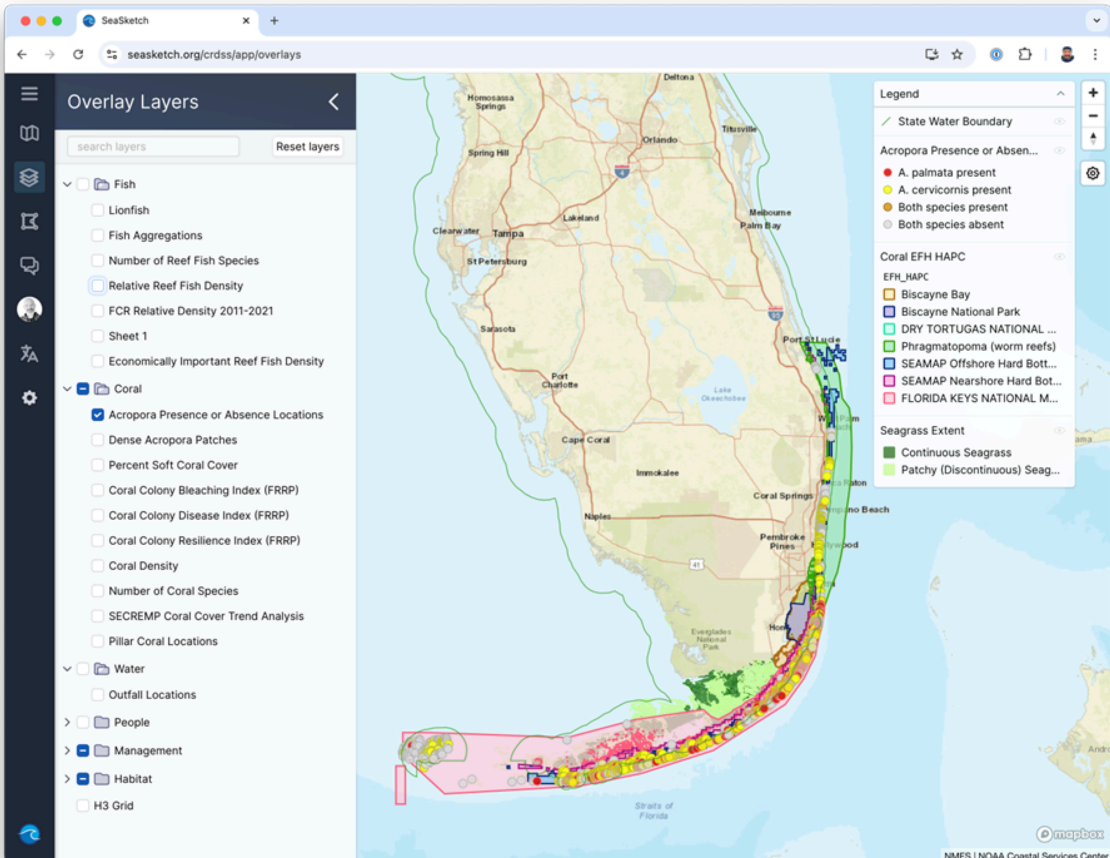
Coral Reef Decision Support System



Coral Reef Decision Support System

Final Report

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Management Summary

The Coral Reef Decision Support System (CRDSS) is a modern, scalable, and interactive tool designed to meet the needs of coral reef conservation and restoration practitioners in Florida. Developed in collaboration with the Florida Fish & Wildlife Research Institute (FWRI), Nova Southeastern University (NSU), and The Spatial Collaborative using the SeaSketch platform, the CRDSS supports restoration site selection and other management needs across Florida's Coral Reef (FCR), which has experienced severe disturbances from extreme heat events and coral disease outbreaks.

In its first year, the project delivered a user-friendly spatial data viewer, a high-performance filtering tool capable of sub-second analysis over millions of planning units, and new analytical workflows tailored for coral restoration site selection. The CRDSS is a flexible and modular software system that allows users to manipulate existing FCR spatial datasets, test potential scenarios, and document decision-making processes. The initial application of the CRDSS supports coral reef restoration site selection and is poised to support future management and conservation needs including shoreline protection, water quality improvement, and construction permitting.

FWC staff and collaborators at NSU have been trained and empowered to manage the CRDSS data layers, cartography, metadata, and related content. Feedback from beta testers has already led to meaningful improvements in usability, symbology, and metadata access. The tool is well-positioned for expanded adoption and enhancement in its second year, with improvements to collaborative data management workflows and further refinement of outputs to support restoration practitioner needs.

Executive Summary

Florida's Coral Reef (FCR) has experienced a series of widespread disturbances, including extreme temperature events and a lethal coral disease outbreak. The loss of coral cover across the reef has led to a large investment in management and restoration activities. In response, the Florida Fish & Wildlife Research Institute (FWRI), Nova Southeastern University (NSU), and The Spatial Collaborative led the development of the Coral Reef Decision Support System (CRDSS)—a modern, scalable, and interactive tool for coral reef conservation and restoration planning.

The CRDSS is built on the SeaSketch platform, a cloud-based system for spatial planning, which has been customized to support the selection, evaluation, and documentation of restoration sites across the full extent of Florida's Coral Reef. The decision to base the tool on SeaSketch allowed for the rapid deployment of core GIS functionality and greater focus on the development of customized features. The platform equips managers, scientists, and practitioners with tools for data visualization, interactive filtering, sketch-based site planning, and automated reporting. These features collectively enable a rigorous and collaborative decision-making environment.

At the heart of the CRDSS is a high-resolution, hexagon-based planning grid (using Uber's H3 spatial index), which supports real-time, sub-second analysis across 7.4 million planning units. A custom-built filtering engine, powered by the DuckDB analytical database, allows users to interactively explore and isolate potential restoration areas based on physical, ecological and human-use criteria. To support site-specific planning, CRDSS users can digitize restoration areas directly on the map. Each polygon is automatically analyzed against a suite of data layers, with tailored reports summarizing conditions such as depth, habitat type, and nearby human impacts. This process enables users to evaluate sites quickly and refine their plans based on immediate data-driven insights.

Extensive documentation and two rounds of user training ensured that staff from FWC, DEP, and NSU were empowered to manage the tool's map layers, cartography, and metadata independently. Feedback from practitioners informed refinements to usability, metadata access, and analytical outputs. The project overcame substantial technical challenges during its first year, including the need to maintain responsiveness while querying millions of records, integrate live NOAA Coral Reef Watch data feeds, and adapt to user feedback. The open-source nature of the CRDSS architecture ensures transparency, future adaptability, and cost-effective enhancements.

Looking ahead, the CRDSS development team has identified several enhancements based on user feedback and technical assessments. Key recommendations include improving the analytical reports for coral restoration sites and developing tools to better support collaborative data management. Additional priorities involve enhancing satellite imagery options for better reef visualization and expanding tools for inspecting individual planning units. Opportunities may also be found for applying the CRDSS to new cases such as shoreline protection or construction permitting.

The CRDSS represents a significant advancement in Florida's reef restoration toolkit and provides a foundation for more data-informed, transparent, and collaborative restoration strategies.

Table Of Contents

1. Background

Florida's Coral Reef (FCR) stretches almost 350 miles from the Dry Tortugas to the St. Lucie Inlet, and is a vital ecological and economic resource, supporting biodiversity, coastal protection, and tourism. However, it faces acute and ongoing threats from coral disease, climate change, pollution, and other stressors. The Florida Fish and Wildlife Conservation Commission (FWC), in collaboration with the Florida Department of Environmental Protection (DEP), has prioritized coral reef restoration as a critical response strategy. Effective restoration efforts require comprehensive, up-to-date data and the ability to engage scientists, managers, and stakeholders in collaborative planning.

The Coral Reef Decision Support System (CRDSS) was developed in response to the Florida Department of Environmental Protection's goal of establishing a collaborative decision support tool for coral reef restoration and conservation efforts along Florida's Coral Reef. FWC advertised a Request for Proposals (RFP) to build the decision support system, which was awarded to The Spatial Collaborative, LLC. As articulated in the RFP, the CRDSS was envisioned to support inclusive and transparent decision-making across spatial and organizational scales, allowing managers and stakeholders to evaluate potential coral restoration sites through mapping, filtering, and analysis tools.

The CRDSS builds upon lessons learned from the "Our Florida Reefs Marine Planner," a prior spatial planning tool used during a stakeholder engagement process in Southeast Florida. While the Marine Planner provided a valuable early platform for proving the utility of a *filter tool* for site selection processes, it was not maintained and is no longer available for use. Development of the CRDSS was guided by archived documentation and screencasts demonstrating the Marine Planner's capabilities, as well as by consultation with individuals from Nova Southeastern University's (NSU) GIS and Spatial Ecology Lab who were involved in its original development and use.

2. Creating a SeaSketch Project

To accelerate development and ensure a feature-rich, flexible tool, the Coral Reef Decision Support System was built on SeaSketch, a cloud-based software service developed and maintained by Chad Burt and Will McClintock at the University of California, Santa Barbara, as an open-source project. SeaSketch has been under continuous development since 2012 and is designed to support collaborative marine spatial planning and conservation efforts.

SeaSketch provides a rich set of features "out of the box" that align closely with the goals of the CRDSS and the Feature Requirements Matrix included in the original RFP. These include:

- A complete map portal solution scalable to thousands of spatial layers, with built-in support for data search, legends, metadata viewing, z-order and opacity controls, map bookmarks, printing, and data export.
- Tools for data ingestion via drag-and-drop uploads or links to external services (e.g., Esri REST endpoints), with styling and metadata management through a visual admin interface.

- Sketch Classes for users to create, analyze, and share spatial plans such as proposed restoration sites. These can be configured with custom data collection forms and evaluated using the platform's geoprocessing framework.
- Discussion forums and scenario-sharing tools that support collaborative planning and feedback.
- A survey module for spatial data collection from stakeholders via desktop or mobile devices.
- Role-based access control and group management, enabling secure administration and content targeting.
- Multilingual support, including full translation capability for administrative content.

Using SeaSketch allowed The Spatial Collaborative to focus on developing the key features which make the CRDSS unique, such as the new high-resolution filtering tool and custom restoration site report, rather than re-implementing common GIS portal features from scratch. This minimized development time and budget while providing CRDSS users with a high-quality, professional-grade experience consistent with other SeaSketch-based tools. The CRDSS will also improve over time as refinements are made to the platform that are funded by other SeaSketch users.

A SeaSketch project for CRDSS was created quickly at the outset of the contract and populated by initial data layers provided by FWC staff. This early deployment allowed collaborators from FWC and Nova Southeastern University to begin reviewing the platform's core functionality and provide early feedback, particularly on data presentation, accessibility, and overall usability. During all of 2024, products from NOAA's Coral Reef Watch program, such as Degree Heating Week and Bleaching Alert layers were added with automated daily updates. The remaining work to customize SeaSketch to the needs of the CRDSS were the development of **Filtering Tools** and creation of **Coral Restoration Site Digitizing Tools** and associated analytical reports.

3. Filtering Tools

Development of the filtering tools began as soon as the initial SeaSketch project was created as it was the most difficult component to build. It provides users with a means to identify areas within the reef tract that may be suitable for restoration. The region is divided into planning units, with each planning unit assigned a set of attributes related to physical conditions, biological measures, management zones, and human uses (e.g. water depth, fish density, outfall distance, or anchorage presence). Users are presented with an interface to select which of these measures are relevant to the work they intend to perform and set criteria for those measures. For example, one might choose to see planning units less than 10 meters deep, with high parrotfish density and low human impact indicators. When using the filtering tools, users can generate such queries interactively and immediately see planning units that meet these criteria highlighted on the map.

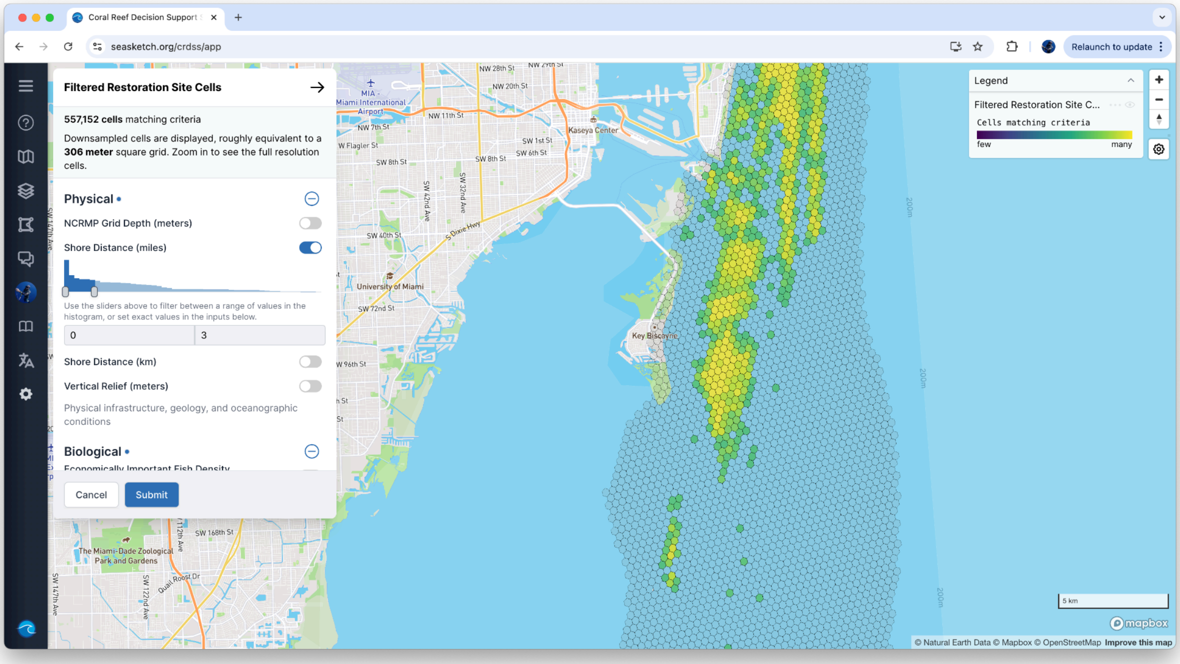

Figure 1: This image shows the user using the Filtering Tools to select planning units no further than 3 miles from shore, which feature at least 80% coral cover.

3.1. Technical Challenges

Early on in the implementation, FWC and NSU collaborators indicated a strong preference for a higher resolution grid-cell size for the planning units, ideally 50 square meters. This higher resolution, combined with an expanded spatial coverage compared to the Marine Planner implementation, would mean evaluating over 7 million grid cells in real-time based on user selections. Such performance in database querying, transmission of results to the client, and rendering of the map presented a serious challenge. Updating the database also proved challenging while the Nova Southeastern University team worked to add new searchable attributes throughout the project.

Ultimately we chose to represent these planning units using the H3 discrete global grid system. Developed by Uber, this spatial indexing scheme represents the earth as a hierarchical grid of hexagonal cells, each with a distinct cell ID. This index has proven popular and now has widespread support in both open-source and proprietary spatial software. H3 facilitated collaboration between the Nova Southeastern University team developing the dataset and The Spatial Collaborative by eliminating the need to convey the spatial boundaries of grid cells, or be concerned with differences in projection, raster grid bounds, or tool interoperability. We simply chose a resolution in the H3 grid system which we would use[1], and shared data in CSV files which referenced H3 cell identifiers. While this dataset is large (1.2GB as of March

[1] H3 resolution 14 was chosen for the CRDSS, roughly equivalent to a 44 square meter cell size

2025), it would have been an order of magnitude larger if it contained the vector geometry of planning units and much more computationally difficult to process.

Using the H3 grid system also helped solve the problem of how to display query results on the map. When visualizing the entire FCR, a given map view may match a large portion of the 7.4 million planning units. Even if the database query is fast, a list of 90% of those cell identifiers could be tens of megabytes even with an optimal encoding. Transmitting that list to the user's browser is impractical and so is expecting the mapping client to evaluate it. The hierarchical nature of H3 helps when it comes to this map presentation. By aggregating adjacent cells into parent cells at lower resolutions when zoomed out, we can dramatically reduce the size of the returned query result while preserving the general pattern and distribution of selected cells on the map. This makes the map view responsive and informative even for complex queries covering large extents. As the user zooms into the map, further detail is revealed by showing higher H3 cell resolutions dynamically. These higher-resolution views are limited in spatial extent, so they no longer pose a performance concern for rendering or transmission. This ensures responsiveness even on lower-powered devices and allows users to explore with precision and speed.

The final technical challenge was to evaluate user filtering requests quickly and support multiple concurrent users. Unlike the map presentation, database queries had to be performed at full resolution to ensure that each cell matched the exact criteria set by users. This proved to be challenging for traditional relational databases (RDBMS). Attempts at implementing an API server to support user queries were made using Postgres, SQLite, and the Cloudflare hosted implementation of SQLite called D1. In each case queries took 5-15 seconds to perform a single query despite many attempts at query and index optimization. While such wait times may be tolerable in isolation, multiple users working in the tool concurrently or even a single user changing filters quickly would quickly overwhelm the database and result in exceptionally long query times, errors and crashes. With these concerns we began evaluating DuckDB. This relatively new technology is an Online Analytical Processing (OLAP) database optimized towards querying and reporting on large datasets, as opposed to optimized for transaction processing as in a RDBMS. With very little optimization work we started seeing queries being evaluated 1 - 2 orders of magnitude faster. When combined with zoom-dependent presentation techniques, SeaSketch is able to respond to filter adjustments and update the map in less than 1 second. This performance exceeded the expectations of the project team and provides users with an interface that is much easier to understand and use.

3.2. Future Updates

The dataset which the filtering tool relies on has been in continuous development over this first year of the CRDSS project. The Nova Southeastern University team has added numerous new layers for filtering, which the developers use to update the database backing the application periodically. This update process is semi-automated and requires special administrative access and systems used by The Spatial Collaborative. The general architecture of a system that could be updated directly by FWC staff or Nova Southeastern University collaborators directly without assistance has been roughly scoped, however building it would be relatively costly compared to utilizing the existing Spatial Collaborative contract to complete data updates.

As new layers are added to the filtering tool, the size of the database increases. We do not anticipate that this will lead to performance issues, at least for the medium term. The column-oriented nature of the DuckDB database means we can double or even quadruple the number of layers in the hex grid dataset before seeing any changes to these performance numbers. The limiting factor would likely be the amount of memory available on the database server, and this could always be increased with a fairly limited budget impact.

4. Coral Restoration Site Digitizing

While the Filtering Tools help users identify general areas for restoration based on their criteria, additional tools are needed to identify and evaluate very specific areas for coral restoration. This may even involve digitizing a polygon directly over the outputs of the Filtering Tools. For this functionality The Spatial Collaborative team configured a custom Sketch Class. Like a Feature Class in desktop GIS, Sketch Classes in SeaSketch define the schema and behavior for spatial features drawn by users within a specific workflow.

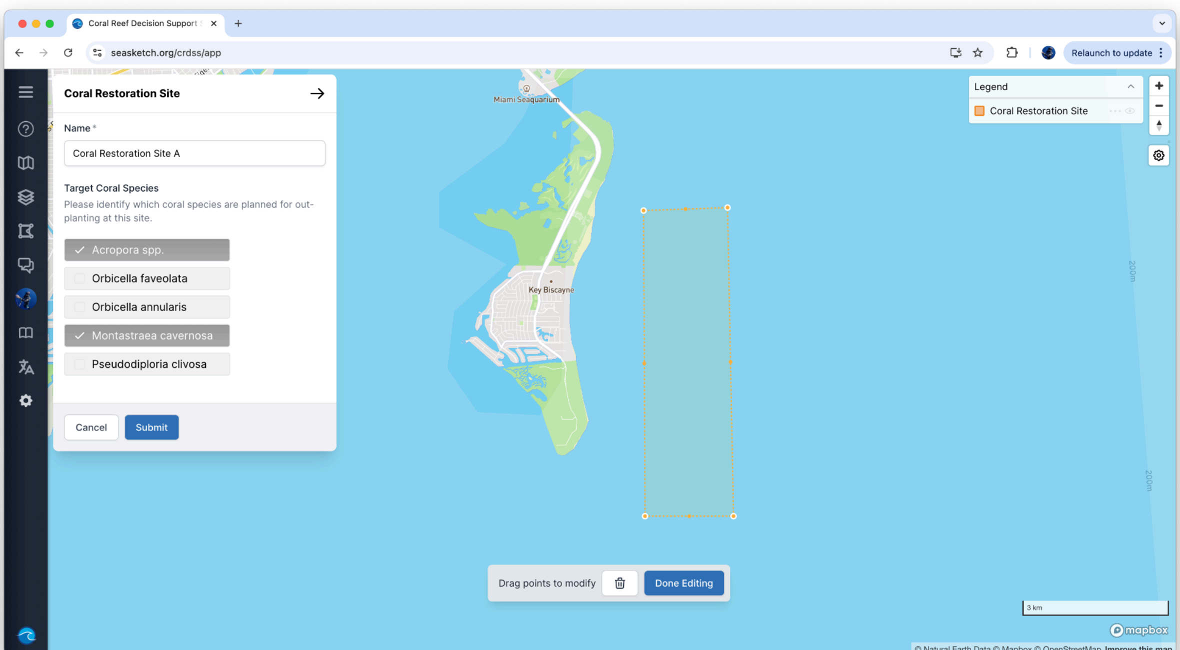

Figure 2: Digitizing a Coral Reef Restoration Site in SeaSketch. Also pictured is the attributes form where users can select which coral species are targeted for restoration.

Each user-drawn coral restoration site is associated with a Sketch Class configured specifically for this workflow. When a site is drawn and submitted, SeaSketch generates a report that evaluates the sketch's spatial overlap with key datasets in the CRDSS, including the high-resolution H3 hex grid used in the filtering tool. Reports summarize environmental parameters such as water depth, presence of coral species of interest, and indicators of anthropogenic pressure. These outputs give practitioners immediate feedback on whether a site meets basic suitability criteria or warrants further exploration.

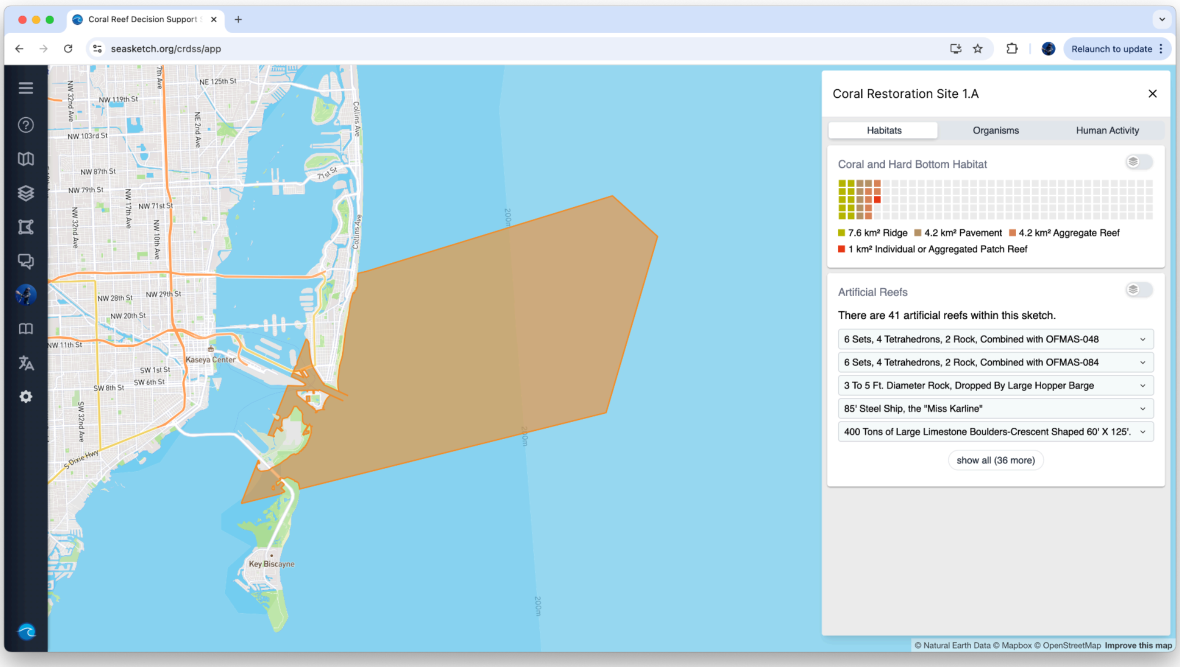

Figure 3: Analytical reports for a Coral Restoration Site. Here it includes a visualization of habitat composition within the polygon, as well as a list of artificial reefs found within.

SeaSketch's visual form-builder allows administrators to configure site attribute forms that accompany each sketch. These forms can include required fields for restoration methods, targeted coral species, or rationale for site selection. This input is captured and displayed in reports, which are stored alongside the sketches for review, discussion, and sharing. As with the filtering tools, sketches and reports can be shared in SeaSketch's built-in discussion forums or made private within specific working groups. This collaborative functionality supports iterative site design and review.

In the second year of development, we plan to enhance the analytical reports in response to specific feedback from restoration practitioners. Anticipated improvements include outputs tailored to individual species restoration (e.g. identifying optimal depth ranges for particular coral types), and could potentially be expanded to support permitting workflows. The system's architecture is intentionally flexible to accommodate evolving user needs and diverse workflows over time.

5. Documentation, Training, and User Feedback

Documentation and training were integral components of the first-year CRDSS implementation strategy.

5.1. Custom Documentation

The Spatial Collaborative authored project-specific documentation tailored to the workflows and tools within the CRDSS. Rather than directing users to generic SeaSketch support materials, CRDSS documentation was linked directly from within the interface and focused on relevant tasks such as using the filtering tools, sketching restoration sites, and interpreting analytical reports. Reviewers suggested that documentation be expanded to include standard operating procedures (SOPs), and future efforts may formalize these recommendations. This user guide can be found online at https://tinyurl.com/crdss-documentation.

5.2. Training Sessions

Two training sessions were held over the course of the project, with recordings made of both. The first was conducted on November 19, 2024, focused on administration of the SeaSketch project. This training included staff from FWC, DEP, and Nova Southeastern University. Attendees were trained in viewing and managing map data layers, cartography, setting up the sketching tools, forums, and basic project administration. A preview of the Filtering Tools and Coral Restoration Site Digitizing functionality was provided, and participants were given administrative access to the project as needed. Attendees were also given instructions on how to provide feedback.

The second training on March 17th included many of the same participants but was also broadened to coral reef restoration practitioners. This training focused on end-user workflows, including the data layer viewing, Filtering Tools, and Coral Restoration Site Digitizing. Participants were asked to work through tasks such as creating an account, digitizing polygons, and sharing content in the forum. They were also requested to fill out an online survey about their experiences using the tools.

5.3. User Feedback

Following the second training, feedback was received both from 10 participants through the online survey and via email. Feedback was compiled for review by FWC Staff and reviewed by The Spatial Collaborative and Nova Southeastern University project teams. This feedback was divided into roughly 33% feedback on the application and tools and 66% feedback and questions related to the compiled data layers. Reviews of the CRDSS application were generally favorable. When asked to score the ease-of-use or utility of various functions of the CRDSS on a scale of 1 - 5, average reviews were 3.9. Major pain points around the mechanics of viewing the reports, layers, and filter tool outputs were identified, as well as difficulty accessing layer metadata. There were also numerous improvements suggested related to working with the map. Early testers also ran into errors in coral restoration site analytical reports due to layer changes that hadn't been accounted for.

Based on this user feedback, the following improvements were made:

- Errors in Coral Restoration Reports based on stale layer references were corrected
- Symbology of Filtering Tool outputs were adjusted to enhance visibility

- Coral Reef Restoration Sites were added to the legend, with controls for adjusting layer opacity and z-order stacking
- Added support for showing mouse coordinates when interacting with the map
- Improved guidance to new users, including an "About Page" in the sidebar, and direct links to the CRDSS user guide
- Links to layer metadata were added to controls in the Filtering Tool so that users could more easily discover information about layers being used for filtering planning units
- Bugs related to the reporting window, legend, and map controls overlapping each other were resolved
- Changes were made to enable the map scale bar visibility by default
- Bugs related to viewing restoration site analytical reports from the forums were fixed
- Improvements were made to the application layout to facilitate viewing map layers on mobile devices

Noticeably absent from most of the reviewers' feedback were thoughts on how to improve the contents of Coral Restoration Site Digitizing analytical reports. These reports were designed mostly as a placeholder to demonstrate the capabilities of the system. To make them useful to restoration practitioners the developers will need feedback on what particular layers and parameters are needed. More work will be required to solicit this feedback in the future.

6. Recommendations for Future Improvement

Several enhancements were identified by FWC staff, Nova Southeastern University collaborators, and coral restoration practitioners that were beyond the scope of what could be accomplished in the first year of development. These all represent opportunities to improve the CRDSS in the future.

1. Coordination among FWC Staff and partners when reviewing unpublished layer edits has proven cumbersome. FWC staff need to review edits before publishing changes publicly, but information on what changes have been made in the administrative interface must be recorded in separate spreadsheets for review. To facilitate this process better, we intend to develop tools to automatically log changes to the layer list since last publication. This way reviewers can know what has changed (e.g. cartography, source data, or metadata), who made the change, and when. This will make for a much simpler data management workflow.
2. Continue to improve the outputs of coral restoration site analytical reports. Improving these reports will require further feedback from coral restoration practitioners so that they can be tailored to the specific species they are working with and criteria they use to select sites.
3. Many reviewers noted difficulty in evaluating sites using the satellite imagery from both MapBox and ESRI. The Spatial Collaborative is investigating whether a cost effective option can be found to incorporate Google Maps satellite imagery into all SeaSketch projects as these base-maps offer the best cloud-free view of offshore coral reefs.
4. Offer more tools to inspect the H3 planning grid cells. Reviewers found that it would be helpful to be able to inspect individual planning units to determine the properties of each cell (e.g. depth or distance to shore), as well as see summary information about all cell values intersecting with a

given restoration site. This would make it easier for users to understand how the overall system works and better understand the outputs of the reports and filtering tools.

Beyond improving support for coral restoration outplanting, opportunities should be sought to adapt the CRDSS to other applications. The original RFP envisioned its use in various FWC initiatives, including shoreline protection, water quality enhancement, and construction permitting. The decision support tool's modular and adaptable design should prepare it to address these needs as they arise.

7. Closing Thoughts

The CRDSS represents a significant step forward in supporting coral reef restoration efforts in Florida. By leveraging the SeaSketch platform, FWC and its partners now have access to a flexible, high-performance, and scalable decision support system tailored to their unique needs. Throughout the first year of development, the project overcame substantial technical and design challenges, resulting in a robust platform that delivers on its promise of enabling data-informed site selection and collaboration, and met all of the criteria laid out in the feature requirements matrix of the Request for Proposals.

Key features include the development of the high-resolution filtering tool, integration of restoration site sketching and reporting capabilities, and availability of training documentation and workflows that empower partners to manage and update the system independently. Early feedback has already led to improvements in usability, and the project is well-positioned for continued refinement and impact.

With further refinement and practitioner engagement, the CRDSS is poised to become an important tool for guiding restoration efforts across Florida's Coral Reef and could serve as a model for similar initiatives elsewhere. The flexible nature of SeaSketch also makes available a platform which can be used for other spatial planning efforts by the State of Florida in the future.

Appendix 1. Source Code

The software systems behind the CRDSS are all open source and can be found in 3 different repositories on GitHub.

SeaSketch Next

Main repository for the software service which hosts the CRDSS.

https://github.com/seasketch/next

Coral Restoration Site Reports

Developed specifically for the CRDSS, all code related to site reports are available within this repository.

https://github.com/underbluewaters/crdss-reports

CRDSS API Server

The API server which hosts the H3 grid database and associated services.

https://github.com/underbluewaters/crdss-api-server