reusable workflows can run independent of mobile device configurations and operating system limitations.

The backend of the ASP.NET Core API is structured to optimise interaction with the front-end interface, incorporating three primary controllers: Sites, Reefs, and Files. These controllers provide essential endpoints, facilitating client access to site-specific information, reef conditions, and file management functionalities, respectively. The business logic is encapsulated within the service classes, ensuring a clear separation of concerns. The data access layer, leveraging Entity Framework Core, establishes connections to a MySQL database, supplying the necessary data to the service layer.

3.4.2 On-Water Decision Support System – Processing Module

The On-Water Decision Support System is designed to be able to run reusable digital workflows on vessel on-demand. However, there are administrative challenges in running such reusable workflows on mobile devices, due to operating systems (Android and iOS) limitations. In addition, the processing power of mobile devices are not consistent and may vary from device to device, or even within a single device based on battery power settings. Instead of running the reusable workflows on the mobile devices hosting the PWA user application, therefore, the reusable workflows run on the On-Water Server when triggered by the user from the PWA.

While the infrastructure architectural challenge of running reusable workflows was solved by deploying the processing logic in the On-Water Server, there was a second application architecture challenge that was resolved by incorporating the reusable workflows in the data model. A reusable workflow is defined as an entity in the data model, which is associated with the scripting language for the workflow, which can be automatically triggered through the PWA.

The module has the capability to execute external scripts to incorporate established data processing methods. This includes the reusable workflow used to ingest control data from the Reef Authority's EotR database, or JSON exports from other applications, like the COTS Control Program data collection applications. Class methods within this module implement decision tree processes to determine the optimal order for culling sites, based on current literature. Additional class methods handle processing of geospatial and data related to reef management to steer and inform providers on water. The development of the processing module into the .NET API facilitates easy access to clients.

3.4.3 On-Water Decision Support System – User Interface Module

The key user-facing component of the application is the User Interface Module (**Figure 22**), which captures user interactions. The user interface module allows the users to: 1) access existing data and insights through advanced visualisations such as maps; 2) ingest new data; 3) trigger the running of reusable digital workflows, and; 4) leverage the decision support system. The User Interface Module has been implemented as a PWA. The codebase consists of a frontend web application, that can be implemented as a cross-platform mobile application. Following best practice, the code for the frontend is completely decoupled from the backend, and interacts with the backend though web APIs. The frontend web development framework for the User Interface Module is React, which is supported by Microsoft and has a large community of developers and contributors.

The adoption of PWA for the User Interface Module enables a "code once and use everywhere" methodology, while ensuring a consistent user experience across devices. This approach allows users to interact with the app in the same way across any laptop or mobile device, largely independent of device capabilities, operating platform, and configuration. This also avoids complexity around installation processes on different platforms, and the potential for breaking changes as a result of system security updates.

The front end of the User Interface Module provides an interface for visualising reef data and creating culling plans. The default home page displays a satellite image view of the GBR with reef polygons indicating the management modes and providers responsible for each reef. Users can select or search for specific reefs, triggering a small overlay that displays relevant management information. This overlay serves as a gateway to a detailed view page for the selected reef, where users can view historical information about the reef relevant for the upcoming voyage, ingest new cull data from the Reef Authority data collection apps, or create a cull plan in a single button click. A satellite image on the view page is overlaid with cull site polygons that illustrate relevant site-specific information when selected. This satellite imagery is provided to a visualisation component, pigeon maps, with a custom API point. This facilitates offline mapping and allows alternative imagery to be used as requirements change.

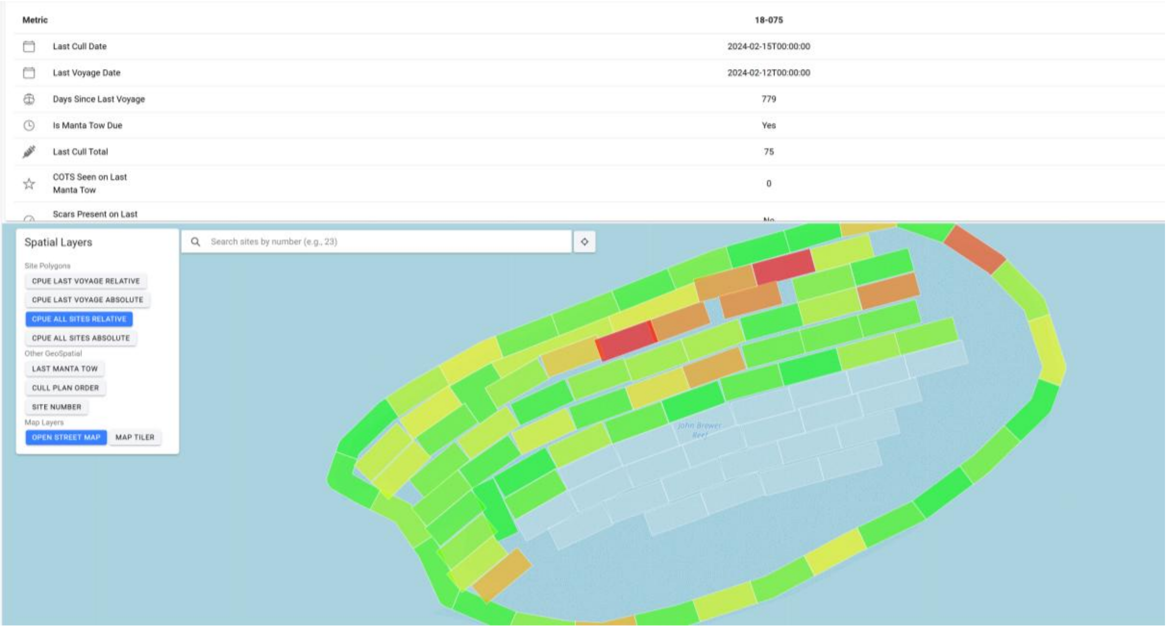

Figure 22. Snapshot of the User Interface of the On-Water App.

4. DISCUSSION AND OUTPUTS

CCIP-R-02 has provided significant innovations across four key areas where data is used to inform decision making in the COTS Control Program.

The speed and simplicity with which Control Program data can be prepared and shared with researchers has been significantly improved through the development of the Reusable Digital Workflows. The approach provides a platform to drive future innovations to speed up the way research data informs management decisions. The open design, the ability to reuse methods, and ability to string methods together to act as a pipeline create an innovation multiplier, allowing innovations in one research area to drive new innovations in the another.

Empirical analysis of the Control Program data provides new insights and opportunities for the Program to adapt its structure and operations. The findings offer the potential to increase Program efficiency by informing the optimal frequency of manta tow surveys to support decision making around site activities, while the effort sink analysis will allow managers to identify outlier reefs early so that they can change strategies or invest resources elsewhere.

Based on questions identified by managers, CCIP research has been interpreted, focused, combined, and delivered digitally to managers through six Manager Dashboards. These purpose-built research translation tools allow managers to understand new ensemble models of larval dispersal and their impacts on the reef prioritisation process; to dynamically explore how different management strategies will affect coral trajectories across the GBR over the coming decades, and at what economic cost; to identify effort sink reefs; and to provide early and actionable insights regarding the initial build-up of COTS outbreaks, based on data aggregated across CCIP and beyond.

New methods and tools to more effectively inform on-water decision making have been designed and developed. The COTS Control Centre will help on-water contractors decide which site to drop cull divers, in what order sites should be controlled, and when a site or reef can be considered complete based on data collected by the COTS Control Program itself. This decision support system has been developed using modern techniques to provide a robust, extensible, and flexible platform providing advanced processing across a fleet of vessels working in a complex environment to reliably inform on-water decisions.

4.1 Reusable Digital Workflows

Reusable Digital Workflows are vital for efficient data sharing, and central to the innovation multiplier of science translation and code reuse across CCIP. The combination of the CCIP Information System as part of project CCIP-R-01 (Fletcher and Rezvani 2026) and the automated, cloud-hosted Reusable Digital Workflows developed here represents a major digital transformation opportunity, improving the way data are shared and utilised across the COTS research and management space. Automated analysis will speed up data flows from COTS managers to researchers, between researchers, and from researchers back to managers. Establishing these workflows as standard practice for data preparation, including when responding to external data sharing requests, represents an important next step, and is discussed further in the management recommendations in Section 5. Open analysis methods, shared via the CCIP Information System, will allow improvements in one area to drive new ideas and methods in surrounding areas, multiplying innovation.

As part of this project (CCIP-R-02), two key workflows have been developed, increasing the efficiency of research data sharing while demonstrating a general platform approach that will underpin many future workflows. The core Control Program Data Preparation automated Reusable Digital Workflow prepares data from the Control Program in the standardised format required by researchers. This is important because most research needs *intermediate data*, such as COTS density estimates, which must be generated from *primary field data*, such as cull rates recorded by the COTS Control Program, as discussed in the Final Technical Report for project CCIP-R-01 *Information Infrastructure to Underpin and Accelerate Innovation in COTS Control* (Fletcher and Rezvani 2026). The Control Program Data Preparation workflow performs these common data processing steps, standardises data so that it can be ingested directly into research pipelines, and increases the speed with which research data can be generated from Control Program data from months to hours.

The Manta Tow To Site Reusable Digital Workflow maps manta tows to nearby cull sites to allow it to guide site-scale management actions. This is a central need for effective day-to-day on-water decision making about which site to dive next at a reef. There are several existing manual and automated methods of completing the task across on-water operators, managers, and researchers. Each method has different strengths and weaknesses. The modular design of the Manta Tow To Site workflow allows different methods to be tested and the optimal method selected for specific tasks, then integrated into information flows across researchers and managers. This ability is vital in the context of a mixed research and operational system where decision support algorithms are likely to be innovated over time, but operational decisions must be reliably informed with stable algorithms until a formal decision is made to adopt a new algorithm.

4.2 Empirical Analyses

The COTS Control Program was designed to use data to both inform day-to-day operational decision making, and adaptively refine the structure of control operations over time. The body of data collected by the Control Program since 2018 provides an important opportunity to improve the way we use data to inform decisions, and adaptively refine key Control Program parameters. Here, we analysed the optimal re-manta tow frequency using the concept of data currency, specifically by examining how often a site transitioned from no culling required to culling required; and tested methods to identify effort sink reefs by analysing the number of dive minutes needed to reduce reef-wide cull density below the Ecological Threshold.

Re-manta tow frequency: Since 2018, six-weekly manta tows have been used by the Control Program to decide the order in which sites around a reef will be culled. The six-week interval between tows was a conservative estimate based on expert input and the data available when the Program was designed. We used data collected by the Control Program to assess how much time can pass following a manta tow before the quality of the decisions it recommends decreases and a new manta tow is required for effective decision making. The analysis identified the instances in which the recommendation for whether a site needed to be culled changed from “No” to “Yes” from one manta tow to the next. The probability of a “No-Yes” transition varied across reefs, and depended heavily on the level of COTS outbreak at a reef, and control activities that had occurred at a site. The model showed little difference in the probability of a No-Yes transition between manta tows being conducted every 42 days and manta tows being conducted every 100 days. The analysis requires further investigation, but it suggests that the current six-week (42 day) interval between manta tows could potentially be extended to up to 14 weeks (100 days) at intensively controlled reefs without a significant increase in the risk of missing a No-Yes transition i.e. the re-emergence of COTS at a site following culling. Such a change could allow a greater proportion of vessel time to be redirected from surveillance to culling activities.

Effort sink reefs: In this project, effort sink reefs are defined as those requiring an excessive amount of effort to reduce the COTS density at all sites to below the Ecological Threshold. The model found that the highest initial cull density, and the proportion of sites at the reef with scars, were positively associated with the total effort required. These results are not surprising, as the effort required is directly linked to the size of a COTS population on the reef. Using this model to determine whether a reef is an effort sink requires definition of an “excessive” amount of effort. As reported in the results, of the 91 reefs included in the analysis, only 12 reefs required more than 50,000 dive minutes. Moreover, of the 79 reefs that required less than 50,000 dive minutes, 78% of reefs required less than 10,000 dive minutes. These results confirm that a small number of reefs required significantly more effort than most reefs. Although this model allows prediction of the amount of effort required to bring all sites to the Ecological Threshold, based on initial COTS density and reef habitat data, we advise using the predictions with caution, because the way the data was structured provided limited power to understand skewness and the different causes of outlier reefs. Understanding these causes is likely to be important to identify appropriate management responses in different circumstances.

Comparing manta tow and COTS cull densities: One clear opportunity for future efficiency gains are methods that can reduce the high false positive rate of manta tow data at low COTS densities. Our analysis comparing manta tow to cull density showed that 75% of sites with scars observed during manta tow already had COTS densities below 0.04 COTS / min. Each time manta tow recommends culling at a site that turns out to have few COTS, a significant amount of effort is expended to drop cull divers at a site that they needn’t have culled. This problem is amplified when most of a reef has been culled to near or below the Ecological Threshold, because manta tow is particularly insensitive to low COTS densities. Methods for informing decisions through a combination of cull and manta data, or new computer vision monitoring methods, could address this and improve Program efficiency.

4.3 Manager Dashboards

Research makes a difference in the real world when it informs decisions made by managers. The innovations driven by CCIP-R-02 have helped drive real world impact for research across CCIP by interpreting and digitally delivering research outputs from CCIP projects to managers at the Reef Authority, at the time and place where decisions need to be made. The CCIP

Research Translation Workshop Group brought together managers and researchers to identify and prioritise management needs that could be addressed by CCIP research. The Research Translation Lead, Ethan Waters, worked across organisations, and closely with managers, to interpret CCIP research and iterate the design of six digital Dashboards so they provided managers the specific information they need to make decisions.

Two Larval Dispersal Dashboards were developed in response to manager requests. Larval dispersal is a critical ecological process driving the spread of COTS outbreaks across reefs in the GBR, and vital to the Reef Authority's reef prioritisation process. A significant innovation provided by project CCIP-R-05 (Choukroun et al. 2026) was the development of novel larval dispersal ensemble models. However, these models produced complex results with uncertain impacts for management decisions. The first Dashboard allows managers to visualise the highly connected reefs in the network, combined with geospatial data, to provide a more intuitive understanding of interconnectedness within the ecosystem. The second Dashboard highlights where the new larval dispersal models developed under CCIP-R-05 diverge significantly from legacy models, allowing managers to thoroughly investigate the implications of the novel larval dispersal ensemble model, and make informed decisions regarding reef management and conservation strategies.

Two Dashboards were developed to allow managers to explore how different management strategies will drive coral trajectories over the coming decades across the entire GBR, in terms of both ecological and economic metrics. Because COTS populations across the GBR are connected by downstream dispersal of larvae, management actions to remove COTS in one region provide both local and downstream benefits. Understanding the effects of management choices on these large-scale ecosystem interactions is complex and non-intuitive. The first Dashboard allowed managers to dynamically explore how different management strategies affected coral cover and the number of outbreaking reefs from today to 2050, using the outputs of the GBR-scale ecosystem model ReefMod-GBR as part of project CCIP-R-04 (Skinner et al. 2025). The second Dashboard allowed managers to assess the performance of these same management strategies through the lens of economic cost-effectiveness, using the methods and research outputs developed under project CCIP-R-06 (Scheufele et al. 2025).

The Effort Sink Reef Dashboard was developed in response to manager requests for tools to help identify reefs that required a disproportionate or unexpected amount of resources to reduce COTS densities across all sites to the Ecological Threshold where coral growth could outpace COTS damage. The Effort Sink Reef Dashboard presents research results of a linear mixed-effects model developed to characterise the expected time required to complete control at a reef, visualised against COTS Control Program data to offer a point of comparison with the modelled results. The insights enabled by this information will allow managers to better manage available resources.

Finally, the Early Warning Dashboard was initiated by managers to provide early and actionable insights regarding the initial build-up of COTS outbreaks. For the first time, this tool aggregates data from a variety of research and management datasets from both the COTS Control Program and other GBR sources, providing managers an easy-to-interpret early indication of emerging problem areas. Of particular relevance to CCIP, the Dashboard incorporates eDNA data from project CCIP-D-03 (Uthicke et al. 2025), SALAD survey data from project CCIP-P-04 (Pratchett et al. 2025), GBR-scale model projections from project CCIP-R-04 (Skinner et al. 2025), and larval connectivity data from project CCIP-R-05 (Choukroun et al. 2026).

4.4 On-Water Decision Support

An effective and ecologically-informed COTS Control Program benefits from decision support underpinned by cutting-edge research at all scales. In addition to the annual, monthly and weekly decisions being made by COTS Control Program managers, there are a range of day-to-day decisions that need to be made on-water by the operators implementing COTS control on individual reefs. As part of CCIP-R-02, the COTS Control Centre On-Water Decision Support System was developed to address on-water needs using modern software designs compatible with on-water operators' practices, the COTS Control Program data collections apps, and the CCIP Information System developed as part of CCIP-R-01 (Fletcher and Rezvani 2026). The new COTS Control Centre uses a modern Progressive Web App architecture accessible across multiple device platforms and a hybrid architecture enabling both cloud sync for data sharing across the fleet and robust local operation when vessels have no network connectivity.

The COTS Control Centre is composed of three components: a hybrid data ingestion system, an advanced decision support processing module, and a platform-independent user interface module. The system employs a distributed server architecture, where each vessel is equipped with a small Linux-based device that manages synchronisation with the CCIP Information System, runs the advanced Reusable Digital Workflows, and manages communications between multiple mobile user interface devices on-water. The decision support processing module implements the IPM framework underpinning the COTS Control Program, using historical data combined with data collected on-vessel during the current voyage to guide on-water decisions about which sites to dive at next. The user interface allows on-water operators to interact with the decision support system and view historical data in context to help inform their own decisions on-water.

4.5 Reflections

The stand-out success for project CCIP-R-02 has been the ability to interpret, translate and deliver research to address the questions that managers need to answer. Research makes a difference in the real world when it informs decisions made by managers. But to be effective, the information that is provided needs to be focused on the questions that managers need to answer, and it needs to be provided at the time and the place that decisions need to be made. This is precisely the goal of the manager-focused Dashboards and the COTS Control Centre On-Water Decision Support System. Through the CCIP Research Translation initiative and the close, iterative feedback between managers and researchers it has enabled, the Dashboards have been designed and customised to directly address managers' needs. This has opened new impact pathways for the innovations developed across CCIP.

The second major innovation provided by CCIP-R-02 has been in establishing the foundation for future digital transformation. In conjunction with the CCIP Information System developed as part of CCIP-R-01 (Fletcher and Rezvani 2026), the Reusable Digital Workflows in CCIP-R-02 provide a platform that makes data sharing more efficient and consistent between the Control Program and researchers, between researchers and other researchers, and from research outputs back to Control Program decisions makers. More importantly, however, it provides a digital foundation on which to build future innovations. As new monitoring methods begin to deliver orders of magnitude more ecological data, this digital foundation will enable researchers to combine multiple sources of data with cutting edge new modelling and analysis methods, and deliver the results to decision makers in hours or days rather than months and years.

Thirdly, the empirical analyses delivered by CCIP-R-02 have enabled the vision of adaptive management outlined when the design for the expanded COTS Control Program was set out in 2018. This has provided important short-term improvements in efficiency, for instance, the re-manta tow frequency analysis suggests that the current six-week interval between manta tows could potentially be extended to up to 14 weeks at intensively controlled reefs without significantly compromising decision quality, allowing a greater proportion of vessel time to be redirected to culling activities. But more importantly, it establishes a flexible approach to adaptively refining the way the Control Program runs based on ecological insights gained from the data being collected by the Control Program itself.

The empirical analyses of manta tow also highlighted an interesting point for future consideration. Manta tow is used in four roles in the COTS Control Program: 1) to assign reef outbreak status; 2) to gather reef intelligence upon first arrival at a reef to guide initial dive plans; 3) during ongoing management at a reef to sequence the order in which sites are culled, and; 4) on completion of a reef to verify that ecological threshold conditions have been achieved. Manta tows completed by the COTS Control Program also contribute to a pool of manta tow data collected across the GBR by a number of other monitoring programs.

The empirical analysis conducted as part of CCIP-R-02 highlights well known characteristics of manta tow: it can cover large areas relatively efficiently to provide reef-scale representative statistics on coral cover and COTS densities, but it is neither particularly accurate nor precise. Limited accuracy means that manta tow detects only a small proportion of COTS at a site, and limited precision means that manta tow struggles to reliably resolve small differences in density between sites.

These characteristics make manta tow more suitable for some of the tasks it is currently used for than others. Averaged over an entire reef, it is well suited to assigning reef-level outbreak status, and contributing to the pool of manta tow data collected across GBR monitoring programs. It is accurate and precise enough to identify high density aggregations of COTS when vessels first arrive at a previously uncontrolled reef to inform control staff about which sites to dive first. However, as management continues around a reef and COTS numbers are reduced by culling, both the absolute density at each site declines, and the relative difference between COTS densities from one site to the next declines even further. This poses a problem for the limited accuracy and precision of manta tow. Our analysis in section 3.2.3 shows that as the density of COTS at a site decreases, the false positive rate increases (**Figure 12**) and the quality of decisions informed by manta tow declines. The results suggest that alternative methods to manta tow should be investigated for sequencing control activities as COTS densities approach the Ecological Threshold. The biggest issue, however, is the use of manta tow to verify whether all sites have had COTS densities reduced below the Ecological Threshold and culling activities at the reef can be completed. By definition, this happens when COTS densities are extremely low, precisely the conditions under which manta tow is most likely to yield a false positive. Because a false positive can trigger additional culls that prevent the reef being closed, there are potentially significant efficiency gains to be achieved by refining the system for verifying reef completion. Several CCIP innovations may provide solutions: in the short term, the COTS Control Centre On-Water Decision Support System and an associated management dashboard could use a combination of cull and manta data to verify reef closure. In the longer term, new cutting-edge computer vision monitoring methods being developed as part of CCIP-D-04 (Bainbridge et al. 2025) could provide the scale benefits of manta tow, with the accuracy and precision benefits of more intensive monitoring techniques.

4.6 Outputs

CCIP-R-02 produced a large number of outputs, clustered into four key themes:

- Reusable Digital Workflows
    - Reusable digital workflow to process/clean COTS control program data for use in modelling (open access R code).
    - Reusable digital workflow to assign manta tows to sites, using modular approach for testing alternative algorithms (open access R code).
    - Cloud platform for automated execution of Reusable Digital Workflows.
- Empirical Analyses
    - Empirical analysis of optimal frequency of manta tow to guide decisions about which sites to dive at a reef.
    - Empirical analysis estimating the effort required to bring a reef to Ecological Threshold based on initial surveillance.
    - Empirical analysis of manta tow and cull data correlations, and the effectiveness of manta tow in informing effective management decisions.
- Manager Dashboards
    - Larval Dispersal Dashboards – two Dashboards, one to allow managers to explore ensemble results, one focused on changes compared to legacy data and consequences for management decisions.
    - GBR Management Scenario Dashboards – two Dashboards, to allow managers to dynamically explore GBR-scale outcomes of different management strategies, the first in terms of coral cover and COTS outbreaks, the second in terms of economic cost-effectiveness.
    - Effort Sink Reef Dashboard – Dashboard to dynamically identify reefs where control is taking or is likely to take an unexpected amount of effort to bring all sites at the reef to the Ecological Threshold.
    - Early Warning System Dashboard – Dashboard integrating wide range of data from CCIP projects (including CCIP-P-04, CCIP-D-03, CCIP-R-04 and CCIP-R-

05) and other GBR monitoring programs to identify reefs at risk of emerging outbreaks.

- On-Water Decision Support System
    - Cutting-edge, platform-independent, multi-tiered cloud-server-client Decision Support System to inform on-water decisions about which sites at a reef to action.

5. RESEARCH SYNERGIES AND NEXT STEPS

Project CCIP-R-02 is strongly connected to multiple research projects across CCIP. It provides the primary path to impact for a number of research outcomes. Through the development of Manager Dashboards and interaction as part of the CCIP Research Translation initiative, CCIP-R-02 has additionally played an important role translating these research outcomes to focus on and address manager's specific needs, amplifying impact.

The Reusable Digital Workflows developed as part of project CCIP-R-02 are deeply integrated with the CCIP Information System developed in project CCIP-R-01 (Fletcher and Rezvani 2026). Together, these projects provide a foundation on which to build a significant digital transformation in the way data is shared between COTS managers and researchers, between researchers, and the way that research outputs are delivered back to managers to inform decision making.

The Empirical Analysis of manta tow and cull data from the Control Program undertaken as part of CCIP-R-02 is linked to work in CCIP-D-02 (Lawrence et al. 2026) comparing different monitoring methods using well-designed field trials.

The Manager Dashboards present research outcomes from a number of CCIP projects, interpreted and focused on the information that managers need to make use of that research. Larval dispersal models developed under project CCIP-R-05 (Choukroun et al. 2026) inform the Larval Dispersal Dashboards. GBR Management Scenario Dashboards allow managers to dynamically explore interpreted research outcomes from project CCIP-R-04 (Skinner et al. 2025) on ecological outcomes, and project CCIP-R-06 (Scheufele et al. 2025) on cost-effectiveness outcomes. The Effort Sink Dashboard links directly to questions raised by COTS Control Program managers over the course of CCIP. Finally, the Early Warning System Dashboard integrates a huge amount of data from CCIP, linking to SALAD survey data from project CCIP-P-04 (Pratchett et al. 2025), eDNA data from CCIP-D-03 (Uthicke et al. 2025), GBR scale ecosystem model projections from CCIP-R-04 (Skinner et al. 2025) and larval dispersal modelling from CCIP-R-05 (Choukroun et al. 2026). It also links to other GBR monitoring programs from AIMS LTMP, the RJFMP, EotR, and RRAP.

5.1 Next Steps

Project CCIP-R-02 has delivered a broad range of work across multiple activities, each of which have provided both immediate improvements to the way COTS control decision making is supported by data, and also laid the foundation for future innovations.

The four top priorities for further development arising from work in CCIP-R-02 are:

- Research translation: Interpret, target, and embed more existing and future CCIP research into managers' workflows at the time and place where decisions need to made using digital decision platforms like the Manager Dashboards.

- Operationalise on-water decision support: Roll out the COTS Control Centre On-Water Decision Support System with on-water operators, and manage the transition from a cutting-edge research product to a core component of the operational Control Program.
- Digital transformation: Build new automated Digital Reusable Workflows addressing urgent management and research needs to speed up and streamline the innovation pipeline connecting researchers to managers, using the digital platform that has been developed in CCIP-R-01 and CCIP-R-02.
- Adaptive management: Leverage the new CCIP data pipelines to drive new empirical analyses that allow adaptive refinement of the COTS Control Program, especially around guiding more effective management responses to effort sink reefs, and refining when and how manta tow and cull data are used to inform key Control Program decision making.

6. MANAGEMENT IMPLICATIONS AND IMPACT

Many of the management implications from the innovations introduced by CCIP-R-02 are already being actioned, as a result of the tight integration between the project and managers in the COTS Control Program. The most notable of these is the Manager Dashboards, which have been co-developed with managers through multiple iterations of feedback. Others, such as the COTS Control Centre, will have significant implications and impact as they move from a research foundation to become integrated in the day-to-day operations of the Control Program. Although each component within CCIP-R-02 was designed to deliver immediate improvements, they were also designed as platforms that could be built on and expanded, so many of the greatest impacts may be realised in the future. This applies to the Manager Dashboards and COTS Control Centre, but the strongest example is the Reusable Digital Workflows, which help process Control Program data for distribution to researchers now, but also provides a platform for automating many more common data processing and interpretation tasks in the future. An important near-term management recommendation is to establish the Reusable Digital Workflows as standard practice for all Control Program data preparation, including when responding to external data sharing requests. Engaging the Reef Authority to embed these workflows into their existing data management practices will be critical to realising this potential.

Several of the innovations generated by the CCIP-R-02 Empirical Analysis sub-project have identified areas for adaptive refinement that could potentially improve the efficiency of the COTS Control Program. The first recommends consideration of extending the interval between manta tows at intensively controlled reefs from the current six weeks to up to 14 weeks, based on the finding that this would not significantly increase the risk of missing the re-emergence of COTS at a site. If adopted, this change could allow a greater proportion of voyage time to be redirected from surveillance to culling activities, improving overall Program efficiency. The second, the development of methods for identifying effort sink reefs, could increase Control Program efficiency by enabling early identification of reefs that are likely to take a disproportionate amount of effort so that strategies can be altered, or resources redirected. Finally, empirical estimates of the statistical quality of manta tow-informed decisions have provided guidance around which decisions should and should not be informed by manta tow. This could increase Control Program efficiency by ensuring that appropriate data is used to inform each decision that needs to be made in the day-to-day operation of the COTS Control Program. In each of these cases, the next step is to establish how these research results, along with their important details and assumptions, can be robustly implemented within the Control Program.

The key entry points for the project into COTS management are the On-water Operations, the Integrated Pest Management Framework, and the Annual Reef Prioritisation Process. The project also connects to the COTS Strategic Management Framework. The connections include:

- **Integrated Pest Management Framework:** The COTS Control Program puts data-based ecologically-informed decision making at the centre of management. Outputs from the Reusable Digital Workflows, the Empirical Analysis, and the Manager

Dashboards all contribute to faster, better, and more innovative and impactful data-informed decision making.

- **On-water Operations and Data Collection:** Two of the innovations generated by CCIP-R-02 contribute significantly to On-water Operations and Data Collection—the Reusable Digital Workflows and the COTS Control Centre On-Water Decision Support System. The Reusable Digital Workflows dramatically streamline the flow of Control Program data to researchers, speeding up innovation. The COTS Control Centre On-Water Decision Support System interprets Control Program data to guide day-to-day on-water decisions.
- **Annual Reef Prioritisation Process:** Multiple Manager Dashboards provide information that is used in the Annual Reef Prioritisation process. The Dashboards allow managers to dynamically interact with interpreted research results focused on the questions they need to answer. Larval dispersal is crucial to the Annual Reef Prioritisation Process, and the Larval Dispersal Dashboard allows managers to better understand new cutting-edge dispersal ensembles. Regional fleet distribution is also central to the Annual Reef Prioritisation Process, and the GBR Management Strategy Dashboards present new insights into strategies for regional fleet distributions, including cost-effectiveness information that has never previously been available to guide decision making. Finally, the Early Warning System Dashboard presents fundamentally new combinations of data that, for the first time, may allow managers to identify and action reefs as outbreaks are just beginning.
- **COTS Strategic Management Framework:** The long-term projections of ecological and economic outcomes from management provided by the GBR Management Strategy Dashboard leverage the scientific innovations of projects CCIP-R-04 (Skinner et al. 2025) and CCIP-R-06 (Scheufele et al. 2025) and interpret them for managers to help guide the appropriate long-term large-scale strategies developed in the COTS Strategic Management Framework. The Early Warning System Dashboard will provide insights into the causes of primary outbreaks.

Project CCIP-R-02 contributed to the overarching outcomes and impacts identified in CCIPs Research Impact Plan and Program Logic (**Figure 1**). It delivers a more efficient and effective operational response by ensuring that: data and research results can be shared between the Control Program and researchers quickly, reliably, and in standardised formats; the COTS Control Program can be adaptively refined in response to new data and research insights; and interpreted research outcomes can be delivered back to decision makers at the times and places where decisions need to be made. The enabling innovations produced by CCIP-R-02 will allow other modelling research areas to improve prediction accuracy, and will help those improved predictions be interpreted appropriately by managers to inform more effective decisions. By effectively improving the link between research and management, it drives impacts across all three areas identified in the CCIP Program Logic: better suppression and prevention of COTS outbreaks, protection of coral cover, leading to benefits for Traditional Owners, the tourism industry, and the Australian community as a whole.

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8. DATA ACCESSIBILITY

The processing code for the Reusable Digital Workflows, outputs from empirical analyses, and code base for the COTS Control Centre are stored in the CCIP Information System developed by project CCIP-R-01. Outputs of the effort sink reef analysis are also available on the Effort Sink Dashboard.

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