Article Title:

ReefKIM: an integrated geodatabase for sustainable management of the Kimberley Reefs, North West Australia

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Abstract

Coral reefs of the Kimberley Bioregion are seldom studied due to limited accessibility and extreme water conditions, which make management of these vital ecosystems a challenging task. Managing reef resources requires a considerable amount of credible, consistent and continual information. We identified the geographic information system (GIS) approach to be useful in developing an integrated geodatabase by acquiring information from different sources relating to the Kimberley reefs. Based on this approach, the study aimed to create a foundation for the first comprehensive geodatabase of the Kimberley reefs, called ReefKIM. The work included compiling existing spatial and non-spatial data, as well as collecting new data to complete information gaps. The study demonstrates how new

technologies can be harnessed to crowdsource data from a wide range of people though a web-based platform. ReefKIM will provide a practical tool for scientists and managers to facilitate better monitoring and sustainable management of these vital natural resources. Moreover, it will support further studies in various disciplines leading to a more detailed understanding of the Kimberley Bioregion reefs.

Keywords: geodatabase, reef conservation, reef management, GIS, crowdsourcing, citizen science

1. Introduction

The coral reefs of Australia's North West Kimberley Bioregion have been recently recognised as being of international significance (Wilkinson 2008 and Chin et al. 2008). The Kimberley reefs are particularly unique in that they inhabit an environment with the highest tidal range in the southern hemisphere (up to 11 m) and appear to endure high levels of turbidity and frequent cyclones. These extreme environments have resulted in coral reefs with unique geomorphological attributes which merit further study (Wilson, 2013). The remoteness of the Kimberley Bioregion has, for an inshore continental reef system, resulted in very low levels of direct anthropogenic impacts (Collins, 2011). While this remoteness has been an advantage in maintaining reef health, the cost of fieldwork and data acquisition can be prohibitively expensive, which has limited the ability of marine scientists and managers to access the region. The result is that compared to regions like the Great Barrier Reef, only a small pool of data has been collected from the Kimberley by a variety of sources including; universities, government agencies, tourism operators, commercial and recreational fishermen and most importantly, the traditional owners that inhabit the region. The result is a small amount of data spread across a large number of stakeholders making information on these reefs either rarely available or inaccessible.

There is a critical need to know what kind of data has been collected from the Kimberley coast and if they are available to share or exchange. In the first instance greater accessibility of data should prevent duplication of previous work, reduce cost, increase data quality (Chesnaux et al. 2011) and allow for multiuse datasets. In order to address these issues and more, this study aims to create a high-capacity, multi-source, easy-to-access and cost-effective geodatabase for Kimberley reefs. The database is a foundation for future marine studies in the Kimberley Bioregion. It provides researchers and managers with critical scientific data and identifies knowledge gaps that need to be addressed.

1.1. Reef geodatabases

A geographic information system (GIS)-based database, or geodatabase, is a computer-based system that can handle a variety of information, including both locational and attribute data of a particular feature. It not only displays and produces maps but can also record and analyse descriptive characteristics of map features. Geodatabases have been developed for many coral reef regions around the world, particularly in the areas of coral reef management and conservation with the efforts of the Great Barrier Reef Marine Park Authority (GBRMPA) in the early 1990s (Hartcher and Shearin 1996) being an early example. Since then, usage of GIS for data management has increased rapidly and expanded worldwide. The construction of the Global Coral Reef Database, also known as ReefBase or ReefGIS, was initiated in 1993 by the International Centre for Living Aquatic Resources Management (ICLARM), and is a good example of a global-scale GIS database (McManus 1994; McManus and Ablan 1997). Another global-scale assessment of total reef area was undertaken using GIS-based technology by Spalding and Grenfell (1997). Similarly, the map-based indicator Reefs at Risk was developed by the World Resources Institute (WRI) and uses GIS to assess potential threats to coral reef ecosystems around the world (Bryant et al. 1998). Dahdouh-Guebas (2002) applied an environmental GIS database to the sustainable development and management of tropical coastal ecosystems by collecting and integrating data from different disciplines. More recently, a regional-scale GIS database named ReefBahia was developed to assist in managing and conserving the coral reefs of Bahia in Brazil (Carvalho and de Kikuchi 2013), and another was created to improve management of the Coral Triangle (Beare 2014; Cros et al. 2014).

Rapid developments in information and communication technology, particularly over the last decade, have led to an exponential increase in computational and networking efficiency, which facilitates the aggregation of vast amounts of data through sophisticated, relatively affordable, and highly accurate devices, such as smart phones, tablets and portable computers (Heipke 2010). Moreover, these devices are often equipped with high-definition digital cameras, built-in global positioning systems (GPS), internet connectivity and high-capacity memory storage, which allow for recording of data and capturing images and videos associated with essential metadata, such as location (geo-referenced), date and time. Other optional information can be entered manually or through a software application menu designed for a particular type of data in order to avoid entry errors (Briner et al. 1999).

1.2. Crowdsourcing data

New technologies have changed the way researchers and managers receive information from the field. The crowdsourcing geospatial data approach for information aggregation has been implemented worldwide for a variety of purposes, including creating and sharing geographic information volunteered by individuals through common and freely available platforms such as Wikimapia and OpenStreetMap (Goodchild 2007; Hacklay 2008) and assisting people during crises through programs such as Ushahidi (Okolloh 2009). Furthermore, the crowdsourcing approach has been employed in many scientific endeavours, including Geo-Wiki, a global network of volunteers helping to improve the quality of global land cover maps (Fritz et al. 2009; Comber et al. 2013). In a recent study, Franzoni and Sauermann (2014) thoroughly discussed benefits of scientific research in open collaborative projects using the ‘crowd science’ or ‘citizen science’ approach. Rovere et al. (2012) also conveyed the advantages of crowdsourcing for the creation of databases of sea levels from the mid-Pliocene warm period.

According to Lewis et al. (2003), community participation played a significant role in re-zoning the GBRMPA. Volunteer involvement in the monitoring program Reef Watch, coordinated by the Conservation Council of South Australia for the sustainable management of marine ecosystems, has helped increase knowledge about the status of temperate reefs in South Australia (CCSA 2009).

Additionally, volunteer divers and snorkelers recorded about 180 marine species in Victoria, Australia, through the monitoring initiative Reef Watch Victoria, developed by the Victoria National Parks Association and Museum Victoria to protect Victoria's marine environment (VNPA 2014). Another remarkable monitoring program called Eye on the Reef, managed by GBRMPA, in partnership with the Queensland Parks and Wildlife Service, enables visitors to the Great Barrier Reef to report reef observations though a web map and/or smartphone or tablet application. The data provide Marine Park managers and researchers with up-to-date information on current reef status (GBRMPA 2014).

The main aim of this study is to establish a geodatabase of information on the Kimberley reefs in order to provide a regional picture of the reef numbers, types and status. The work included compiling existing spatial and non-spatial data and collecting new data through online GIS sources. Furthermore, the database allows for crowdsourcing of future data to fill in information gaps. The geodatabase has been developed through a partnership with the Western Australian Marine Science Institution (WAMSI) for the Kimberley Marine Research Program (KMRP) and implemented with the sponsorship of the Government of Western Australian. This geodatabase will improve our knowledge and provide decision makers with helpful information for the sustainable management of this vital reef ecosystem.

2. Methodology

Constructing a useful geodatabase requires a considerable amount of different types of data distributed across both time and space. ArcGIS 10 software developed by the Environmental Systems Research Institute (ESRI) was selected for developing the database due to its high performance and wide recognition. Procedures used in this study are illustrated in Figure 1.

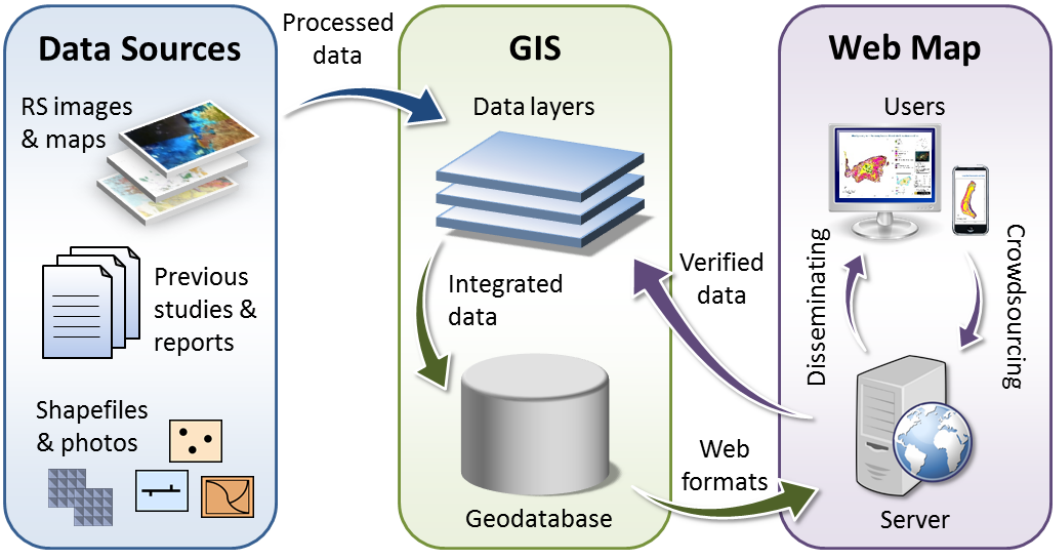


Figure 1. Methodological scheme of data acquisition, processing, integration and storage for the Kimberley reef geodatabase (ReefKIM).

2.1. Data sources

The information related to the study area was acquired from various sources (Table 1). Most of the datasets used in this study were available in digital formats (i.e. raster and vector); otherwise, they were digitised. Satellite images, maps, charts and other datasets covering the entire study area were compiled. The database comprises more than 90 satellite image scenes acquired between 1998 and 2014 from Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+) and Operational Land Imager (OLI) sensors. The geodatabase also contains 18 geological maps, 12 bathymetric charts and a set of 24 very high resolution orthophotographs covering the entire Kimberley coast and nearshore islands. Moreover, there are over 2,500 ground truth points, about 295 km of seismic lines, 52 core points and 800 site images. Other related data were extracted from a wide range of secondary and tertiary sources, such as reports, publications, atlases, books, maps and encyclopaedias. The geodatabase was designed to allow modification of current data and addition of new information and photographs, which can be aggregated or crowdsourced through a web-map platform (e.g. Google Earth) using laptops, smartphones or tablets.

Table 1. Datasets used in this study and their sources

Dataset	Source of data*	Data format
Kimberley coastline	Satellite images (USGS), orthophotos (Landgate, Western Australia and DPaW).	Raster
Islands	Satellite images (USGS), orthophotos (Landgate, Western Australia and DPaW), bathymetric charts (AHO), geological maps (GSWA)	Raster
Coral reef	Satellite images (USGS), orthophotos (Landgate, Western Australia and DPaW), bathymetric charts (AHO), geological maps (GSWA) WAM/Woodside Collection Kimberley Project 2008-2011; Brooke 1995, 1997; Wilson 2011, 2013	Raster Points
Seabed geomorphology	Geoscience Australia	Polygon
Sea surface temp.	NOAA	Polygon
Bathymetric contours	GA, AHO	Polyline
Sub-bottom profiles	Collins et al. 2015	Polyline
Ground-truth	WAM/Woodside Collection Kimberley Project 2008-2012; Wilson and Blake 2011; Wilson et al. 2011; WAMSI 1.3.1 Reef Geomorphology Project 2012-2015	Points
Reef coring	Solihuddin et al. 2015	Points
Weather and tide	BOM	Various

*Note: The data were sourced from national and international government agencies, including the Department of Parks and Wildlife (DPaW), Geoscience Australia (GA), the Western Australia Marine Science Institute (WAMSI), the Geological Survey of Western Australia (GSWA), Western Australian Museum (WAM), Australian Hydrographical Service (AHO), Australian Bureau of Meteorology (BOM), the United States Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA).

2.2. Data processing

Initial preparation of the data (pre-processing) is important to ensure accuracy and reliability. The satellite imagery was processed using ENVI 4.3 software prior to data extraction. ArcGIS was then used to integrate various images with other data sources. Maps and charts were geo-referenced and projected according to the Geocentric Datum of Australia (GDA 94) for consistency and homogeneity. All remotely sensed images were calibrated and atmospherically corrected. Moreover, some images were pre-processed to offset problems with band data and to recalculate DN values. Subsequently, a range of map features, including coastline, islands, reefs and areas of shoaling, were precisely digitised and geomorphological zones and associated habitats and substrates were determined.

2.3. Data integration

Because a single dataset usually does not contain all the necessary information, data integration was employed to fill in the missing information. The use of GIS data overlays enables comparisons to be made and links created between datasets with common spatial properties. Such overlays enhance data interpretation, reveal correlations and allow distribution patterns between different phenomena and zones on reefs to be identified (El-Raey et al. 1996; Bryant et al. 1998; Salm et al. 2000; Crosby et al. 2002). Further, GIS allows digitised and georeferenced non-digital data to be integrated with other data (Chapman and Turner 2004). Integration allows for data verification, detection of changes, and data updating (Gösseln and Sester 2005). It has also been used to combine multiple sources of data for the same object or feature in order to extract information or add value. As a result, a consistent and accurate dataset that is more informative than the original can be produced.

The resulting features were stored in vector format so that they could be presented using different colours and symbols for easy differentiation. Each feature was linked to its attributes, such as the feature name, type, area, location, date of survey, source of data and any other related information. All this data was then saved in an attribute table enabling further data analysis to improve understanding of linkages between geological substrate, reef geomorphology, reef classification and distribution.

Subsequently, all data were compiled into a data library, and information relevant to this project was extracted, rectified and entered into a database. The selected information was represented as feature classes and raster-based datasets in ArcGIS as usable data layers. This geodatabase also contains the most significant elements and conditions that influence reef growth in the region.

2.4. Data accessibility

A GIS-based database enables an administrator to control and restrict access to authorised users only, to avoid accidental loss of data. It also supports a wide range of database queries and operations. For example, users can search for information within the database using Structured Query Language

(SQL). A copy of reef and island data layers was converted to an open, web based format using Keyhole Markup Language (KML), in this case to enable visualisation in Google Earth. Dissemination of data though a web-based platform allows aggregating new information though consistent crowdsourcing. These outsourced data must be rectified before being compiled into the geodatabase.

3. Results

A geodatabase of the Kimberley reefs, termed ReefKIM, was constructed. A variety of sources were used in this study to foster and maximise extraction and interpretation of data. As a result, six feature classes were derived from these datasets and saved consistently in the geodatabase. The feature classes (described in Table 2) include *reefs*, *coastline*, *islands*, *geomorphological zones*, *habitats and substrates* and *other studies and work*.

Table 2. Resultant feature classes included in ReefKIM

Feature class	Contents	Format
Reefs	853 reef features including sizes, shapes and types were recorded.	Vector
Coastline	A 5,300 km line of the mainland coast was mapped using the mean low water neap (MLWN) level to ensure that mangroves and reef flats were not included.	Vector
Islands	Over 2,400 island features (i.e. islets, exposed rocks and exposed cays) as defined by Geoscience Australia were recorded.	Vector
Geomorphological zones	Five reef geomorphologic zones (i.e. land, reef flat, lagoon, reef crest and fore-reef slope) were recorded for 30 reefs.	Vector
Habitats and substrates	Seven key habitats and substrates (i.e. mangroves, sand, seagrass and algae, coral rubble, reef pavement with algal turf, crustose coralline algae and coral communities) were recorded.	Vector
Other studies and work	This class encompasses geographic locations of all studies, work and information related to the Kimberley reefs that have been encountered and accessed (e.g. ground truth points, survey, sample collections, coring sites, sub-bottom profiles, images, etc.)	Vector

Each resulting feature class can be displayed in ArcGIS either as a solo data layer or in conjunction with other data layers according to the information that needs to be illustrated and/or calculated. For example, three feature classes (*reefs*, *islands* and *coastline*) are displayed simultaneously in Figure 3, showing the extent of the Kimberley coastline and the distribution of reefs and islands on a regional-scale map. 853 reefs and 2,413 islands were mapped along the 5,300 km coastline, for which number, areas, geographic distribution and distance from coastline can be calculated. The numbered reefs highlighted in orange indicate the locations of 30 reefs that have been mapped in detail.

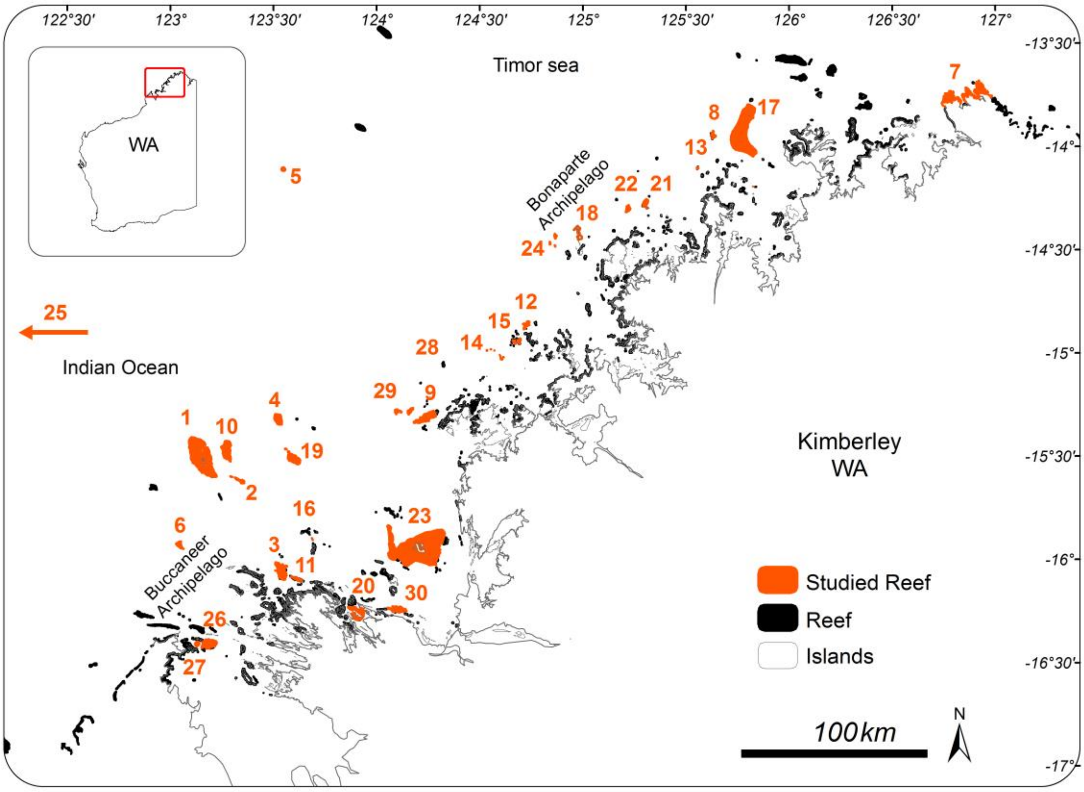


Figure 2. Spatial distribution map of the Kimberley reefs and islands compiled in ReefKIM. The arrow on the left-hand side of the map points toward reef number 25, Scott Reef.

The 30 reefs are listed alphabetically in Table 3 along with sources of information used to map them in more detail. Landsat images, geological maps and bathymetric charts were used for all these reefs, while ground truth data were available for 90% of the studied reefs. However, sub-bottom profiling and coring data were only available for fewer than 23% of the reefs. Adele Reef and Cockatoo Island had the largest number of data sources. On the other hand, Beagle Reef, Cape Londonderry, Mavis Reef, and King Island had the fewest available data sources.

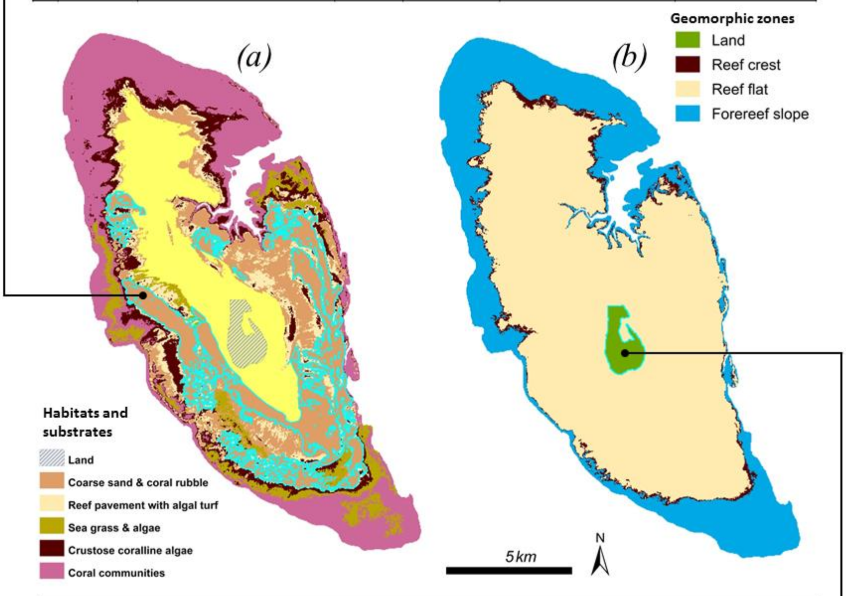
Table 3. Data sources used to produce geomorphic, substrate and facies maps for targeted reefs (reefs are listed in alphabetical order)

	Reef	**Data sources***									
		LS	**OP**	**HR**	**GM**	**GT**	**SBP**	**BC**	**PS**	**CO**	**SI**
1	Adele Reef	✓		✓	✓	✓	✓	✓	✓	✓	✓
2	Albert Reef	✓		✓	✓	✓		✓			
3	Bathurst and Irvine islands	✓	✓		✓	✓	✓	✓		✓	✓
4	Beagle Reef	✓			✓	✓		✓			
5	Browse Island	✓		✓	✓	✓		✓	✓		✓
6	Brue Reef	✓		✓	✓	✓	✓	✓			
7	Cape Londonderry	✓	✓		✓			✓			
8	Cassini Island	✓		✓	✓	✓		✓	✓		
9	Champagny Island	✓	✓		✓	✓		✓			
10	Churchill Reef	✓			✓		✓	✓	✓		
11	Cockatoo Island	✓	✓		✓	✓	✓	✓	✓	✓	✓
12	Colbert Island	✓		✓	✓	✓		✓	✓		
13	Condillac Island	✓	✓		✓	✓		✓			
14	De Freycinet Island	✓		✓	✓	✓		✓			
15	Hedley Island	✓		✓	✓	✓		✓	✓		
16	King Island	✓			✓	✓		✓			
17	Long Reef	✓	✓		✓	✓		✓	✓		✓
18	Maret Island	✓		✓	✓	✓		✓	✓		✓
19	Mavis Reef	✓			✓	✓		✓			
20	Molema Island	✓	✓		✓	✓		✓	✓		✓
21	E. Montalivet Island	✓	✓	✓	✓	✓		✓	✓		✓
22	W. Montalivet Island	✓	✓	✓	✓	✓		✓	✓		✓
23	Montgomery Reef	✓	✓		✓	✓	✓	✓	✓		✓
24	Robroy Reef	✓			✓	✓		✓	✓		
25	Scott Reef	✓			✓	✓	✓	✓	✓	✓	
26	Sunday Island	✓	✓		✓	✓		✓		✓	✓
27	Tallon Island	✓	✓		✓	✓		✓		✓	✓
28	White Reef	✓	✓	✓	✓	✓		✓	✓		
29	Wildcat Reef	✓	✓		✓	✓		✓	✓		
30	Woninjaba Island	✓	✓		✓			✓	✓		

*Note: Data source acronyms are LS = Landsat images, OP = orthophotos, HR = higher resolution satellite images, GM = geological maps, GT = ground truth, SBP = sub-bottom profiling, BC = bathymetric charts, PS = previous studies, CO = coring and SI = site images.

The geodatabase can also present information at the reef scale to display further details on individual reefs. For instance, the *geomorphic zone* feature class can include information on geomorphology, including shapes, areas and distributions, for specific reefs. Moreover, further information on associated habitats and substrate coverage for these geomorphic zones were stored in the *habitats and substrates* feature class. Figure 3 illustrates an example of geomorphic zones and habitat and substrate maps for Adele Reef. Geomorphic zones are presented in different colours to delineate the boundaries of each zone, while related information, such as the zone's name, area, percentage of coverage and other values, is recorded in an attribute table and linked to a certain map feature. For example, in Figure 3a, a land zone is highlighted on the map, and information related to this selected feature is shown in the bottom attribute table, revealing that land area on Adele Reef is 0.28 km^2, covering approximately 0.2% of the total reef. Similarly, Figure 3b shows the distribution of habitats and substrates on Adele Reef with distinguishable boundaries for each feature. The highlighted feature represents the *coarse sand and coral rubble* class. The statistical information of this selected feature is presented in the top attribute table, revealing that the coarse sand and coral rubble class covers over 41 km^2, which represents more than 24% of the total reef coverage.

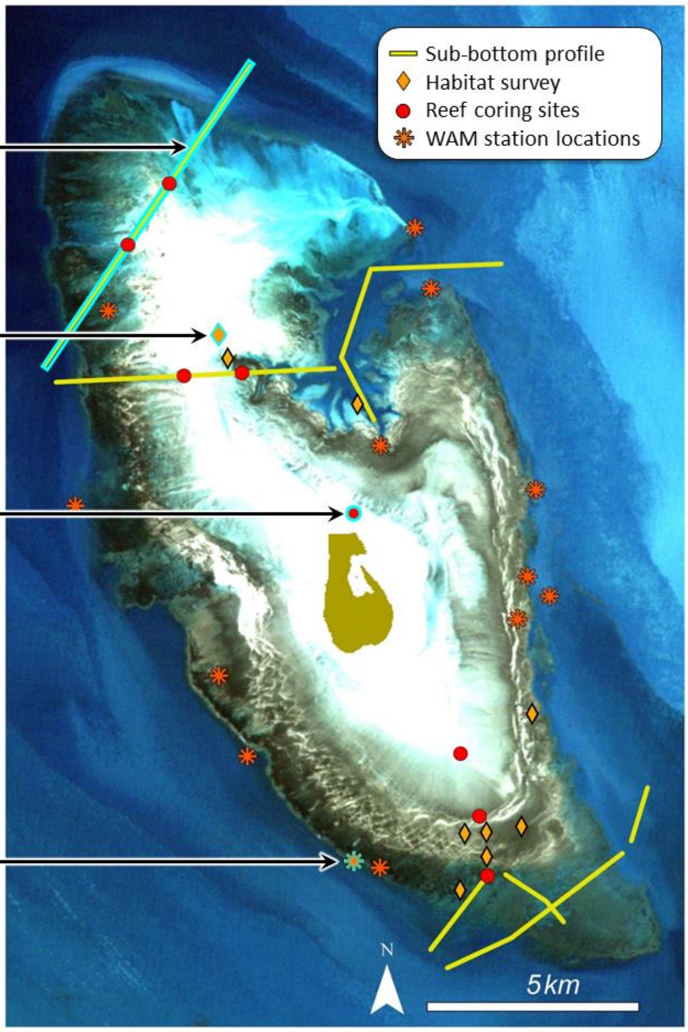
	OBJECTID*	Class_Name*	Class_ID	Reef	Percentage_coverage (%)	Shape_Area (Km²)
	45	Sand	01	Adele	28.5	47.82
▶	47	Coarse sand & coral rubble	02	Adele	24.6	41.40
	48	Reef pavement with algal turf	03	Adele	6.8	11.51
	49	Sea grass & algae	04	Adele	7.6	12.82
	50	Crustose coralline algae	05	Adele	9.0	15.14
	51	Coral communities	06	Adele	23.5	39.39
	52					



	OBJECTID*	Class_Name*	Class_ID	Reef	Percentage_coverage (%)	Shape_Area (Km²)
▶	13	Land	01	Adele	0.2	0.28
	14	Reef crest	02	Adele	3.2	5.4
	15	Reef flat	03	Adele	66.2	111.2
	16	Forereef slope	04	Adele	30.5	51.2
	17					

Figure 3. Two maps of Adele reef: (*a*) intra-reef geomorphic zones and (*b*) distribution of habitats and substrates on the reef platform. Each map feature is connected to an attribute table in the geodatabase.

Information on previous studies and work on the Kimberley reefs are also presented on a reef-scale map. Figure 4, for example, shows the locations of some available information sourced from a variety of studies and work on Adele Reef. Each source of information is represented by a distinct symbol on the map. On Adele Reef, for instance, seven sub-bottom profiles have been surveyed, and nine habitat sites have been studied. Additionally, 13 monitoring stations have been established, and eight sites have been cored. All the information is stored in the *other studies and work* feature class with links to its origin in the attribute table.



	OBJECTID*	Feature_name	Reef/Island	Data_type	Data_source	Restrictions
	202	WAM station locations	Adele	Field survey	WAM&Woodside Collection Project (KIM) 2008-2011	Copyrights
▶	203	WAM station locations	Adele	Field survey	WAM&Woodside Collection Project (KIM) 2008-2011	Copyrights
	204	WAM station locations	Adele	Field survey	WAM&Woodside Collection Project (KIM) 2008-2011	Copyrights
	205	WAM station locations	Adele	Field survey	WAM&Woodside Collection Project (KIM) 2008-2011	Copyrights
▶	134	Reef coring sites	Adele	Stratigraphic	KMRP, WAMSI Project 1.3.1 (2012 – 2015)	Copyrights
	135	Reef coring sites	Adele	Stratigraphic	KMRP, WAMSI Project 1.3.1 (2012 – 2015)	Copyrights
	136	Reef coring sites	Adele	Stratigraphic	KMRP, WAMSI Project 1.3.1 (2012 – 2015)	Copyrights
	137	Reef coring sites	Adele	Stratigraphic	KMRP, WAMSI Project 1.3.1 (2012 – 2015)	Copyrights
	413	Habitat survey	Adele	Photos	Solihuddin, T	Copyrights
▶	414	Habitat survey	Adele	Photos	Solihuddin, T	Copyrights
	415	Habitat survey	Adele	Photos	Solihuddin, T	Copyrights
	416	Habitat survey	Adele	Photos	Solihuddin, T	Copyrights
	357	Sub-bottom profile survey	Adele	VSP	KMRP, WAMSI Project 1.3.1 (2012 – 2015)	Copyrights
	358	Sub-bottom profile survey	Adele	VSP	KMRP, WAMSI Project 1.3.1 (2012 – 2015)	Copyrights
▶	359	Sub-bottom profile survey	Adele	VSP	KMRP, WAMSI Project 1.3.1 (2012 – 2015)	Copyrights
	360	Sub-bottom profile survey	Adele	VSP	KMRP, WAMSI Project 1.3.1 (2012 – 2015)	Copyrights

Figure 4. Satellite image of Adele Reef showing locations of previous studies and works on this reef with links to their origins in attribute tables.

Reef data was converted to KML for visualisation in Google Earth. Figure 5 depicts reef distribution in vivid orange across the entire Kimberley coast in Google Earth. It also demonstrates that some reefs can have map pins and name labels as visualisation tools. The layers panel on the left-hand side of the map allows users to choose (by turning on or off) the information to be displayed over the map in the map view.

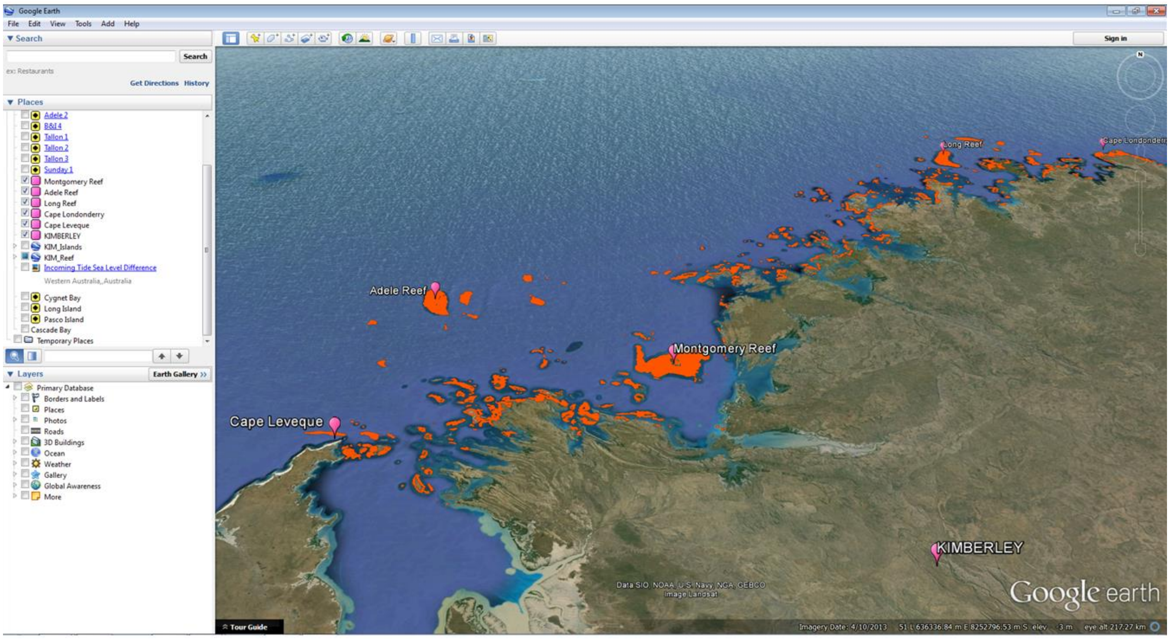


Figure 5. Screenshot of an oblique view of the Kimberley Bioregion. Reefs are shown in vivid orange in Google Earth.

Moreover, additional information crowdsourced into the map was examined. Figure 6 shows an example of photos taken using smartphone cameras from 10 different locations and added into the map. After the photos were uploaded, their locations were marked on the map by yellow map pins, which can be clicked for further information. For instance, the pop-up window shown in Figure 6 points to one of these yellow map pins, located on a reef flat between Bathurst and Irvine islands. The window presents the reef picture and essential information, such as the name of that site, date, time and coordinates.

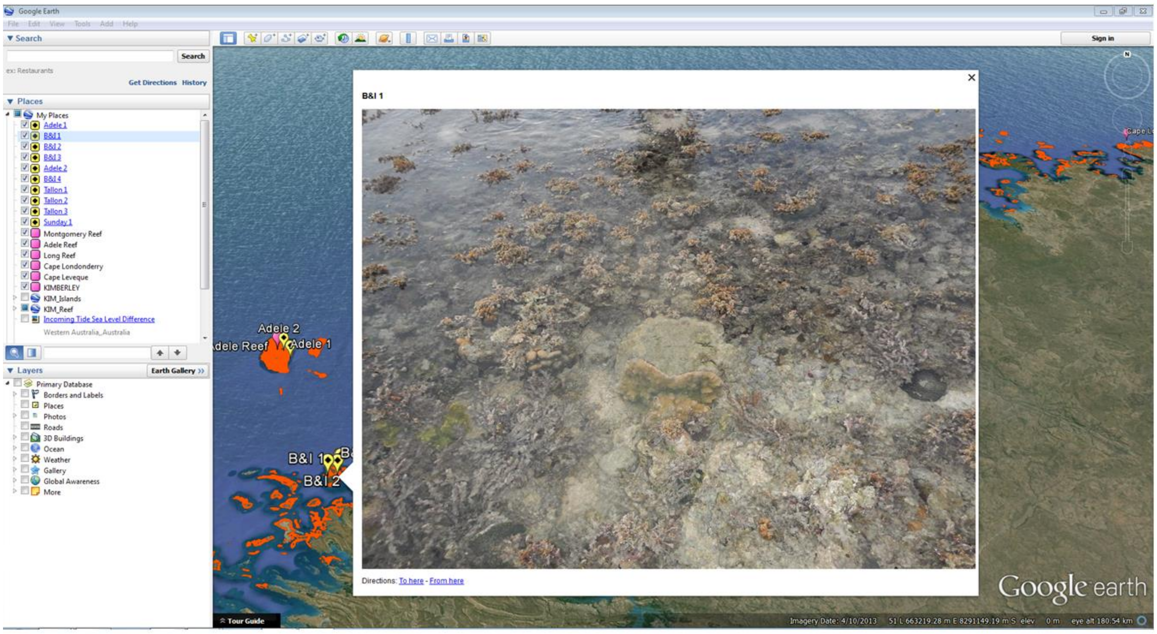


Figure 6. Screenshot showing photo locations (as yellow map pins). A pop-up window displays a reef photo with relevant information.

4. Discussion

Prior to the gazetting of the KMRP, there had only been a handful of studies that investigated the coral reefs and marine environments in the Kimberley Bioregion. While additional information had been collected by scientists and managers over the course of decades, much of this information remained unpublished, or housed as internal reports making access to information difficult.

ReefKIM is the first attempt to collate and integrate this information related to the Kimberley reefs into one comprehensive geodatabase. Accordingly, the preliminary focus in this stage of ReefKIM is mainly on obtaining and recording essential information, such as reef occurrence, spatial distribution, geomorphic classification and typology and key habitats and substrates. ReefKIM users are consequently able to explore any reef system as well as individual reefs through reef-scale maps, to obtain details on reef dimension, habitats and substrate cover and other information related to management efforts. Acquiring new information will necessitate additional literature searches and the involvement of a wide range of stakeholders and other individuals.

The study developed a process for constructing an integrated geodatabase using various types and sources of datasets, fostering data fusion and maximising accessibility of important information for a better understanding of the Kimberley coral reefs. This data integration approach has resulted in significant improvements in reef mapping. It showed, for example, that the number and area of Kimberley reefs are approximately 60% greater than described by previous studies, as many areas that may comprise reefs were unmapped due to lack of information. Reef number and area are anticipated to increase considerably as more information becomes available. The data integration approach also led to the creation of detailed reef-scale maps of 30 reefs in different geographical locations within the Kimberley Bioregion. Intra-reef geomorphic zones and associated biosedimentary substrates were mapped. Such spatial analyses support marine park and coastal managers in their efforts to monitor coastal development and assess the impacts of different hazards on the coastal environment (Gayanilo et al., 1998; Freire, 2001; Puotinen, 2005, 2007; Ma et al. 2013).

During field work in the Kimberley Bioregion, it was noticed that many people connected with the marine environment (e.g. rangers, fishermen, pearl farmers, traditional owners, nature photographers and tourists) possess valuable information, such as site images, underwater videos and photos and aerial photography of marine fauna and flora, including reefs. This information has had a significant role in the verification of satellite images when reef habitats and substrates have been mapped. Optimistically, these people were willing to share their knowledge for the sake of conservation of this vital ecosystem.

Some information in the geodatabase can be made accessible to the public through a web-based interactive map allowing the selection, query and addition of information. This reef map can be used as a platform for crowdsourcing information from other participants to help implement reef monitoring. ReefKIM, as with many newly constructed geodatabases, requires frequent updates and insertion of new information to increase efficiency and effectiveness at long-term monitoring. Google Earth was employed to examine reef data visualisation due to its capabilities in handling various types of imagery and other geographic information and viewing and searching for specific locations.

Furthermore, this platform enables crowdsourcing of information, through which users can easily contribute to the development of this geodatabase by adding and sharing their knowledge.

Crowdsourcing is a promising approach for filling knowledge gaps and enhancing the understanding of such complex reef ecosystems. Both scientists and managers need a tremendous number of data points to be collected, which may not be feasible with small teams. However, the task may be more achievable if a large number of people are involved. Each data entry can be verified, labelled according to its reliability, referenced and acknowledged. Crowdsourcing will help produce more reliable information as the project progresses. The management efforts of the GBRMPA and its associated ecosystems are considered a model example of the contemporary reef management process. ReefKIM will allow the best practices from these efforts to be replicated for the Kimberley.

ReefKIM's data is expected to enable the detection of changes and quantification of current reef conditions at the regional and national levels, helping keep managers and conservation organisations informed and equipped to implement the required policy changes (Ma et al., 2011, 2013). In addition to being a management tool, ReefKIM can be also useful in pinpointing future research priorities (cf. GBRMPA).

5. Conclusions

ReefKIM is a GIS-based database constructed upon previous and current work, incorporating a wide range of datasets, including remote sensing images, bathymetric charts, site photos and many geological and biological datasets into one inclusive geodatabase. It is intended to provide researchers with an overview of essential information on the Kimberley reefs, where many reefs have yet to be mapped. It also constitutes a significant decision-making tool, as it can provide managers with practical support for the implementation of their plans and will help shape the direction of future management policies of coral reefs in the Kimberley region.

The database was designed to be developed in collaboration with other regional and national institutions as well as individuals through a web-based map. The crowdsourcing approach allows many people already in the field, such as researchers, rangers, fishermen, tourists and traditional owners, to become involved in mapping and share their valuable knowledge.

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