2017

TAKATA Experience

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COASTAL HABITAT CARTOGRAPHY PROJECT PHASE II

Project report including objectives, resources used, methodology and results

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FIGURE LIST

ABREVIATION LIST

AGGRA	Atlantic and Gulf Rapid Reef Assessment
GIS	Geographic Information System
MAR	Mesoamerican Reef
RMP	Reef Monitoring Program

INTRODUCTION

While a great deal of people depends on coral reefs to survive, it first provides habitat for hundreds of species. The Mesoamerican barrier reef system is one of those ‘’ rainforest of the sea’’ teaming with life. Having understood the necessity of such communities, it makes it all the more disheartening to see it crumble in the wake of coral bleaching, diseases and hurricanes. Humans also play a big part in the destruction of corals reef ecosystem through destructive fishing and boating practices, chemical pollution, sedimentation following coastal construction, etc. And yet, we have very little data to measure the decline and or recovery of the reef ecosystem healths.

TAKATA experience has taken upon itself to oversee these changes in the coastal habitat of Mahahual which is included in the Mesoamerican barrier reef system. With this purpose in mind, they have contracted the help of volunteers. The goal is to put in place a database to monitor and manage the coastal ecosystem of Mahahual. With these objectives in mind, the research center is currently implementing the Atlantic and Gulf Rapid Reef Assessment (AGRRA) protocol to gather data for its Reef Monitoring Program (RMP).

This report compiles the phase II of the habitat cartography project undertaken in an internship from September 17 to December 18, 2017. It contains a contextual setting for both the location and contributors. We then explain the initial objectives for this project. We continue by elaborating on the resources and the methodology used during this assignment. And finally, we will present the subsequent results and accomplishments.

CONTEXTUAL SETTING

MESOAMERICAN REEF

While our research may be localized around the coastal habitat surrounding the city of Mahahual, its fringing reef is a part of the Mesoamerican Reef (MAR). Also known as the Great Mayan Reef, the MAR is a marine region covering an extent over 1000 km long starting from the tip of the Yucatán Peninsula, down to Belize, Guatemala and all the way to the Honduran Bay Islands (see appendix 1). It is the largest barrier reef in the Western Hemisphere and is second worldwide only to Australia's Great Barrier Reef.

Home to numerous types of coral, it provides shelter and food to hundreds of fish species, marine turtles, sharks and other marine curiosities. The MAR has several protected areas and parks including Cayo Chochinos, Hol Chan Marine Reserve, Sian Ka'ann biosphere reserve, Arrecifes de Cozumel National Park and the Belize Barrier Reef. It hosts more than 65 species of stony coral and has one of the most vivacious and diverse marine life of the world, including quite a few endangered species.

The exquisiteness of the region coastal area makes it a prime tourist destination. This is especially true in the wake of the 2017 Atlantic hurricane season which left other tourist hot spots north of the MAR devastated. Several Cruise ships were forced to change course towards unscathed destinations such as the city of Mahahual.

MAHAHUAL

Located on the Quintana Roo coast of the Yucatán Peninsula Mahahual is a paradise for divers and snorkelers alike. Originally a small fishing village, it has quickly developed into a resort for water sports and ecotourism. Just south of Playa Del Carmen, Cozumel and Cancún, this lesser known refuge offers unspoiled mangroves and impressive reefs.

The city was nearly razed to the ground following hurricane Dean in 2007 but has since rebuilt itself and is rapidly expanding. This accelerated growth brings a number of challenges regarding the urbanization of the coastal habitat of Mahahual. It also poses a risk for well-being of the surrounding fauna and flora. The mangroves are the perfect hatcheries for hundreds of species and attract a great deal of migratory birds to feed and breed safely. The expansion of Mahahual threatens the integrity of the mangroves and by extension of the reef healthiness which is in close harmony with the mangroves.

These challenges are taken seriously by local organizations who understand that the vitality of Mahahual is co-dependent on the wellness of its coastal habitat. One of the organizations leading the charge to protect the integrity of Mahahual is Takata Experience.

TAKATA EXPERIENCE

TAKATA Experience is a dive center that seeks to protect coastal ecosystems through community education, environmental research and conservation. To that end, it hosts the TAKATA Research Center which is an NGO specialized in marine ecology, sustainable coastal management, and public awareness. It employs volunteers, interns and full time staff qualified in ecology, environmental management and wildlife conservation.

The organization seeks to promote endangered wildlife and habitat conservation. Its mission is to protect coastal ecosystems through community education, environmental and social awareness. It is also an ambassador for the reef, collaborating with both the local community and government to grow Mahahual into a sustainable town and an ecofriendly destination.

Concretely, these goals materialize themselves through a number of programs put in place at the research center, including:

- The environmental awareness campaign
- The coral reef restoration project
- The Reef Monitoring Program of which this report is comprised.

The RMP is currently building a database pertaining to the state of corals and reef ecosystem boarding Mahahual. The ensuing data is to be compared on a yearly basis to assess any changes in the reef conditions. Based on these findings propositions can then be relayed to local authorities in order to put in place long lasting conservation measures. To ensure a concerted effort between local and regional authorities, the methodology employed within the RMP follows the AGGRA protocol.

AGGRA PROTOCOL

Founded in 1998, the AGGRA program has been a leader in coral reef conservation. This international collective comprised of scientists, administrators, and local supporters is hard at work to preserve regional reefs in the Western Atlantic and the Gulf of Mexico. Its mission is to “examine the condition of reef-building corals, algae and fishes and support the conservation of the coral reef ecosystem[1]”. In order to achieve these goals, AGGRA “curate and distribute data, research and educational materials that support this mission[2]”.

Initially, it put in place standardized indicators used to analyze spatial and temporal patterns found in regional reef condition. Since then, over 2300 surveys have been conducted all over the Caribbean. It constitutes one of the largest public databases of coral reef conditions. AGGRA promotes effective communication to a wide audience to enhance the conservation impact. It also offers “a learning platform through trainings, exchanges and open-access education materials[3]”.

“The vitality of a reef depends on complex relationships among corals, fishes and algae. Therefore, to evaluate the condition of a reef from a one-time assessment, it is critical that multiple indicators of the corals-algae-fishes relationships are examined. These different indicators are measured by the AGRRA protocol.[4]”

[1] About Us, Atlantic and Gulf Rapid Reef Assessment [ONLINE]. (http://www.agrra.org/about-us/)

[2] IDEM

[3] IDEM

[4] IDEM

OBJECTIVES

While the general objective of the internship was to help put in place the RMP, many specific tasks were initially planned during its span. Through the use of Geographic Information System (GIS) a number of maps were to be created to help collect, analyze and spatialized data regarding the reef surrounding Mahahual. The database and the maps would then serve as decision-making tools for local authorities and organizations. More specifically, it gives an understanding of the state of the reefs fauna and flora.

As a means to set up the database, it was crucial to integrate the AGGRA protocol to the data collection effort of TAKATA experience. Parallel to the protocol, an extensive database regarding the activities of the RMP was to be included. Participative cartography was also part of the tasks at hand. It seemed essential to include the feedback from other dive shops. This allows us to gain an understanding of Mahahual diving habits. An online map containing information about the reef extent and the state of the dive sites was also part of the task at hand. All maps legends and titles were to be in English.

It was also planned to use open source softwares for all tasks to ease the financial strain ensued by further updates of the database. Large scale habitat mapping is usually expensive. Especially when using remote sensing data, imagery costs can range from hundreds of dollars to tens of thousands. Online free data sources and low-cost data collection were preferred when choosing the methodology. The downside of open source data is usually lower resolution imagery which does not allow analysts to distinguish some features when mapping the reef such as the reefs geomorphology, community types, coral health, etc. Such data will have to be gathered on location through a number of dives thus elevating the costs of the project.

RESOURCES

As stated earlier, a number of open-source softwares were used during this project. Among those, the main one used to map the coastal habitat was a GIS QGIS, an application that supports viewing, editing, and analysis of geospatial data. Along with QGIS, we used various extensions to add features to the original program. One of those extensions was QGIS2Web which allowed us to port our map to a web map service.

But we also had access to physical resources such as a boat, scuba diving equipment and a float. We also gathered spatialized data using a Garmin GPS model Etrex 10 and Garmin sonar Echomap sv 74. A software called Homeport allowed us to convert .ADM files to .CSV format. .CSV can be read in QGIS while .ADM cannot.

METHODOLOGY AND RESULTS

USE OF GIS

The use of GIS is a crucial step in the research regarding coral restoration. Our cartography tools allow us to collect, structure, visualize, analyze and share spatialized information. This information can then be used to help decision making regarding the management of both anthropic and natural environments surrounding the reef. The resulting maps are also a great tool to help understand the state of the local reef and raise public awareness. Furthermore, they serve as a reference for future data gathering to monitor changes to commonly used indicators of marine ecosystem health.

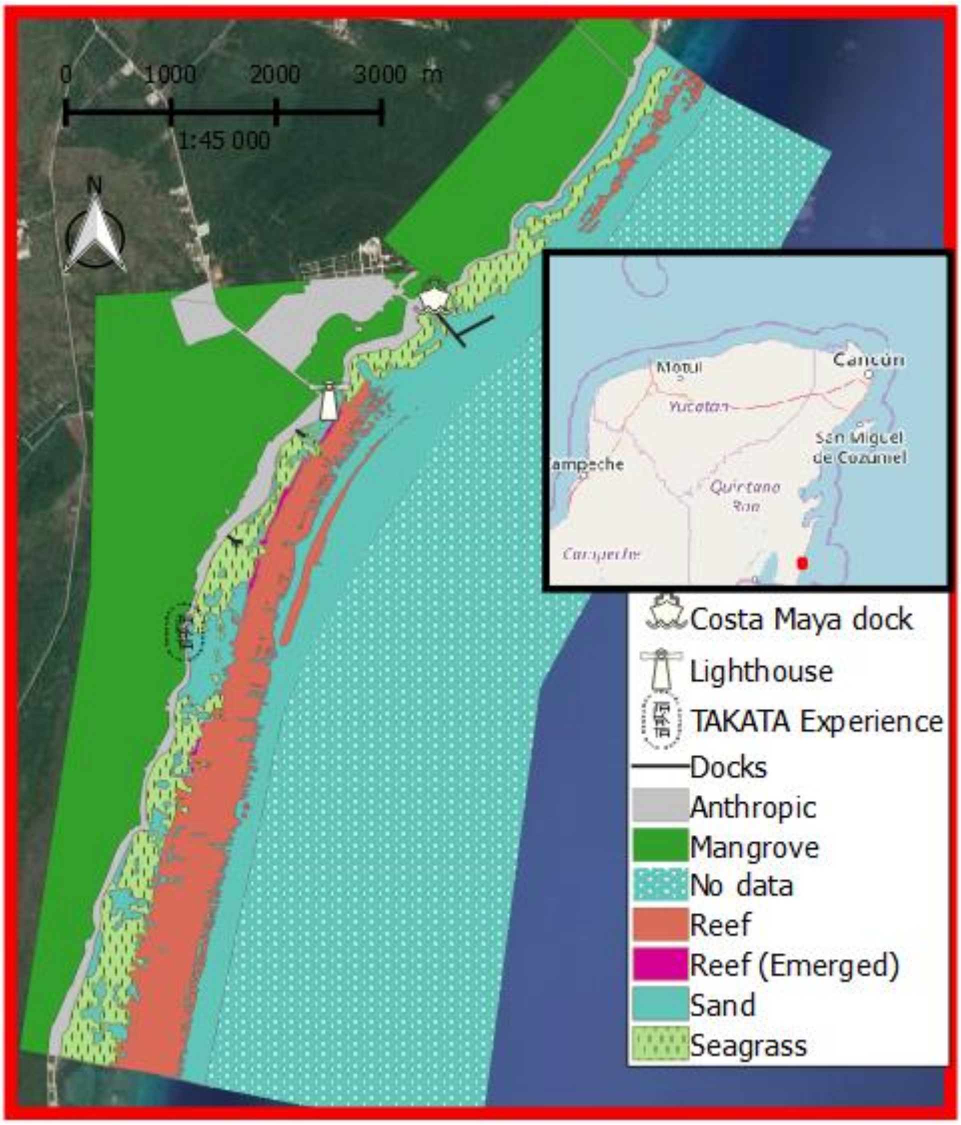
While this report explains the progress made during the second phase of the habitat cartography project, it is necessary to understand what was achieved beforehand. The first phase began in May 2017 through June 2017. Its goals were to produce a vectorial layer dividing the coast of Mahahual in separate habitats such as the reef, the lagoon, the mangrove and the seagrass. It used a Landsat scene and a satellite image from Google Earth to produce a vectorial layer of the coastal habitat. The resulting polygon feature managed to map the extent of habitat types for depth above 15 meters. This contains the seagrass, the first line of reef along with its emerged section and parts of the second line of reef.

REEF CARTOGRAPHY

To continue the mapping effort initialized through teledetection during the first phase, we have been collecting GPS tracks along the reef. To accurately collect these tracks, we have been following the reef during scientific dives. We were attached to a freediving float containing a GPS tracking our position. We have been diving mostly on the side of the reefs slope to acquire new reef limits, but also on the reefs flat to validate previously drawn contours from satellite images. Our method has its weakness; it is both time consuming and somewhat costly. We also have to consider the error margin. Depending on how deep our survey is, the rope has more leeway to drift because of the wind and the waves. At 30 meters deep which is the maximum depth of our survey, the float could drift to a maximum of 7 meters of our position. We also have to add the margin of error of the GPS which is 3 meters. In total, the maximum imprecision possible would be of 10 meters. To avoid that scenario, we made sure to reel in the rope as much as possible to give the minimum leeway conceivable.

We imported the tracks in .GPX format from the GPS into QGIS using the embedded tools within the software. The tracks along the slope are then used to define the limits of the reef at depths greater than 15 meters. In order to do so, we activated the snapping features with a tolerance of 0,0001 map units. We set it to snap along the habitat layer called Habitat.shp and the GPS tracks to update existing features of the reef. This allowed us to redraw new borders for the reefs polygons along the lines of the tracks. As for the tracks along the reefs flat, they helped correct the true extent of the second line of reef which couldn't be achieved through analysis of satellite images. We used the same method with the reefs flat as we did with the reefs slope. We can see the extent of the new reef boundaries and contextual geography in FIGURE 1.

FIGURE 1: MAHAHUAL REEF CONTEXTUAL GEOGRAPHY



URBAN FEATURES

We also wanted to acquire information about the urban features of the shore. Among those required features, we were looking to map the roads and a number of buildings visible from the sea. These are often used as a reference point for boat captains to locate dive sites which do not yet have buoy to pinpoint their locations. They can also be used by researchers looking to update the RMP database when entering or coming out of the water. To locate these urban features, we used two methods. For some buildings such as dive centers and hotels, we simply went around with a GPS to mark a waypoint with their locations. These waypoints are then entered into QGIS the same way we did with the tracks. But for most landmarks and roads we used a different method. We used information stored in existing basemaps to create shapefiles of the features. To extract those features from the basemap, we used a plugin from QGIS called “osmdownloader”. This gave us all the points and lines within a chosen extent surrounding the map. To keep only relevant information, we selected the features by attributes and clipped them to the map extent with the clip tool. We then regrouped the roads that were split in multiple lines with the regroup tool. This gave us the OsmBuildings.shp and Roads.shp features.

AGGRA DATABASE

So as to integrate the AGGRA protocol in our map, we first needed to create a grid of the AGGRA survey sites. “A site is defined as a more or less homogenous habitat, roughly 200 x 200 m in spatial extent[5]”. The AGGRA protocol recommends avoiding “hardgrounds, pavements or bedrock that lack constructional reef frameworks and depths below about 20 meters.[6]” We wanted

[5] AGGRA. 2010. *selecting survey sites from AGGRA protocols Version 5.4 3 pp.*

[6] IDEM

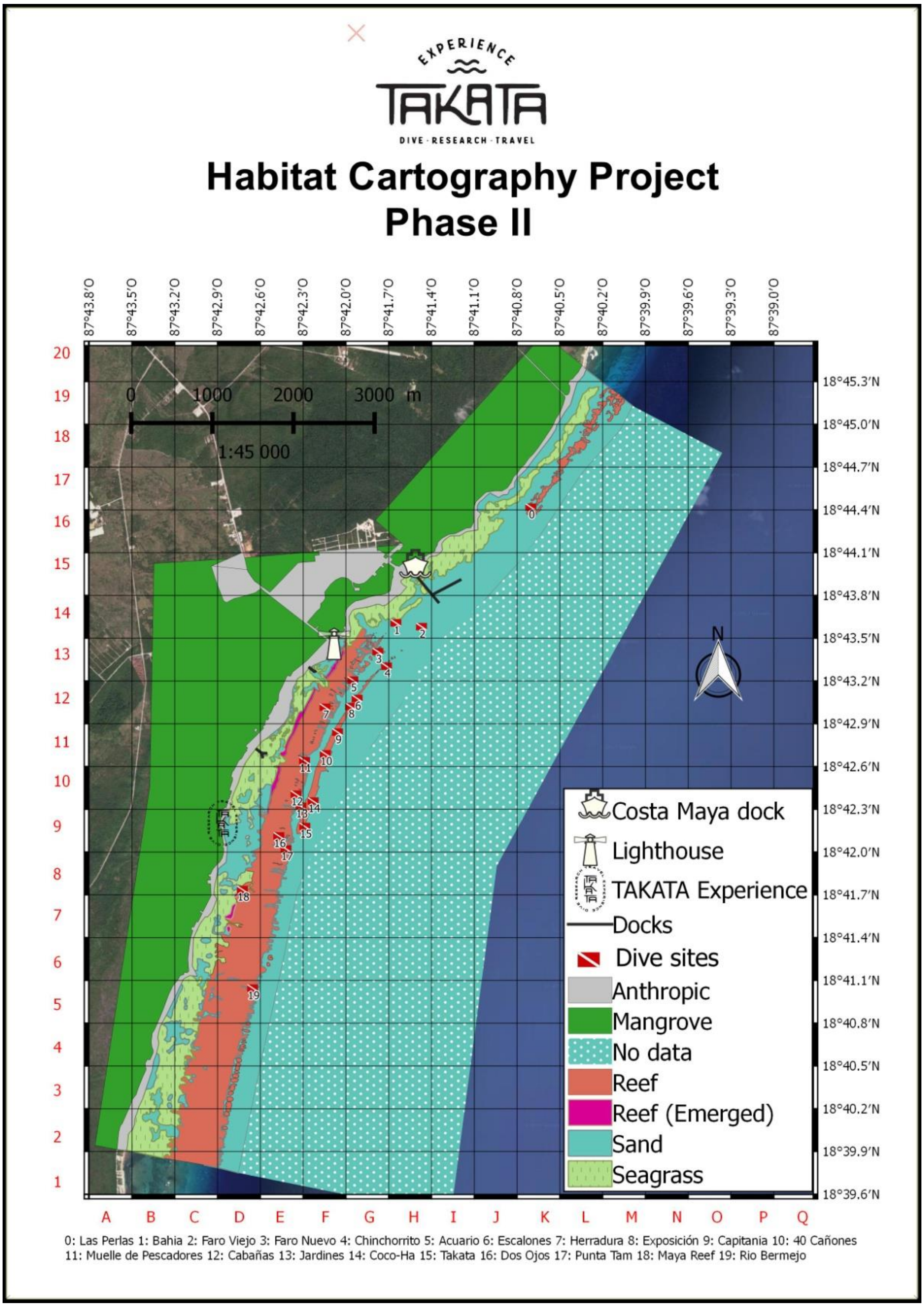
to overlap a grid with squares of 200 m^2 on top of the reef features to define the extent of each survey sites. Each square would be an independent polygon with an attribute table that can be filled with indicators proposed by the AGGRA protocol.

To create this grid, we first had to make a layer of random points within the extent of the map. Each point had a distance of 200 meters with their closest neighbor and would serve as centroid for AGGRA sites. We then used the fixed distance buffer with only one segment to form square buffers around the centroids. We saved the buffers which covered the full extent of the map to AGGRA_MAPEXTENT.shp. But we didn't need the full extent for the database so we made two new layers covering a smaller extent. One for the extent of the sea called AGGRA._SEA.shp and another one for the extent of the known reef called AGGRA_SITES.shp. To isolate these layers, we extracted the desired extent using a selection by location that intersected the buffers. We also linked the buffers and the centroids with a spatial join to merge the attributes.

Once we had our grids, we simply added new rows in the attribute tables containing the indicators. The format of these indicators was inspired by the Healthy Reefs for Healthy People Initiative which was heavily influenced by the AGGRA protocol but also expands upon it (See appendix 2 for reference).

In order to survey the AGGRA sites, surveyors can refer to the navigation booklet provided alongside this report. The navigation booklet provides sectors and coordinates to plan a survey. Figure 2 shows the full extent of the navigation booklet at a scale of 1:45000. Other maps included in the navigation booklet are zoomed in at a scale of 1:8000 and include AGGRA sites for the full extent of the sea while the reference map does not. It also includes common dive sites.

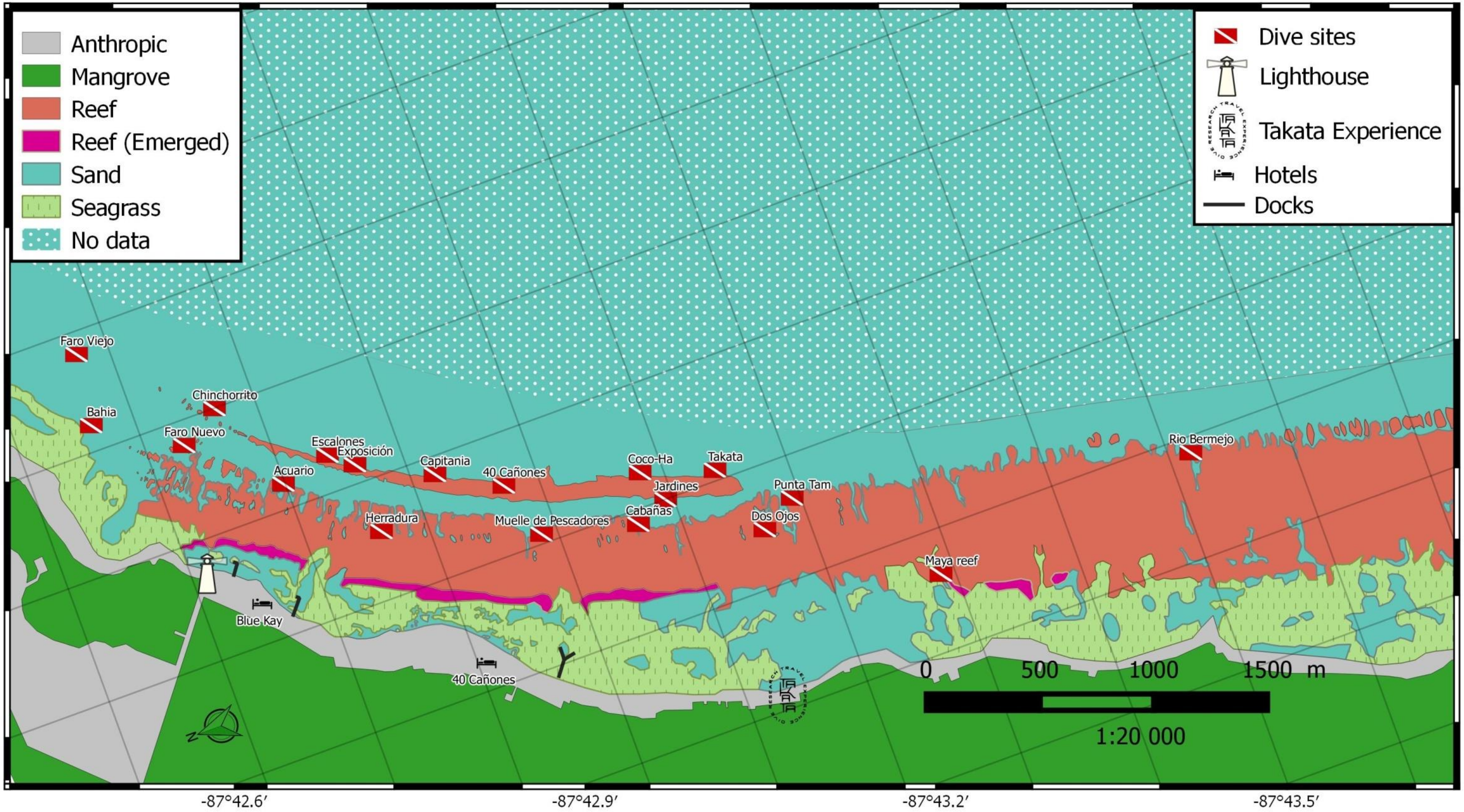
FIGURE 2: AGGRA DATABASE REFERENCE MAP



PARTICIPATIVE CARTOGRAPHY

In order to gain information about each dive sites popularity and locations, we have relied on participative cartography. This means that we have been going to ask each dive centers about their dive habits. Most centers usually maintain a logbook indicating which dive sites were visited and the frequency of those visits. This allowed us to pinpoint the location of previously unknown dive sites along with their names and to inventory the usage of each sites. Participative cartography is an ongoing project and could be used to create a heatmap representing dive site popularity upon completion. For now, we have created a template for a dive site map that could be distributed to dive centers around Mahahual vicinity (see FIGURE 3).

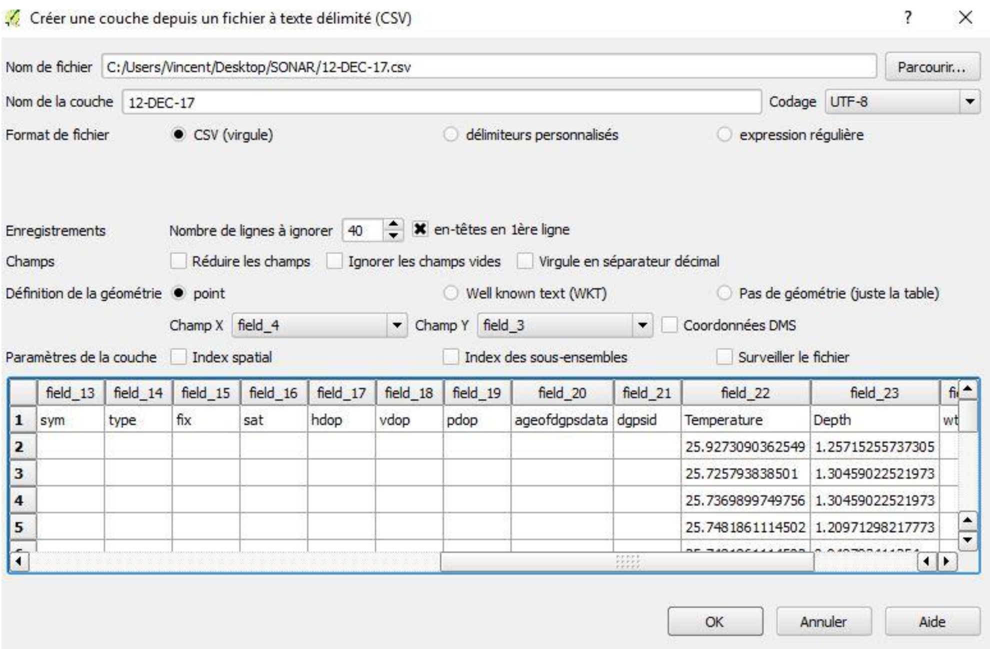
FIGURE 3 : MAHAHUAL DIVE SITES MAP



SONAR

The next step was to collect and extract bathymetric data and generate map-images of the seabed from sonar recording. TAKATA experience partnered with the University of Quintana Roo in order to acquire these data. The University graciously provided sonar equipment and expertise. Dr. Itzel Zamora accompanied us around the shore of Mahahual. The goal was to record side views of Sonar recordings and waypoints containing punctual depth. The Sonar recording would be of use later for TAKATA experience in order to interpret shapes of the sea bottom and distinguish benthic features. The waypoints could be used to create a bathymetric map of areas relevant to diving.

We collected waypoints and sideview recording over the course of 4 days. This allowed us to get data for most of the 1^{st} and 2^{nd} reef line of Mahahual. We collected a total of 7373 usable depth waypoints. The waypoints contained the depth while the sideview gave us an image of the sea bottom for further analysis. We saved the waypoints to the ADM format which could be read in Garmin software called Homeport. This enabled us to visualize data but we needed to port it to QGIS in order to work with it. .ADM files cannot be read in QGIS, we decided to extract the latitude, longitude and depth to Excel in order to save it as a .CSV table. We can then import the .CSV file into QGIS. We have to make sure to skip the first 42 lines to get to the actual data and to choose the appropriate X and Y coordinate accordingly to the longitude and latitude. This gives us a point Shapefile with information about the depth of each waypoint.

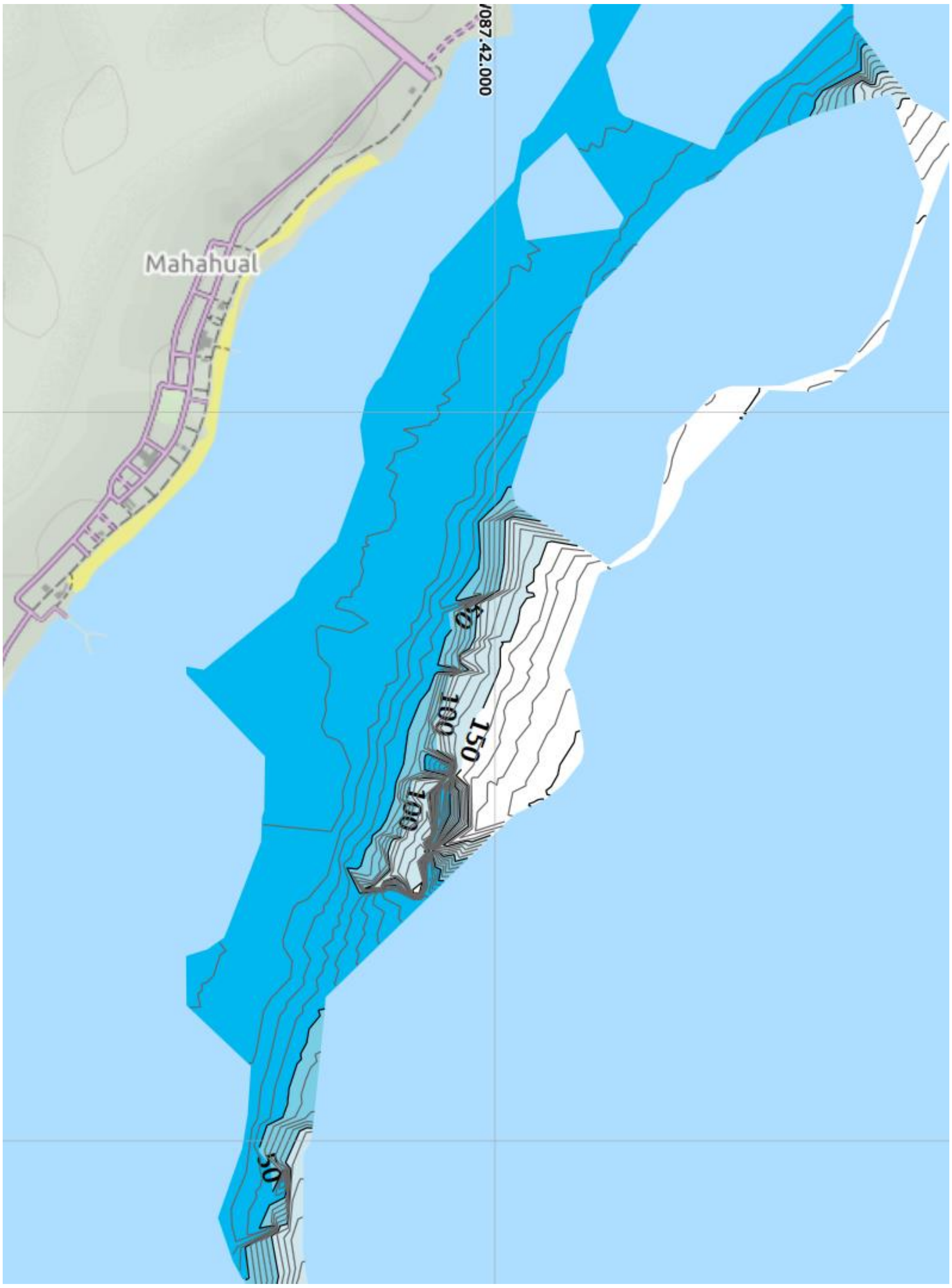


The waypoints were to be converted into a raster with the interpolation tool. This allows the program to construct new data points within the range of a discrete set of known data points. The output would be a raster image where each pixel has a depth value. We could then use the contour tool and create a hydrographic datum. This would allow us to draw depth curve of equal depth connecting the bathymetric contour.

But QGIS turned out to be an unreliable tool when interpolating data. It gave us random and unusable results. Other software such as ArcGIS would probably fare better with the methodology mentioned above. We found an alternative software called ReefMaster 2.0 that proved more reliable when using waypoints for contour mapping. While you need a paid license to use the software to its fullest, the trial version was sufficient to complete the mandate.

ReefMaster 2.0 does not support shapefiles (.SHP) but it can use Garmin's native extension such as .GPX. It also supports .CSV files which contains the depth necessary to map the reef unlike .GPX files. Although more data is essential to finish mapping the reef surrounding Mahahual, these tests serve as a proof of concept encouraging the project to use ReefMaster 2.0 for further data analysis as shown in Figure 4.

FIGURE 4: CONTOUR MAP PROOF OF CONCEPT

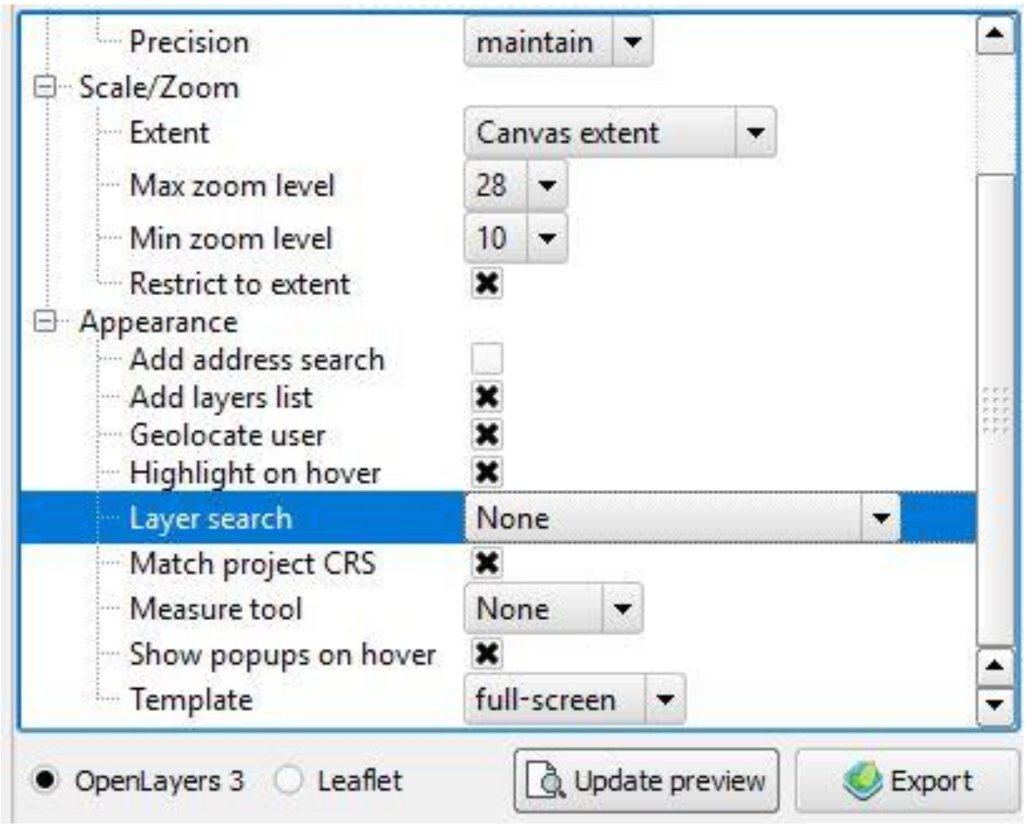


WEBMAP

We aimed to produce an online map to share progress with the database and to popularize the ensued data. It was also supposed to serve as a visualization tool for new volunteers and interns at TAKATA looking to give a hand in the RMP. But we needed to port our project to a format that can be used online. One plugin within QGIS called QGIS2Web allowed us to do just that. It allowed us to export our QGIS project to either a Leaflet or an Openlayers 3 webmap without any server-side software. It made it possible to highlight and show popups on hover. These popups could be filled with information from the attributes tables. We could also search the user geolocalisation with a Searchbar. This is useful to find how far we are from a specific AGGRA site or a dive site for exemple.

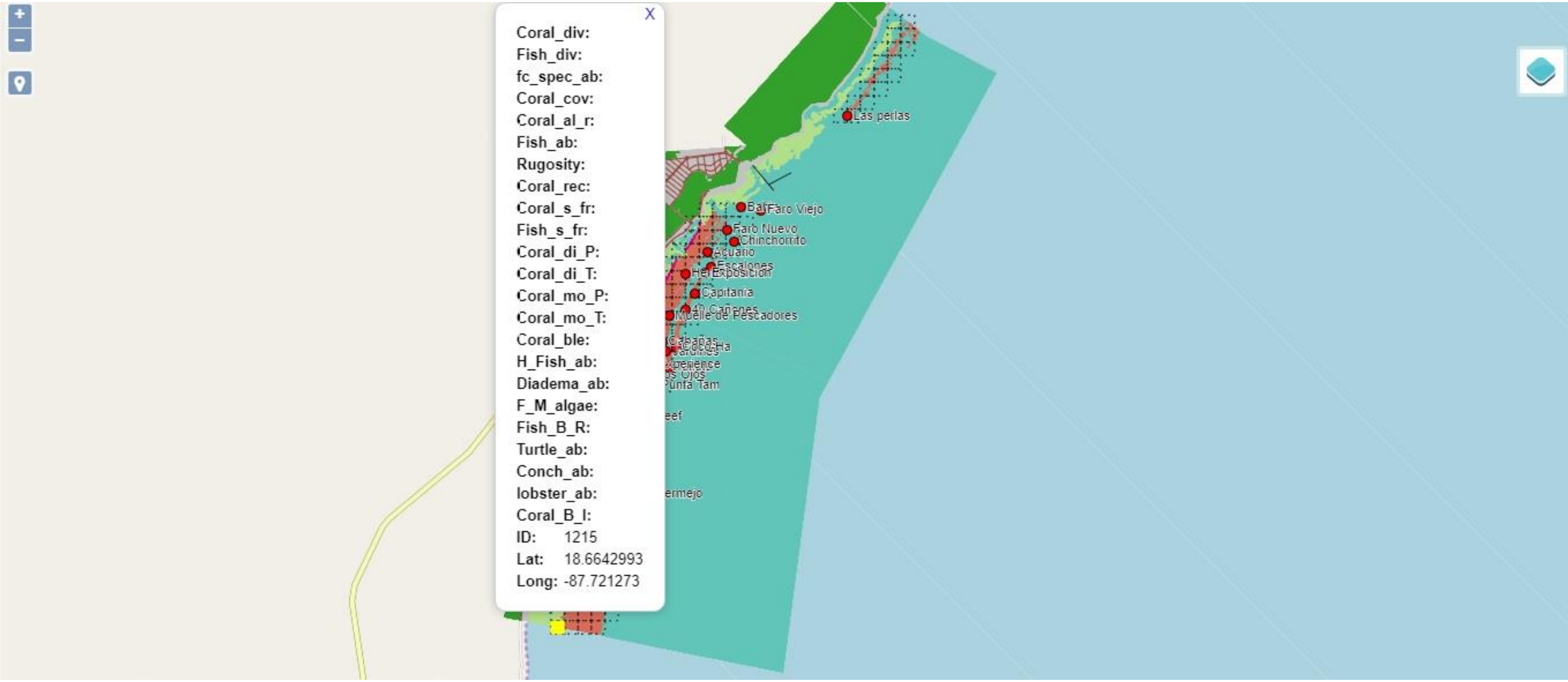
However, these online mapping technologies have their limitations, meaning some of the features included in previous maps couldn't be ported. Among the elements that couldn't be used were SVG point markers, dashed lines and line and polygon labels. We also had to convert our habitat map from vector to raster to avoid confusion when highlighting elements upon hovering with the cursor on top of them. We chose to use Openlayers 3 because it offered the best stability with rasters. This plugin is still in development and some features are not implemented yet. For example, you cannot set a search query for multiple layers as of now. This means that we had to choose to one feature over the others as demonstrated in Figure 5.

FIGURE 5: WEBMAP SETTINGS



We chose to restrict the zoom level to an extent that kept the map relevant to the user. We elected to include the geolocalisation tool to locate the user. This forced us to not include a layer search function or the measuring tool as they conflicted with the geolocalisation feature. Features will highlight upon hovering with the mouse cursor and a popup will give information about the attributes as shown in Figure 6.

FIGURE 6: WEBMAP TEMPLATE



CONCLUSION

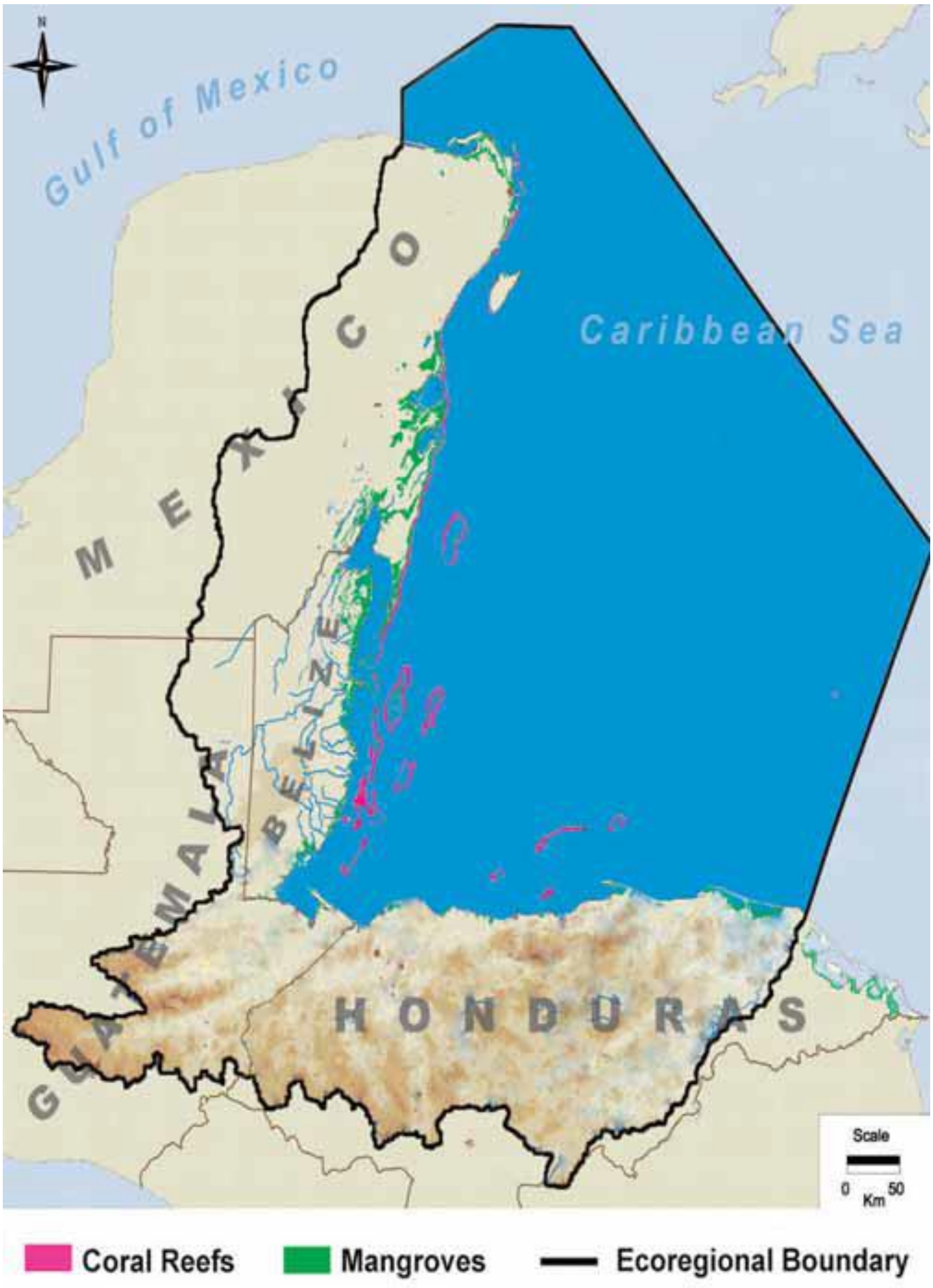
During this internship I had the opportunity to put into practice my GIS expertise within a professional setting. I came to gain an edge in GIS and fulfilling my tasks at TAKATA granted me that experience. What we are taught in university gives us the tools necessary, but those tools need to be sharpened with workplace experience.

While my knowledge of the reefs dynamics was minimal, TAKATA experience gave me the knowhow to tackle the challenge of mapping the coastal habitat. I rose to the status of Advanced Open Water Diver and learned much about coastal ecology.

I learned a lot by using open source software's with which I was less familiar with such as homeport or QGIS and its extensions. I also learned to build a database with the AGGRA protocol template. The quality of each maps I produced kept going up over the course of the internship. Even though I was held back by the limited computing power of my laptop, I learned how to use the QGIS in ways that didn't push my machines such as using only a partial Basemap to reduce loading times. While QGIS has limited tools compared to ESRI's ARCGIS, I learned to use workaround to achieve the same results. I even got a chance to work with new tools such as Garmin's Sonar and software's.

Overall, my time at TAKATA was a formidable experience boosted by both the geographical context, and the supportive staff. It also confirmed my desire to work within my field of study by reaffirming the multitude of opportunities available.

APPENDIX 1: Map of the Mesoamerican Reef Region



Taken from McField, M. and P. Richards Kramer. 2007. *Healthy Reefs for Healthy People: A Guide to Indicators of Reef Health and Social Well-being in the Mesoamerican Reef Region.* With contributions by M. Gorrez and M. McPherson. 208 pp.

APPENDIX 2: AGGRA database indicators guide

Indicator format:

INDICATOR NAME (page number in healthy reefs guide) (*indicator name in attribute table*) Data type and range or formula.

Biodiversity

CORAL DIVERSITY (14) (*Coral_div*) Float value depend on other indicators and uses the Shannon diversity index.

The Shannon diversity index (H) is commonly used to characterize species diversity in a community. Shannon's index accounts for both abundance and evenness of the species present. The proportion of species i relative to the total number of species (p_i) is calculated, and then multiplied by the natural logarithm of this proportion ($\ln p_i$). The resulting product is summed across species, and multiplied by -1:

$$H = -\sum_{i=1}^{S} p_i \ln p_i$$

Shannon's equitability (E_H) can be calculated by dividing H by H_{max} (here $H_{max} = \ln S$). Equitability assumes a value between 0 and 1 with 1 being complete evenness.

$$E_H = H / H_{max} = H / \ln S$$

Variables

H	Shannon's diversity index
S	total number of species in the community (richness)
p_i	proportion of S made up of the *i*th species
E_H	equitability (evenness)

FISH DIVERSITY (16) (*fish_div*) Float based on average sightings.

S2 FISH DIVERSITY

Two measures that approximate diversity and abundance are REEF's Density Index and Sighting Frequency. The following text is from REEF's website on interpreting REEF data (www.reef.org/data/interpret.htm).

> The REEF Density Index (DEN) is a measure of how many individuals of a species are observed based on a scale ranging from 1 to 4. Abundance category weights are Single = 1; Few = 2; Many = 3; and Abundant = 4. This weighted density average (Den) is calculated as follows:

$$DEN = \frac{(S * 1) + (F * 2) + (M * 3) + (A * 4)}{(\text{\# of surveys in which species was observed})}$$

FOCAL SPECIES ABUNDANCE (18) (*fc_spec_ab*) Integer, number of sightings for a specific specimen (determine species to focus on).

Community structure

CORAL COVER (22) (*Coral_cov*) Float (%) the amount of live stony coral tissue, relative to algae.

CORAL ALGAE RATIO (22) (*Coral_al_r*) Float (% the proportion of live coral cover to macroalgal cover.

FISH ABUNDANCE (24) (*Fish_ab*) Integer (g/100m$^{3)}$ Fish size and density (number of fish per unit area) Requires fish biomass.

RUGOSITY (26) (*Rugosity*) Integer, is measured in centimeters.

The diver measures the reef height — that is, the distance from reef top to reef bottom. (Reef bottom in this case refers to the base level at which corals grow. Measurements should not include the lower sand valleys in spur-and-groove systems).

Reproduction and recruitment

CORAL RECRUITMENT (46) (*Coral_rec*) Float (recruits per m^2) spotting baby coral can prove too difficult, use ceramic plates to improve chances of sightings.

CORAL SIZE FREQUENCY (50) (*Coral_s_fr*) Integer (cm) average coral size (average maximum diameter).

Using a 1-meter PVC bar marked off at 10-cm intervals. Each coral head encountered along a 10-m transect is characterized in terms of its maximum diameter (*x*), width (*y*) and height (*z*).

FISH SIZE FREQUENCY (52) (*Fish_s_fr*) Integer (cm).

Fish size refers to the estimated length of a fish. Divers count and measure key species encountered along ten transects (2 m wide by 30 m long) at each site. The fish are typically classified according to these (AGRRA) size categories: 0-5 cm, 6-10 cm, 11-20 cm, 21-30 cm, 31-40 cm, and > 40 cm).

Coral condition

CORAL MORTALITY (56) two indicators:

Coral mortality percentage (*Coral_mo_P*) Float (%) of dead coral.

Coral mortality type (*Coral_mo_T*) Text format, extent of mortality.

•Recent = (partial colony mortality with no algal cover to minimal algal cover)

• Old = (partial colony mortality covered by algae and noticeable calcification)

• Dead (colony decimated)

CORAL DISEASE (58) two indicators:

Coral disease percentage, (*Coral_di_P*) Float (%) Disease prevalence is expressed in terms of the percentage of total colonies affected.

Coral disease type (*coral_di_T*) Text format and disease type:

•BB = Black band. Concentric/linear band, maroon to black, 1-30 mm wide.

• WB = White band (*Acropora* only). Exposes skeleton in a band advancing from the base toward the branch tips.

• WS = White pox (or spot), patchy necrosis (*Acropora* only). Irregular lesions on the top sides of branches, 5-10 cm diameter. Re-infection results in a mosaic of recently exposed and older, algae-covered lesions.

• WP = White plague. Denuded skeleton is intact. The disease front is a sharp line; no microbial community is visible.

• RB = Red band. Dense band, maroon to red, 1-25 mm wide. Less common than black band disease.

• YB = Yellow band, yellow blotch. Concentric pale-yellow band, living tissue. Small spot in the center is recently killed and becomes large as the disease expands outwards.

• DS = Dark spot. Irregular dark patches of tissue. Surface is often slightly depressed.

• UK = Unknown.

CORAL BLEACHING (60) (*Coral_ble*) Integer (extent of bleaching with numeral code) these parameters can be calculated at the site or **regional level** (including all coral species in one reef wide average) or calculated by species, at a variety of scales.

The degree of bleaching can be categorized by severity (e.g., AGRRA):

0 = No bleaching,

1 = Pale (discoloration of coral tissue),

2 = Partly Bleached (patches of fully bleached or white tissue), and

3 = Bleached (tissue is totally white, no zooxanthellae visible).

Bleached corals can be monitored for subsequent mortality or disease.

Herbivor

HERBIVOROUS FISH ABUNDANCE (72) (*H_Fish_ab*) Integer (fish per m^2)

Divers measure fish density and size along belt transects. For example, the AGRRA methodologies recommend ten replicate transects, 2m wide by 50 m long.

DIADEMA ABUNBANCE (74) (*Diadema_ab*) Integer (number of urchin per m^2)

AGRRA methodologies recommend six transects (each 1 m wide and 10 m long) per site Measurements need to be standardized for the time of day to the extent possible (usually made between 10:00 a.m. and 2:00 p.m.).

FLESHY MACROALGAL INDEX (*F_M_algae*) (76) Integer (index calculated with algal cover % and average algal height).

Exact formula unspecified, requires more research on the subject.

FISH BITE RATES (78) (*Fish_B_R)* Integer (number of fish bite per unit of time and area)

Observation: A diver visually counts the number of fish bites during a specified time and area (e.g., 5 min in a 1-m plot). Grazing rate measurements need to be standardized for the time of day (usually made between 10:00 a.m. and 2:00 p.m.).

GREEN TURTLE ABUNDANCE (80) (*Turtle_ab*) Integer (sightings and nest count).

Tracking the number of nests in the MAR may not suffice. Collaborations with marine tour guides and fishermen are needed to develop a sighting frequency reporting protocol.

Fishing

CONCH ABUNDANCE (*Conch_ab*) (106) Integer (individual sightings per AGGRA site)

SPINY LOBSTER ABUNDANCE (106) (*lobster_ab*) Integer (harvest amount) requires coordination with fishermens or (individual sightings per AGGRA site)

Global climate change

CORAL BLEACHING INDEX (116) (*Coral_B_I*) Methodology unclear, see https://coralreefwatch.noaa.gov/satellite/ for more info.

APPENDIX 3: Layers summary

Under group Basemap:

- Hotels (saved as Hotels.shp) [CRS : EPSG : 4326, wgs84] point
  Vector shapefile describing the location of Mahahual hotels
  Classified under a unique symbol

- Lighthouse (saved as Lighthouse.shp) [CRS : EPSG : 4326, wgs84] point
  Vector shapefile describing the location of Mahahual lighthouse
  Classified under a unique symbol

- TAKATA_experience (saved as TAKATA_experience.shp) [CRS : EPSG : 4326, wgs84] point
  Vector shapefile describing the location of Mahahual diving shop TAKATA experience
  Classified under a unique symbol

- Docks (saved as docks.shp) [CRS : EPSG : 4326, wgs84] polyline
  Vector shapefile describing the extent of Mahahual docks
  Classified under a unique symbol

- Habitat (saved as Habitat.shp) [CRS : EPSG : 4326, wgs84] polygon
  Vector shapefile describing the general features of Mahahual coastal habitat
  Classified in 7 values:
  Anthropic: urban areas
  Mangrove: mangrove populated area
  NA: sea area awaiting data
  Reef: extent of the mapped submerged reef area
  Reef (Emerged): extent of the mapped emerged reef area
  Sand: extent of the mapped sandy seafloor area
  Seagrass: extent of the mapped seagrass covered seafloor area

- Basemap_cropped (saved as Basemap_cropped.tif) [CRS : EPSG : 3857, wgs 84/pseudo mercator] Raster
  Raster of a satellite image serving as a basemap for Mahahual
  Multiband color

Under Group AGGRA:

- AGGRA_SITES (saved as AGGRA_SITES.shp) [CRS : EPSG : 4326, wgs84] polygon
  Vector shapefile serving as a grid splitting the extent of the mapped reef in zones of 200m^2
  Classified under a unique symbol

- AGGRA_MAPEXTENT (saved as AGGRA_MAPEXTENT.shp) [CRS : EPSG : 4326, wgs84] polygon
  Vector shapefile serving as a grid splitting the extent of the map in zones of 200m^2
  Classified under a unique symbol

- AGGRA_SEA (saved as AGGRA_SEA.shp) [CRS : EPSG : 4326, wgs84] polygon
  Vector shapefile serving as a grid splitting the extent of the sea in zones of 200m^2
  Classified under a unique symbol

Under Group Unused:

- OsmBuildings (saved as OsmBuildings.shp) [CRS : EPSG : 4326, wgs84] point
  Vector shapefile describing the location of Mahahual buildings, some of them are used by captains to find diving sites
  Classified under a unique symbol

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List of dive centers interviewed for participative cartography:

- Dreamtime
- Pepe Dive Mahahual
- Takata Experience