Faculty of Science and Engineering

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Evaluation of the coastal inundation and erosion process in the Mid-West coast of Western Australia

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

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Abstract

At present the coastal inundation and erosion is a major problem all around the world and this issue will be more severe in the future due to sea level rise. Australia has a long coastline around the country, thus it focus on the coastal vulnerability due to sea level rise. Taking these facts into account, this research was focused on the evaluation of the coastal inundation and erosion process in the Mid-West coast of Western Australia. Within the Mid-West region, a seventy five kilometre stretch was selected for the study.

The major highlight of this research is the integrated modelling approach and the result of the modelling carried out for evaluation of the coastal inundation and erosion process. Widely used coastal model, MIKE 21 was selected as the dynamic model for the study. As data plays very important part for this research, an intensive data collection campaign was conducted to collect the required data. Bathymetry data, coastal boundary data, topography data, wave, water levels and wind data, were collected using discrete data sources from variety of government, local and private organizations. Extreme value analysis for water levels, wind and wave was done using Gumbel and Weibull distributions.

The final results of the inundation and erosion extends have been presented in terms of spatial maps. The maps are categorised based on locations which are of high importance; Port Denison, Granny's Beach/Surf Beach, South Beach North and South, Seaspray Beach/Irwin River, Seven Mile Beach, Freshwater Point and Cliff Head North and South. A series of inundation and erosion maps were developed for several scenarios which were based on present and future sea level rise with several average recurrence interval (ARI) of storm events. Therefore 24 maps were developed for each identified location; two processes (inundation and erosion), four sea level rise scenarios (0, 0.5m, 0.9m and 1.5m) and three average recurrence interval events (1, 100, and 500 years). Each map is then discussed considering the identified inundation/ erosion extents, water depth and potential risk to identified assets.

Overall modelling results clearly show that future climate change and sea level rise have adverse impacts on the selected coastal region. Inundation will be expanded

inland creating more areas inundated by severe weather conditions. Erosion will be more active and erode the beach at most of the locations, especially where extreme wave conditions occurs. Among the selected locations, all the locations predict higher degree of inundation and erosion under sea level rise in the future. Specially integrated impact of extreme water levels (1 in 100 year extreme events and 1 in 500 year extreme events), would create more vulnerable situation. Regions such as Port Denison, Seaspray Beach, South Beach (North) and Cliff Head (South) are highly populated areas with residential and commercial establishments. Other areas such as Seven Mile beach, Freshwater Point and Cliff Head are environmentally valuable regions as higher diversity of ecological and environmental assets are located at these regions.

The outcome of this study will be useful for authorities and decision makers in developing coastal hazard risk management and adaptation plans to enhance the sustainable management of the coastal zone. Also these results give very good information for coastal communities in understanding the future coastal changes and behaviours. Thus, the evaluation of costal inundation and erosion is very important task of the coastal hazard management.

Acknowledgement

I would like to express my sincere gratitude to my supervisor Dr. Priyantha Ranjan Sarukkalige for his strong support extended to me till the point where I submit my thesis. I am sure that the accomplishment of this work would not be possible without his support. It was a great privilege to work under the guidance of such a good teacher. I would like to make this an opportunity to thank him for all valuable advice that were given to me during this period. Also my sincere thanks goes to the Associate Prof. Andrew Whyte, Head of the Department of Civil Engineering and all academic and administrative staff of the Department who helped me to carry out the research work.

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Last but not least, I would like to thank my husband Shanaka for being behind me throughout, encouraging me, extending the moral support required to accomplish this difficult task, allocating his time on the site visits to Dongara and help me focus on the research and to complete the thesis on time.

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List of Abbreviations

ABS	Australian Bureau of Statistic
ARI	Average Recurrence Interval
BoM	Bureau of Meteorology
DEM	Digital Elevation Models
DoT	Department of Transport
DoP	Department of Planning
GIS	Geographic Information System
GSWA	Geological Survey Western Australia
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging
SLR	Sea Level Rise
SPP 2.6	Western Australian State Coastal Planning Policy 2.6
SoI	Shire of Irwin
WAPC	Western Australian Planning Commission

1 Introduction

1.1 Background

The coastal zone of a country plays an important role in the social, economic and environmental context of its. Socially people associating multitude of recreational activities, economically it is an important contributor to the country's finances by developing ports, harbours and tourism and environmentally it has great diversity of flora and fauna. Moreover, coastal areas are transitional areas between the land and sea considered by a very high biodiversity and include some of the richest and most important ecosystems on earth. Further 84% of the countries of the world have a coastline either with the open oceans, inland seas or both (Martinez et. al, 2007) and the total coastline length for the world is approximately 1.6 million km (Burke et.al, 2001). In 1995, over 2.2 billion people, which is 39% of the world's population lived within 100 km of a coast in the world. In year 2001, 85% of Australians lived within 50 kilometres of the coastline around Australia (ABS, 2004). Most of the people lived in Australia's capital cities, and also rapid growth is shown in the coastal areas outside of the capital cities. According to the Australian Bureau of Statistics, 91.1% coastal population was in Western Australia in 2001. The above statistics emphasize the importance of the coastline for people from all around the world with special concern in Australia.

Coastal hazards are major problems in the coastline around the world. Coastal inundation, erosion and recession are main hazards in the coastal zone. Coastal inundation and erosion/recession have been affecting the coastal communities and have adverse impacts on society, economy, environment, culture, heritage, ecology and biodiversity of the area by temporary or permanent flooding and removal of material from a part of the coast. Further, risk of property damage, loss of life and environmental degradation are some considerable issues due to the coastal hazards.

Climate change could affect coastal areas in several ways. Climate changes trigger impacts such as sea level rise (SLR), frequency and magnitude of coastal storms and ocean waves are the main reasons for the coastal inundation and erosion. Main causes of SRL are thermal expansion caused by the warming of the oceans, the melting glaciers and ice caps and the polar ice sheets (IPCC, 2007). Thus, there is a challenge to reduce the impacts of anthropogenic activities which cause the future effects of climate change and the possible sea level rise. Numerical modelling is one of the best way to understand the coastal process and it has capability to analyse the inundation and erosion process of the coastal zone and impacts of external forces such as storm, wind and sea level rise.

Most of the countries have their policies and guidelines to protect the coastline. The main focus of these policies are on land use and development within the coastal zone and protection of the coastal values. To do that guidelines include several methods to fulfil the police requirements. Planning time frame, coastal classification, calculation of coastal process, costal hazard management process and adaptation plans are some of the important criteria in guidelines. Before the coastal hazard management and adaptations, need to recognize what are the current and future hazards in the coastal zone, for that coastal process (inundation and erosion) should be analysed.

Mid – West Coast of the Western Australia is highly vulnerable for severe inundation and erosion due to widely changing coastal dynamic processes. The potential impacts of climate change in Mid-West region such as sea level rise presents a significant issue for the region's ports and coastal towns, home to the majority of the region's population and vital infrastructure (AECOM, 2010). Therefore this study was based on the coastline in Mid – West Coast of the Western Australia. The research was focused on 75km section of the coastline from South Illawong to Bookara (Close to Nine Mile Beach). Findings of the study will be definitely useful for the authorities and decision makers in the area for a management of coastal zone and sustainable coastal zone developments activities.

1.2 Aim and Objectives

The main aim of this study is to develop numerical modelling process to correctly simulate the coastal inundation and erosion process of the study area and to evaluate the impacts of sea level rise and extreme storm events on the coastal inundation and erosion process in the study area.

To achieve this main aim, this study has the following main objectives;

- Understand the coastal processes and hydrodynamics in the study area (Mid-West Coast of Western Australia).

- Review the historical coastal issues and coastal hazards in the study area.
- Numerical modelling of coastal inundation and erosion process to assess the impacts of future sea level rise, storms and winds.
- Identify the spatial and temporal extend of inundation and erosion in the study area.
- Develop recommendations to support sustainable coastal zone management of the Mid-West Coast of Western Australia.

1.3 Scope of the Research

This study focused on coastal process analysis for current and future hazards due to sea level rise with selected extreme events (1, 100 and 500 years ARI). Statistical analysis method was selected to find extreme values for water levels, wave and wind. Weibull and Gumbel probability distribution functions were used for the extreme value analysis. As numerical modelling is the best method to find the coastal process and to analyse the inundation and erosion process of the coastal zone, MIKE 21 integrated model was selected as the best numerical model for this study. MIKE 21 model is sophisticated and user friendly software to simulate the coastal process with higher accuracy within limited time frame to complete the study.

1.4 Significance of the Study

The coastal zone is experiencing various impacts due to natural and anthropogenic activities. These include population growth, increased construction, a rise in tourism numbers, modification of sediment transport processes, sea-level rise, storm surges, tides and wave actions. As there is development along the coastal zone, coastal erosion and inundation also present a significant pressure. These impacts can separately and/or accumulatively influence the coastal assets and diminish the assets' operations.

Australia is facing these issues for decades and several local and regional studies have been conducted with wide range of research objectives, as each of the impacts operate at different spatial (local to regional), temporal and economic scales. There are lack of research in Mid – West Coast of the Western Australia, but anthropogenic stress is ever increasing in that area. For example the population of the Mid – West Coast of the Western Australia is gradually increasing over time and extending further along the coastline (Landvision, 2000). The scale of increased construction reflects this pattern throughout the region. There is an influx in tourism numbers during peak holiday times, bringing with it a surge in the local economy. The popular recreational beaches such as Granny's Beach, Surf Beach, Seaspray Beach are subject to coastal erosion (from wave movements and ocean swell), at varying levels throughout the year (SoI, 2013).

Without effective management, these current impacts will continue into the future. Furthermore, climate change will exacerbate impacts through rising seas levels, increased number of extreme events, increased temperature and decline in rainfall. In the face of this predicted global climate change, the local governments and other authorities in the Mid – West Coast of the Western Australia have been faced lot of challenges pertaining to the management and maintenance of its valuable coastal resources and infrastructure. The diversity and conservational significance of the coastal zone's natural environments and the expanse of 'coastal living' throughout the area, mean the effects of climate change are likely to have a significant impact on the natural/social balance within the study area in years to come.

Therefore, to face the present and future impacts due to climate change, coastal hazard risk management and adaptation should be enhanced for the coastal zone. Thus, the evaluation of costal inundation and erosion processes is a very important task when it comes to the coastal hazard management. The best method of evaluating the coastal inundation and erosion processes is by using the dynamic model coupled with the hydrodynamics, wave impacts and sediment transport. Further the sea level rise can be included for future scenarios. The dynamic model which is a numerical model, can simulate the wave setup and run-up effect. Further the numerical modelling is cost and time effective than the physical modelling.

1.5 Overview of the Thesis

This thesis is structured into eight chapters, which presents the evaluation of the coastal inundation and erosion process in the Mid-West Coast of Western Australia. Chapter one includes the background of the study, aim and objective, significant of the study area and overview of the thesis. The background presents the brief introduction of importance of the coastal zone, coastal hazards, impact of climate change, coastal protection polices and guidelines, importance of numerical modelling of costal process and about study area.

Chapter two provides a literature review that describe costal hazards (coastal inundation, erosion/recession), sea level rise, modelling methods, statistical analysis, government policies and guidelines. Definition of coastal inundation, coastal erosion and recession have been discussed under sub topic coastal hazards. The sub topic, modelling methods includes different concept and software for numerical modelling.

Chapter three describes the study area. Coastal regions in Western Australia, selected coastal stretch for inundation and erosion modelling, climate, oceanography and geology of the study area, recorded coastal hazards in the study area have been discussed in detail.

Chapter four describes the data collection, the methodology for extreme value analysis, results from extreme value analysis and particle size distribution test. Data has been collected for MIKE 21 modelling software, which was used for constructing the model domain. Median Grain Size (D_{50}) of the sand in study area has been determined from the particle sizes distribution test results. Extreme analysis section consists of the probability distribution functions, the method of parameter estimation and the method of finding extreme values for selected average recurrence intervals (ARIs). The extreme values from Weibull and Gumbel distribution have been compared with each other using Correlation Coefficient and Root Mean Square Error (RMSE) and decided what has been the best distribution for the model.

Chapter five presents the model scenarios, model domain, numerical modelling, assumptions and limitations. Current and future extreme events with sea level rise have been defined under the model scenarios. The method of selecting boundaries, deciding mesh sizes, applying bathymetry to the mesh and developing a model domain have been explained under the mesh generation section. The numerical modelling section describes about the MIKE 21 and MIKE 21/3 software and the modules that have been selected.

Chapter six describes calibration and validation of the numerical model. Using MIKE 21 global tidal height prediction, tide data has been selected for two different time periods for calibration and validation. Then the model output and the extract data for the selected point has been compared.

The simulation results of the inundation model have been presented in chapter seven. Inundation results have been given in the selected areas which are highly important for tourism, recreation, environment and economy. Results have been presented in ArcGIS maps. In the results, the zero sea level rise is considered as the present situation (2014), 0.5m for 2070, and 0.9m and 1.5m correspond to medium and high sea level rises respectively in year 2110.

Chapter eight presents the erosion model results. Erosion results have been given in the selected areas which have been selected in inundation model. The erosion results have been presented by adding historical shoreline movement and a distance for uncertainty to the model results. Results have been presented in ArcGIS maps. In the results, the zero sea level rise is considered as the present situation (2014) 0.5m for 2070, and 0.9m and 1.5m correspond to medium and high sea level rises respectively in year 2110.

Chapter nine presents the overview of future coastal vulnerability and recommendation for adaptation in the selected location in the coastline. Chapter ten presents conclusion of the research and recommendations from this study for future studies. Appendix A gives the sample dataset for water levels, wave and wind. Appendix B and Appendix C give inundation and erosion maps for South beach (north and south), Seaspray beach/ Irwin River, Seven mile beach, Freshwater point, Cliff Head (North and South) respectively.

2 Literature Review

2.1 Introduction

As the first step of the study, the literature review process has been conducted aiming to collect and review all available information, whilst identifying research requirements. One of the method for collecting literature was through the library database, most of them are papers published in journals and books available in the library. Past relevant researches in Western Australia were obtained from government websites (Department of planning, Department of Transport and other local governments etc...) and Northern Agriculture Catchment Council web site (NACC). Further information of other countries and other states in Australia were collected through web surfing. Moreover, there were web sites with valuable information. As an example, Australia Commonwealth Scientific and Industrial Research Organisation (CSIRO), Intergovernmental Panel on Climate Change (IPCC) etc...

The literature review was conducted under several sub topics including coastal hazards, impact of sea level rise on coastal process, modelling method of coastal process, statistical analysis.

Following sections of this chapter present the details of the literature collected which helped to develop the main aims and objectives of this study.

2.2 Coastal Hazards

Coastal hazards can happen due to natural process and anthropogenic impacts (NACC, 2015). Natural disasters (hurricanes and tsunamis) and shoreline erosion are two of the main threats that coastal communities face (NRC, 2007). Further there are several types of natural coastal hazards that affect the coastal zone, coastal erosion caused by storms and/or long-term processes, coastal inundation caused by storms or gradual inundation from sea-level rise and coastal inundation caused by tsunami, (NZCCO, 2004). Volcanic explosion and meteorites can also be a cause for coastal flooding in some areas of the world (Wolf, 2009). Following sections discuses coastal inundation and erosion due to storm and sea level rise.

2.2.1 Coastal Inundation

Coastal inundation is the flooding of coastal lands by raised ocean waters and can be combined by flooding in adjacent lowland rivers, estuaries and lakes (MCDEM, 2010). Further coastal inundation may occur during extreme weather, when higher water levels cause sea water to flood inland. However coastal inundation can also be caused by a tsunami. The primary causes of inundation are storm surges combined with astronomical tide (highest tide) due to a combination of low barometric pressure and extreme wave events due to the extreme winds (VGDSE, 2012). Increase of the mean sea level cause the extent of coastal inundation. Further wave set-up landward of the surf zone and wave run-up over the upper beach which can overtop low coastal barriers are other factors for storm inundation. However elevated water levels from any add-on rainfall causing river floods or flash floods can be a reason for the coastal inundation.

Figure 2.1 illustrates the components of storm tide and wave braking process. The ‘storm tide level’ is a combination of the astronomical tide level and storm surge. Wave set-up and run-up affect the maximum sea level at the shore by adding it into the storm tide level.

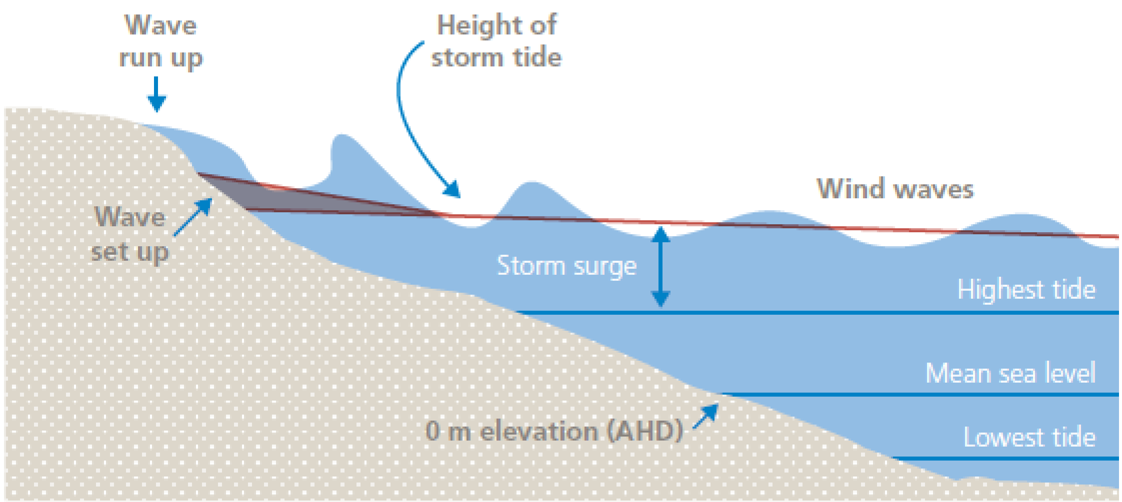

Figure 2.1: Components of storm tide and braking wave processes
(Source: Victorian Coastal Hazard Guide, 2012)

Natural and anthropogenic methods can use to reduce oceanic inundation. Some of them are sand dunes which act as a barrier to oceanic inundation and they provide for an important morphological and environmental change from marine to terrestrial environments (DLWC, 2001). If natural sand dune is damaged due to anthropogenic activities, properties and facilities near the back of the beach may be subject to inundation from the ocean. Reduction of the dynamism of wave attack, help to deflate foreshore erosion.

2.2.2 Coastal Erosion/Recession

Coastal erosion / recession is caused mainly by high waves and high storm tides (storm surge and highest astronomical tide) (VGDSE, 2012). This can result in temporary, long-term or permanent removal of part of the coastline and it is depending on the shoreline type. The occurrence and scale of coastal erosion /recession is anticipated to increase with sea levels rise (NSWG, 2010). The position of the coastline/shoreline is determined by coastal processes, coastal landform types and characteristics, the sediment supply and geological factors such as subsidence (VGDSE, 2012).

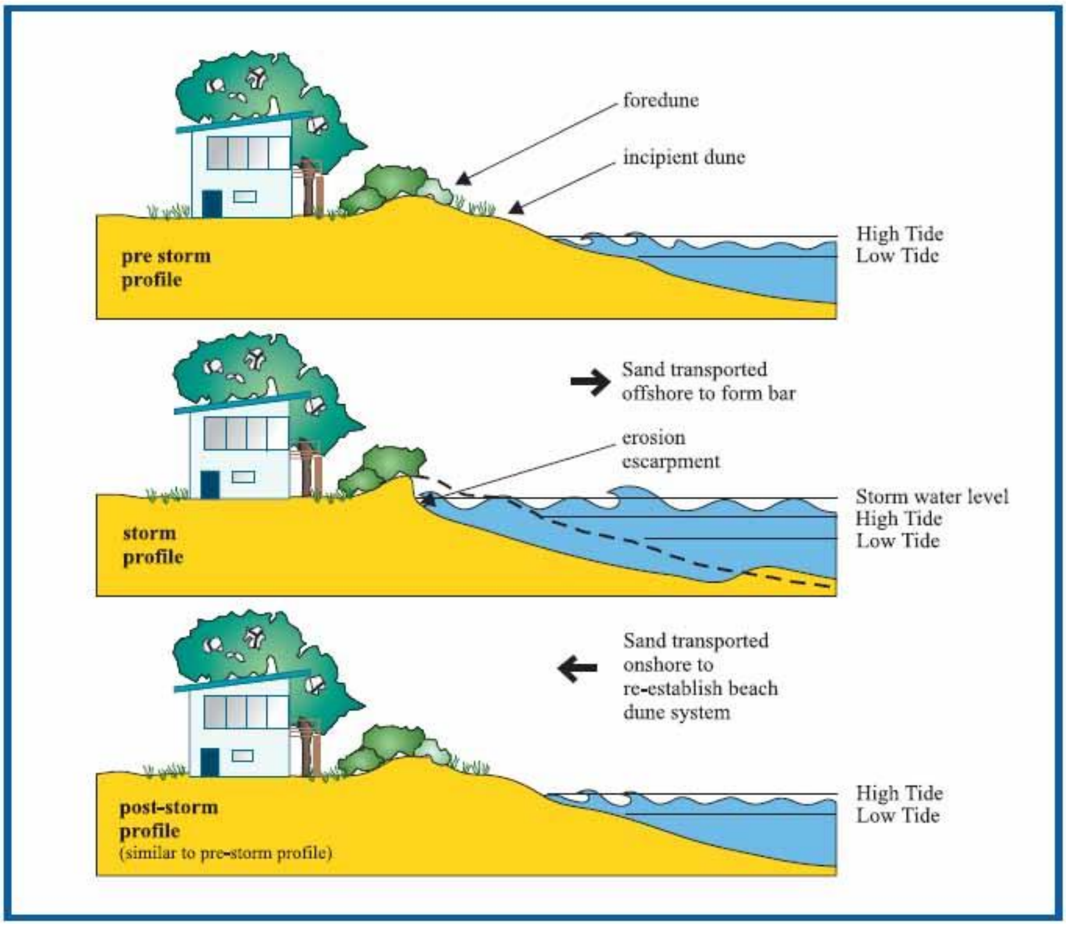

Figure 2.2: Beach erosion/accretion cycle response to a storm event- no permanent sand loss or shoreline retreat
(Source: Department of Land and Water Conservation, NSW, 2001)

Sandy beaches are highly vulnerable to changes in the storm climate as well as cyclic dynamic system, because coasts could erode rapidly over a very short time and tend to start recovery soon after the storm period passes, as sand from the offshore bar is re-established on the onshore as shown in Figure 2.2 (VGDSE, 2012 and DLWC, 2001).

Figure 2.3 illustrates long term erosion/recession that occurs at slower rate than the cyclic beach erosion. Recession may result from insistent landward movement of sand due to dune instability. However, due to continued sea level rise, increased storm frequency and intensity and anthropogenic activities could initiate the recession in the coastline (DLWC, 2001).

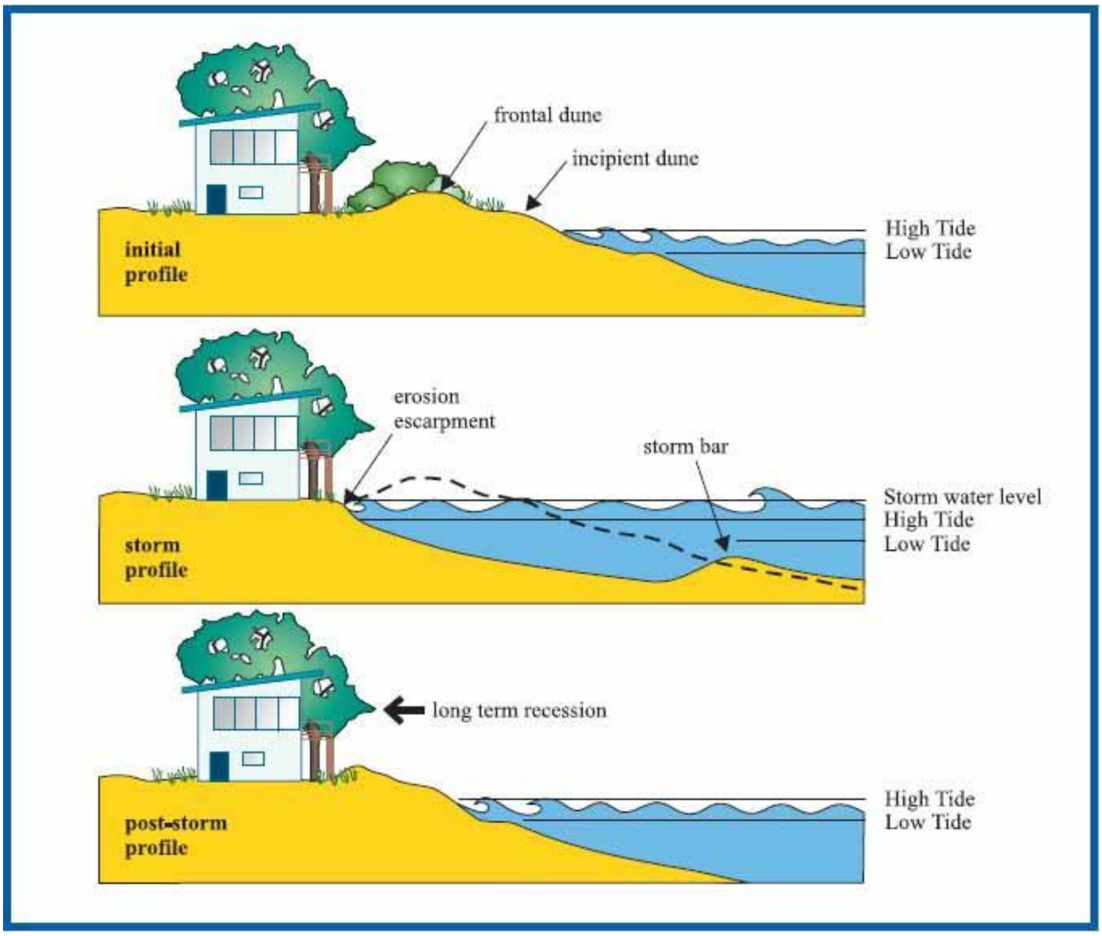

Figure 2.3: Long term beach erosion (recession) profile- displaced landward due to permanent sand loss

(Source: Department of Land and Water Conservation, NSW, 2001)

Further changes in the sediment movement pattern and channel migration may also accelerate erosion and cause permanent changes to the coastline (DEHP, 2016).

2.2.3 Inundation and Erosion Induced Coastal Hazards

Coastal inundation and erosion can affect lives, property and economies. Coastal inundation creates many risks, including impacts on health and well‑being, damage to coastal ecosystems and disturbance of people’s lives, in addition to these, coastal inundation is risks to coastal infrastructure around the world (Steffen et. al., 2014). Further the impacts of ongoing erosion take account of the loss of recreational and scenic amenity of the beaches, economic loss as tourism declines, and the loss of foreshore ecosystems (DEHP, 2016). As an example Australia’s multi-billion dollar tourism industry depend on Australia’s beautiful sandy beaches, from the Gold Coast to Fremantle to Wine Glass Bay. Sandy beaches are at risk from coastal erosion (Steffen et. al., 2014).

2.2.4 Government Policies and Guidelines for Coastal Planning in Australia

Most of the countries have coastal policies and guidelines to protect the coastline. National perspective guidelines have been prepared by each state and examples are Guidelines for Preparing Coastal Zone Management Plans, NSW (NSW, 2010), Victorian Coastal Hazard Guide (VGDSE, 2012), Guideline for Preparing a Coastal Hazard Adaptation Strategy, Queensland (QLD, 2013), State Coastal Planning Police Western Australia (State Planning Police 2.6 (SPP 2.6)) (WAPC, 2013) and Coastal hazard Risk Management and adaptation planning guidelines (WAPC, 2014). These policies and guidelines provide guidance for decision-making within the coastal zone including managing development and land use change; establishment of foreshore reserves; and to protect, conserve and enhance coastal values.

The calculation of costal processes was mentioned in the State coastal planning policy (SPP 2.6). Therefore special care has been taken to highlight the recommendations from SPP2.6 (WAPC, 2013) in relation to; the planning time frame; storm event for modelling; allowance for sea level rise; allowance for storm surge inundation; and allowance for erosion. Further recommendations on an appropriate allowance for mean sea level change to be used in coastal planning in Western Australia are given by Bicknell (2010).

Numerous Coastal Hazard Risk Management and Adaptation studies have been undertaken focusing on the potential impacts of coastal inundation and erosion hazards on the Western Australian coastline. Some of them are such as the Gingin-Dandaragan Coastal Hazard Risk Assessment (NACC, 2015) follow the objectives of SPP 2.6 and the guidelines provided within the Coastal Hazard Risk Management and Adaptation Planning Guidelines for Western Australia. This study considers both present extremes of climate and also projected changes in future climates until the year 2100 for the Gingin-Dandaragan coastline.

Further Yanchep Surf Life Saving Club (YSLSC) was done for the redevelopment of the YSLSC facilities (Cardno, 2014). This report is to be used for the decision-making process for the entire 50 years (2070) design life of the Club's facilities. Coastal inundation and erosion processes were calculated according to the SPP2.6. Cockburn Sound Coastal Vulnerability Values and Risk Assessment Study (2014) identified the cost of risk to the coastal assets and presented an approach to managing these coastal risks. The study further provided a strategy for coastal management, incorporating present and future coastal hazards to develop an adaptation plan (BMT, 2014).

The Coastal Adaptation Decision Pathways Project initiated to develop flexible pathways for the Peron-Naturaliste Coastal Region of Western Australia. The project consisted of three phases; a synthesis of coastal hazards affecting the region; a regional-based assessment of impacts, comparing present day conditions with those projected at snapshots in time up to 2110; and a detailed locally-based assessment at four case study areas of impacts and potential responses, which will change over time (PNP, 2012). This project was largely innovative and has generated a great deal of new learnings, knowledge and sharing of information and resources for the partnership (PNP, 2012).

2.3 Impact of Sea Level Rise on Coastal Processes

There has been sea level changes over the last 140,000 years. The sea level has risen over 120m at the end of the last ice age (CSIRO, 2016). After that, sea level stabilised and little change showed between about 1AD and 1800AD. Sea level started to rise again in the 19th century and speeded up in the early 20th century. According to the Satellite altimeter measurements, the rate of sea-level rise was about 3 mm/year since the early 1990s and the rate further increased after. The dominant reasons of the global mean sea level rise in the 20th century were ocean thermal expansion and glacier melting (AR5, 2013). Figure 2.4 illustrates global mean sea level from 1880 to 2014. According to the graph, after 1990s there is a rapid change for last 24 years and it's almost 90mm.

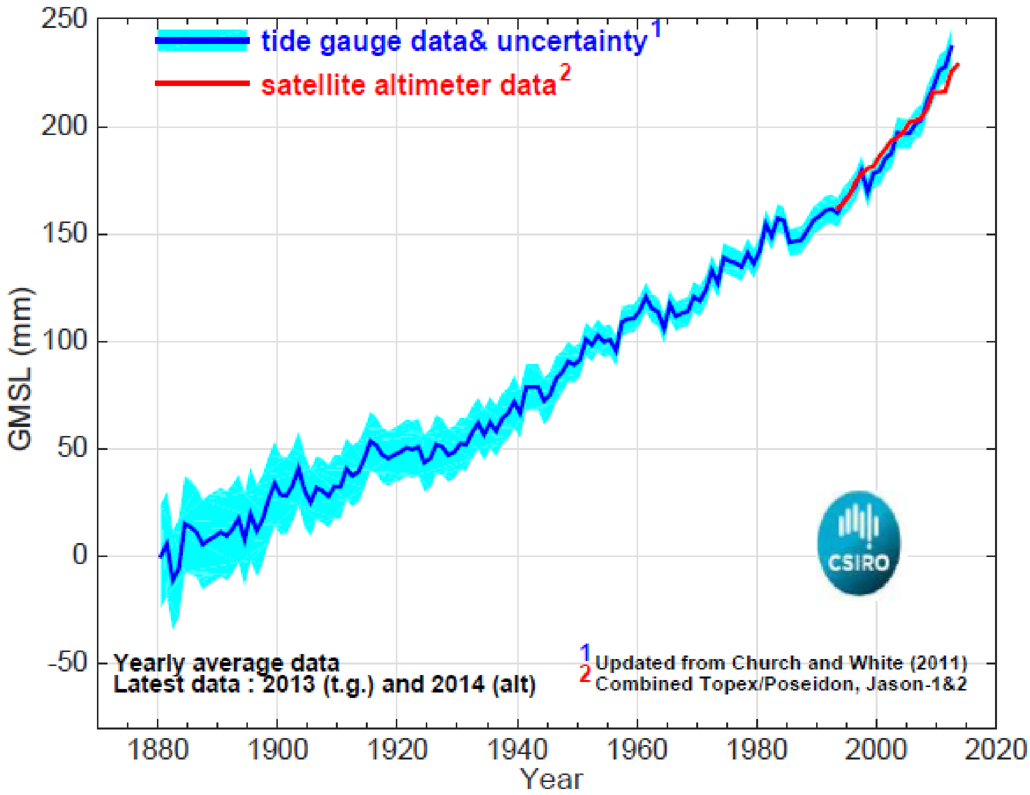

Figure 2.4: Global mean sea level (GMSL) - 1880 to the end of 2014

Source: (CSIRO, 17/05/2016)

http://www.cmar.csiro.au/sealevel/sl_hist_few_hundred.html

According to the "Sea Level Rise" web site of CSIRO-ACE CRC in 2016, the thermal expansion and the ocean mass (addition of water to the ocean from the land) are the main contributors to long-term sea level change, as well as being part of regional and short-term changes. Further tides, surface waves and storm surges are short term variabilities for sea level change. One of the other factors is earthquakes causing a very quick vertical movement of the ocean floor and generate tsunamis (tidal wave). For an example: 2004 December 26th Tsunami in the Indian Ocean.

Figure 2.5 illustrates global mean sea level projections through the 21st century with emission scenarios. These scenarios published in 2000 IPCC special report under the topic “Emission Scenarios” (Bicknell, 2010). As illustrated in Figure 2.5, the red line depicts the fossil intensive (A1F1) scenario. Approximately 50-70% of sea level rise is gained due to thermal expansion.

According to IPCC 2007, Global averaged sea levels are projected to increase by 26 to 79 cm by year 2090-2099 relative to the year1980-1999 due to thermal expansion of the oceans. The melting of glaciers and ice sheets and an additional allowance for a potential rapid future increase in the dynamic ice sheet contributes to sea levels although it is emphasised that this contribution is highly uncertain and larger values cannot be excluded (McInnes et al, 2012).

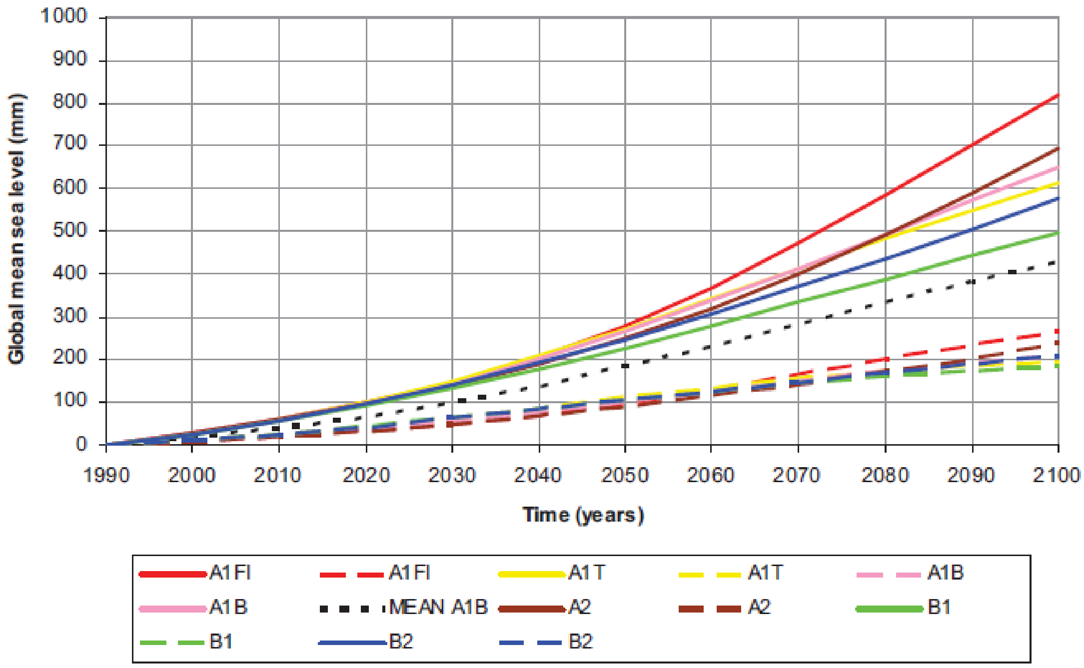

Figure 2.5: IPCC AR4 sea level rise projections through the 21st century including scaled-up ice sheet discharge (dashed lines for 5th percentile and solid lines for 95th percentile).

Source: Sea Level Change in Western Australia (Bicknell, 2010)

The mean sea-level rise around Australia for the periods 1966–2009 and 1993–2009 was 2.1± 0.2mm/yr and 3.1±0.6 mm/yr, respectively, which compares with the global-average sea-level rise with the same periods of 2.0 ± 0.3mm/yr (from tide gauges) and

3.4± 0.4 mm/yr (from satellite altimeter) Over these periods, the mean sea-level rise around Australia was therefore close to the global-average (White, et. al., 2014).

Figure 2.6 illustrates the allowance for sea level rise Western Australia in 2110 is 0.9m. The rate of sea level rise from 2090 to 2100 was taken as the same from 2100 to 2110 (Bicknell, 2010). Understanding of the past and future sea levels changes is important for developing strategies for the management of coastlines and adaptation decisions.

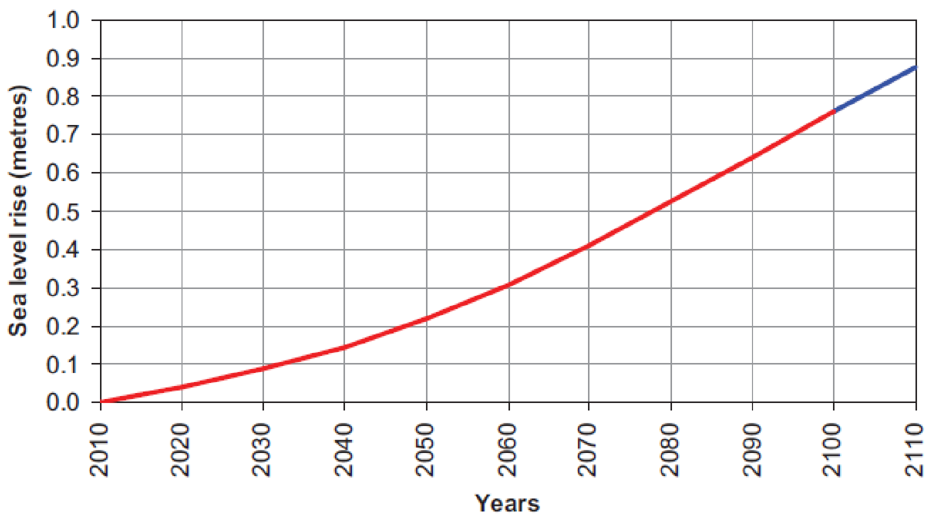

Figure 2.6 : Recommended allowance for sea level rise in coastal planning for Western Australia

Source: Sea Level Change in Western Australia (Bicknell, 2010)

Sea level rise is one of the main impact for the coastal inundation and erosion. According to the website "The Department of the Environment and Energy in Australian Government" in 2016, at present, a mid-range sea level rise of 50cm extreme sea level event occur once in every few years, but in 2110, there will be a greater probability for this to occur once in every few days. Further on average, Australia will experience roughly a 300-fold increase in flooding events in future. This means that an infrastructure which is presently flooded once in 100 years will be flooded several times per year with a sea level rise of 50 cm.

On the other hand the sea level rise impacts the economy of a county. Examples are tourism and real estate industries in coastal areas (Harvey, 2015). Further there is a threat to fauna and flora in the coastal region, not only that sea level rise is increasing the salinity of coastal groundwater and pushing salty water further upstream in estuaries, affecting salt-sensitive plants and animals. Thus, farming and drinking water can also be affected due to sea level rise. As an example sea level rise affected the loss of freshwater habitats in coastal regions such as Kakadu National Park in Australia's Northern Territory (Steffen et. al., 2014).

2.4 Modelling Methods of Coastal Processes

There are two types of modelling methods called numerical modelling and physical modelling (Kamphuis, 2010). Numerical modelling is more cost effective and has a lower operating cost, are major advantages. Physical modelling normally requires large laboratory facilities and demanding a substantial staff with technical backgrounds which would become a heavily cost to the government or sponsors. Even though the physical modelling produce qualitative solutions, numerical modelling would seem to be a natural choice, because of the low maintenance cost, advent of the computers with enormous speeds and capacities, sophistication of software and development of information technology.

Furthermore, the modelling concept can be mainly categorised into two; the simplified bathtub models and the dynamic models (Storlazzi, et al 2013). The literature shows that the "bath tub" approach is a first order estimation for inundation modelling (Foulsham, et al, 2012). Further Murdukhayeva, et al in 2013 said bathtub model results can serve as a preliminary assessment of potential inundation regions. Furthermore bathtub model makes the assumption that infill the terrain at lower elevation to the same level by the water modelled at the coast and can utilize the advantages of a high resolution dataset of topography (McInnes et al, 2012). Figure 2.7 illustrates the different between GIS base passive "Bathtub" Model and Figure 2.8 illustrates Dynamic Model that includes Wave-driven Set-up and Run-up.

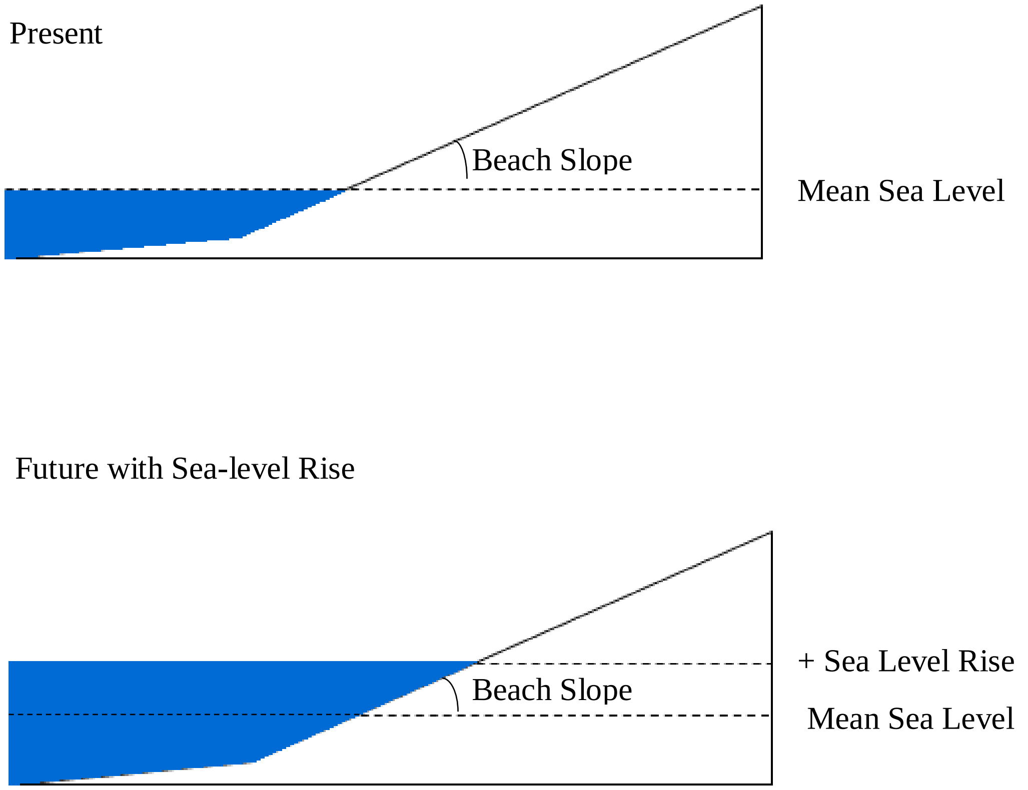

Figure 2.7: GIS-based passive "Bathtub" models

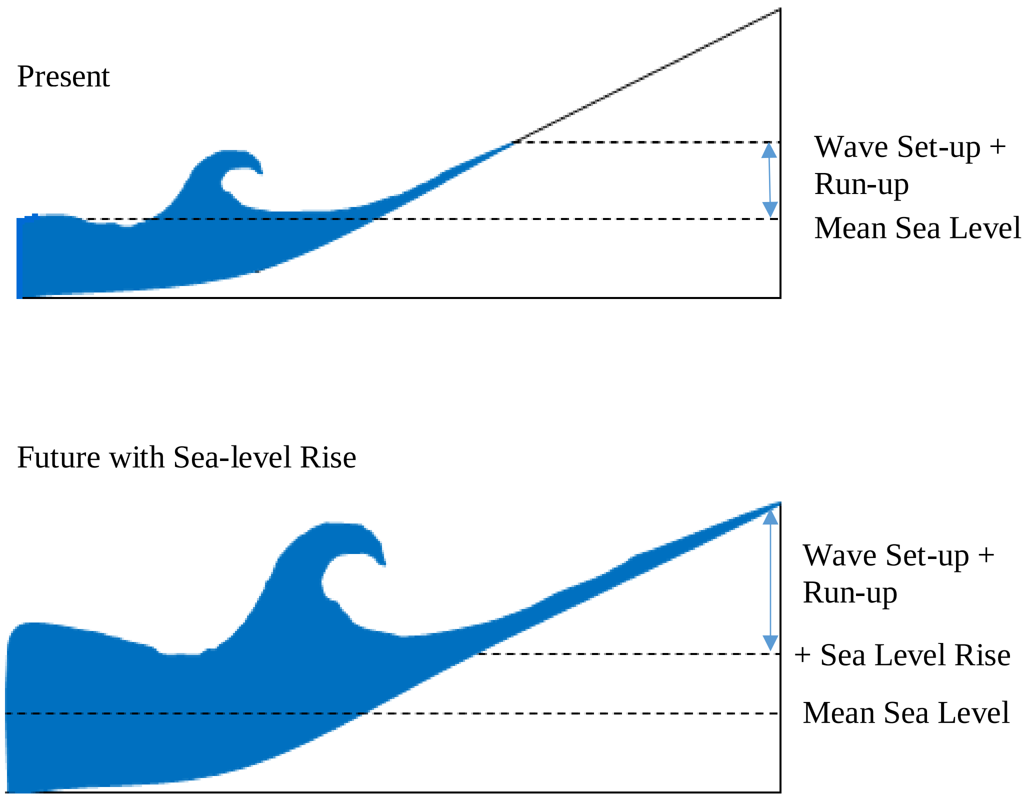

Figure 2.8: Dynamic model that includes wave-driven set-up and run-up

Source: (Storlazzi, et al 2013).

However, an analysis that considers both inundation and erosion modelling is substantially more complex and therefore the bath tub model is not capable of modelling the whole process. Therefore researchers used the bath tub approach for inundation and another model (usually XBEACH and/or SBEACH) for cross shore erosion (CSCA, 2013, Martin, et al., 2014). In 2012, Corbella, S. and Stretch, D. predicted costal erosion trends using three process based model , from these three Time Convolution model was the simplest model, the SBEACH was considered as a far more sophisticated and the XBEACH model provided the best calibration results and was used to simulate potential future long-term trends in beach erosion. Further the NSBEACH (New SBEACH cross shore model) was applied to nearshore nourishment and bar movement with beach berm and dune building at Southern Gold Coast Beach (Yuan and Cox, 2014). Furthermore sensitivity study of Delft3D and XBEACH models were done based on hydrodynamics and sediment transport in the surf zone (Trouw, et al, 2012). ANUGA hydrodynamic inundation model was used for coastal inundation modelling for Busselton, Western Australia, under current and future climate (Martin, et al, 2014). ANUGA was developed by the Australian National University and Geoscience Australia.

MIKE21 is an advanced model, which is developed by the Danish Hydraulic Institute (DHI). The advantage of MIKE21 is that it’s capable of modelling both inundation and erosion processes together as identified through the literature (Evelyn, 2013, Kulkarni, 2013, Pattiaratchi and Wijeratne, 2011). MIKE 21 consists of several modules including MIKE21 SW, MIKE21 HD and MIKE21 ST. MIKE21 SW model is appropriate for both nearshore and offshore wave modelling (Strauss, et al. 2007) and the hydrodynamic flow module MIKE21 HD is used to calculate surface elevation and depth integrated currents (Kristensen et al., 2016, Grunnet, 2014 Kulkarni, 2013 and Samaras et al., 2013). The sediment transport is calculated by MIKE21 ST which uses local flow, wave and sediment characteristics to calculate the sediment transport at each computational cell. Further the model system is solved on a flexible 2D grid. A coupled three-dimensional storm surge model system was applied for the study to investigate the hydrodynamic response in the Hangzhou Bay to tropical typhoon by using MIKE 3 FM and MIKE 21 SW FM (Pan and Liu, 2015). The model to represent the hydrodynamics and sediment transport patterns prevalent at the Ural coast of the Baydara Bay, Russia, using MIKE21 (Kulkarni, 2013). Sensitivity analysis of the sediment transport was depend on grain size diameter, waves and model formulations. The waves were of primary importance compared to tidal currents according to the sensitivity analysis. Pattiaratchi and Wijeratne, (2011) did a study regarding Port Geographe: Sand and Seagrass Wrack Modelling Study, Western Australia and MIKE 21, 2D model were used to predict the waves, currents and changes in morphology.

2.5 Statistical Analysis

Statistical analysis is very important for extreme value analysis for water levels, wave and wind. Extreme value analysis is one of the main section of statistics. A common aim is to estimate what future extreme levels of a process, based on a historical series of observations (Coles, 2001). As such, this method is widely used in engineering applications that need an assessment of extreme environmental conditions: for example, sea-levels, wind speeds, wave analysis or river flow. The study of extremes and the estimation of the return period is made more easily for coastal sites for which many years of data exist (Tsimplis, 1997) in the study area.

There are two methods to select the sample data set, which are The Peaks-Over-Threshold (POT) method and Annual Maxima method (AMM) (You, 2012 and Goda, 2010). The annual maxima method picks up the largest significant value (wave height etc.) in each year, whereas the peaks-over-threshold method takes the peak values (wave heights etc.), over a certain threshold value (Goda, 2010). The POT method was applied for selecting the data sample for flood risk in the Vidaa River system (Filho, 2013).

In the extreme value analysis, many distribution functions are used that fit to the samples. Some of these distribution functions are Fisher-Tippett type I (FT-I) or Gumbel (GUM) distribution, Fisher-Tippett type II (FT-II) or F'rechbt distribution, Generalized extreme-value distribution (GEV), Weibull distribution and Lognormal distribution (Goda, 2010). Further the probability distributions such as the Gumbel or Weibull distribution were fitted to the measured data to obtain wave heights for return periods greater than the recorded length of the data by extrapolation (Kamphuis, 2010). Furthermore the Weibull distribution was used for the water level extremes in the study of flood risk in the Vidaa River system (Filho, 2013) and according to the You, Z.J. (2012), FT-I distribution was best fitted for the extreme water levels at the NSW coastal entrances. However, to find the extreme water level exceedance probabilities around the coastline of Australia, the classic annual maxima method (AMM), fitted to both Gumbel (GUM) and Generalized Extreme Value (GEV) distributions was used to compare results obtained from the r-largest method (RLM) (Haigh et. al., 2012).

Extreme statistical analysis begins from a search of most suitable distribution function for unknown population and find the shape, scale and location parameters. (Goda, 2010). There are several methods for parameter estimation. The method of moments (MM), the maximum likelihood method (ML), the least-squares method (LS), method of L-moments and graphical fitting method were most commonly applied to estimate the distribution parameters. (You, 2012 and Goda, 2010).

You (2012) mentioned the LS method is simple to determine the distribution parameters especially for three-parameter distribution functions such as Weibull and Pearson-III, further it is easy to visualize the goodness of fit from a linear plot, abnormal data points (not outliers) can be easily identified and subsequently removed from the analysis, and the LS method can easily manipulate extreme water level data to give the best fit to high water levels. Moreover Gumbel method and method of moments were used to determine extreme water-level events and extreme waves were calculated using the both Gumbel and Weibull procedures for inundation and erosion study for Glenelg Shire Council (AECOM, 2010a).

3 Study Area

3.1 Land Formation and Geomorphology of Coastal Regions in Western Australia

Various coastal studies have been done in the Mid-West region. Gingin-Dandaragan Coastal Hazard Risk Assessment, The Coast of the Shires of Coorow to Northampton, Mid-West, Western Australia: Geology, Geomorphology and Vulnerability, Dongara to Cape Burney Coastal Geomorphology and Port Denison Beach Erosion Investigations Report are some of them (NACC, 2015, Damara, 2012, Damara, 2011and Paul, 2001).

Western Australian coast line was divided into thirteen coastal regions as shown in Figure 3.1. Coastal regions were formed based on the areas with recurring patterns of landform and geology (Damara, 2012). Unconsolidated sediments of the Quindalup geological system is mainly in the inshore seabed, beaches and dunes along the Mid-West coast. The Mid-West is an intermediate region physically and climatologically. The shallow reefs and inshore lagoons are common in south of Dongara. The Irwin River at Dongara, Chapman River at Geraldton and several small streams are located in this region.

The Mid -West coastal region was categorised under three types of sediment cells, which are Primary, Secondary and Tertiary (DoT, 2014). Sediment cells are spatially separated areas of the coast within which marine and terrestrial landforms are likely to be connected through processes of sediment exchange. A hierarchy of sediments cells was developed to provide an application in engineering, science, planning and management of the coastal area.

As per the coastal sediment cells for the Mid-West coast in 2014,

- "Primary cells are related to large landforms, and are most relevant to potential change in large landform assemblages or land systems over longer coastal management timescales of more than 50 years."
- "Secondary cells incorporate contemporary sediment movement on the shoreface and potential landform responses to inter-decadal changes in coastal processes."

- "Tertiary cells are defined by the reworking and movement of sediment in the nearshore and are most relevant for seasonal to inter-annual changes to the beachface. Mapping of tertiary cells was limited to the beachface point because of insufficient resolution of the available datasets."

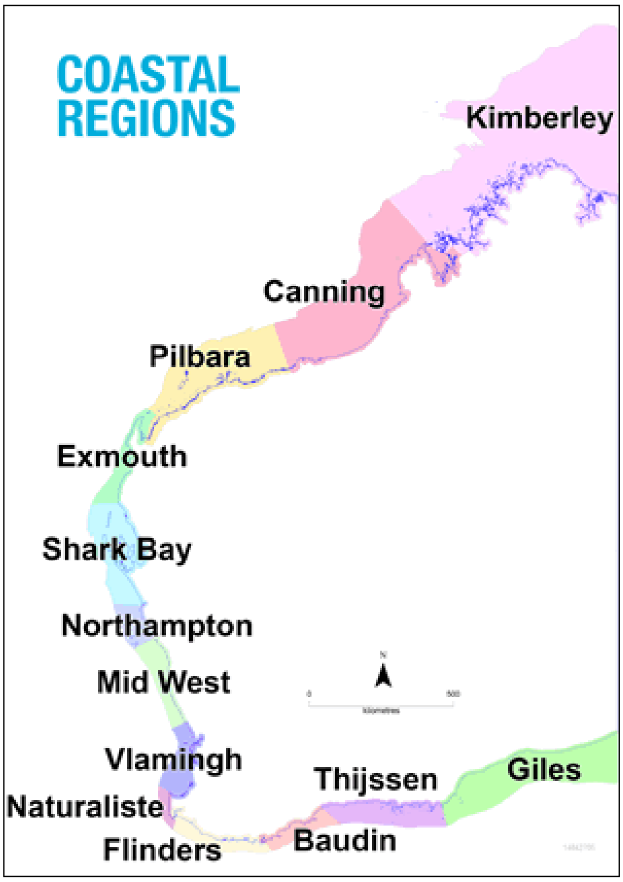

Figure 3.1: Coastal regions in Western Australia

Source: Department of Transport Website

(http://www.transport.wa.gov.au/imarine/coastal-erosion-and-stability.asp)

Table 3-1: Primary, secondary and tertiary sediment cells of the Mid-West region

Region	Primary	Secondary	Tertiary
R07 Mid-West Region from Moore River to Glenfield	F. Phillips road Coast to Glenfield	15. Point Moore to Glenfield	c. Chapman to Glenfield
			b. Geraldton west to Chapman
			a. Point Moore to Geraldton west
		14. Cape Burney South to Point Moore.	b. Separation Point to Point Moore
			c. Cape Burney South to Separation Point
		13. Phillips Road to Cape Burney	a. Phillips Road Coast to Cape Burney South
	E. Leander Point to Phillips Road Coast	12. Nine Mile Beach to Phillips Road Coast	b. Headbutts to Phillips Road Coast
			a. Nine Mile Beach to Headbutts
		11. Leander Point to Nine Mile Beach	c. Seven Mile Beach to Nine Mile Beach
			b. Harleys Hole to Seven Mile Beach
			a. Leader Point to Harleys Hole
	D. South Illawong to Leander Point	10.Cliff Head to Leander Point	b. White Point to Leander Point
			a. Cliff head to White Point
		9. South Illawong to Cliff Head	a. South Illawong to Cliff Head
	C. Middle Head to South Illawong	8.Fisherman Island to South Illawong	d. Coolimba to South Illawong
			c. Leeman to Coolimba
			b. Point Louise to Leeman
			a. Fisherman Island to Point Louise
		7. Middle Head to Fisherman Islands	c. Sandy Cape to Fisherman Islands
			b. North Head to Sandy Cape
			a. Middle Head to North Head
	B. North Wedge to Middle Head	6. Grey to Middle Head	f. Island Point to Middle head
			e. South Booka Valley to Island Point
			d. Black Point to South Booka Valley
			c. Thirsty Point to Black Point
			b. Kangaroo Point to Thirsty Point
			a. Grey to Kangaroo Point
		5. North Wedge to Grey	b. Kearn Reef to Grey
			a. North Wedge to Kearn Reef
	A. Moor River to North Wedge	4. Magic Reef to North Wedge	b. Wedge to North Wedge
			a. Magic Reef to Wedge
		3.North Break Reef to Magic Reef	c. Narrow Neck to Magic Reef
			b. Dide Point to Narrow Neck
			a. North Break Reef to Magic Reef
		2. Ledge to North Break Reef	c. Edward Island to North Break Reef
			b. Fence Reef to Edward Island
			a. Ledge to Fence Reef
		1. Moore River to Ledge	c. South First Bluff to Ledge
			b. Seabird to South First Bluff
			a. Guilderton N to Seabird

Note: Blue shading indicates the sediment cells in the study area

(Source: Coastal Sediment Cells for the Mid-West Coast, 2014)

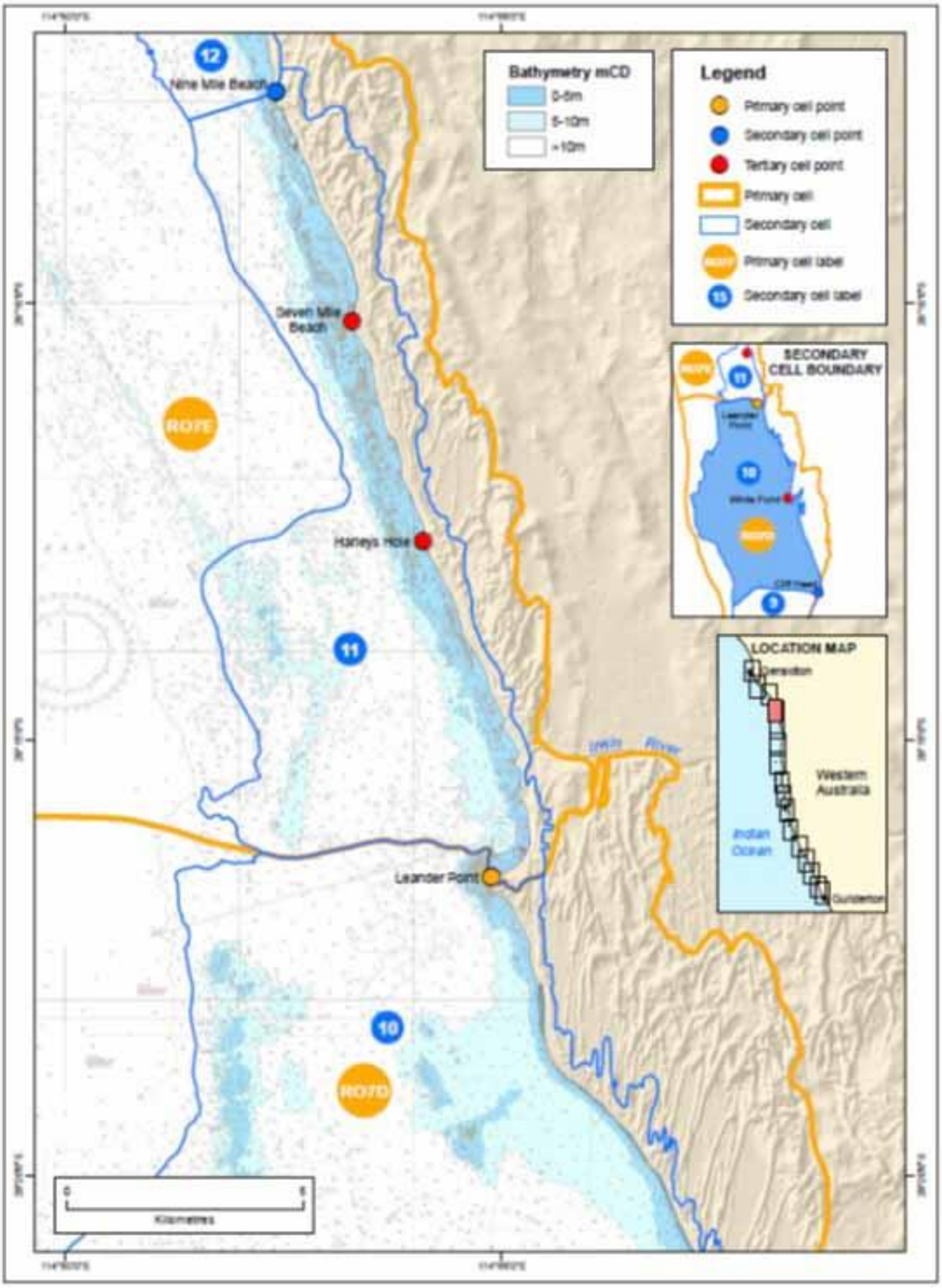

Figure 3.2: Secondary cells and tertiary cell points from Nine Mile Beach to Leander Point (Port Denison) and adjacent to the Leader Point.

(Source: Coastal Sediment Cells for the Mid-West Coast, 2014)

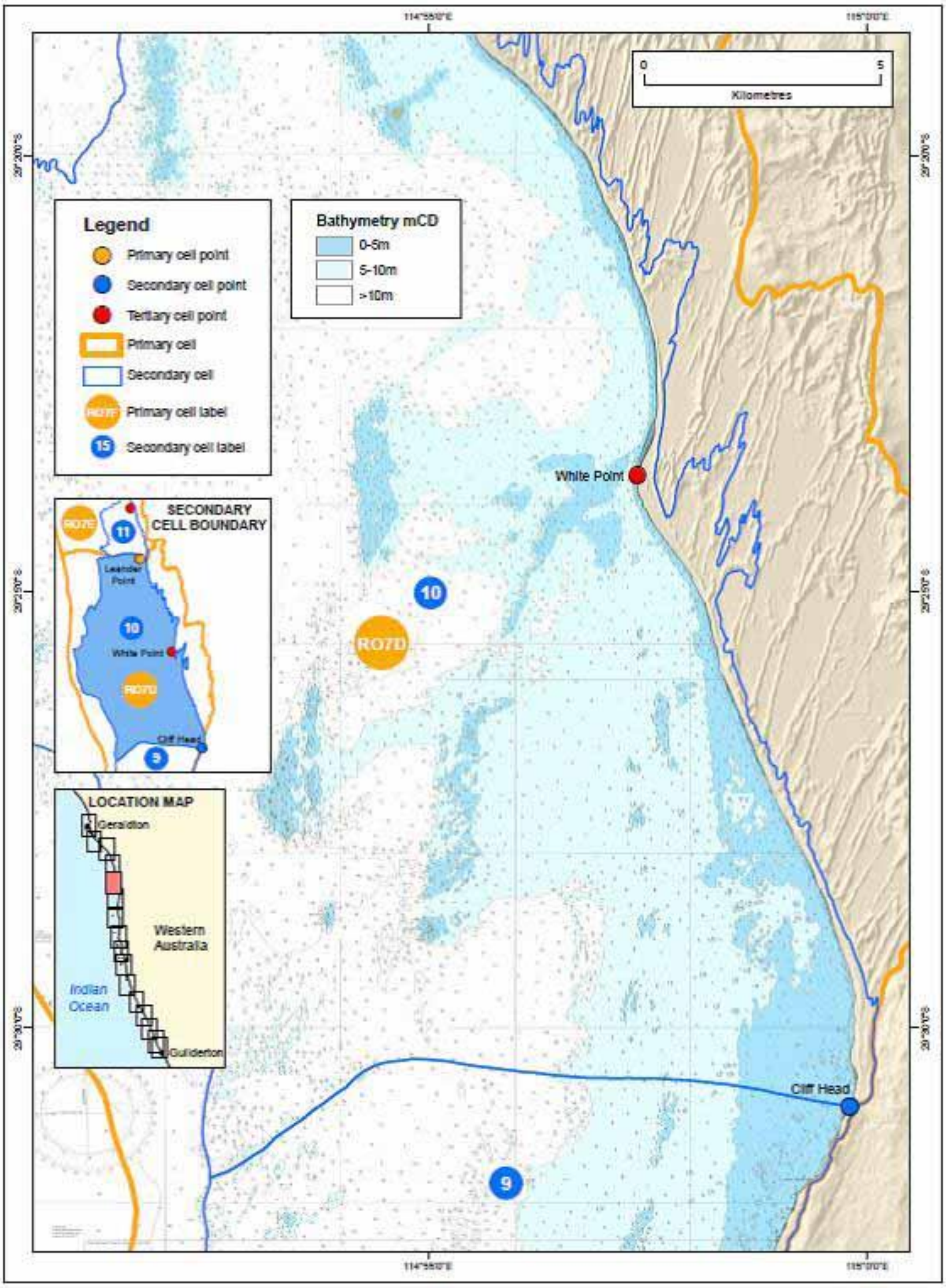

Figure 3.3: Secondary cells and tertiary cell points from adjacent to the Leander Point (Port Denison) to Cliff head

(Source: Coastal Sediment Cells for the Mid-West Coast, 2014)

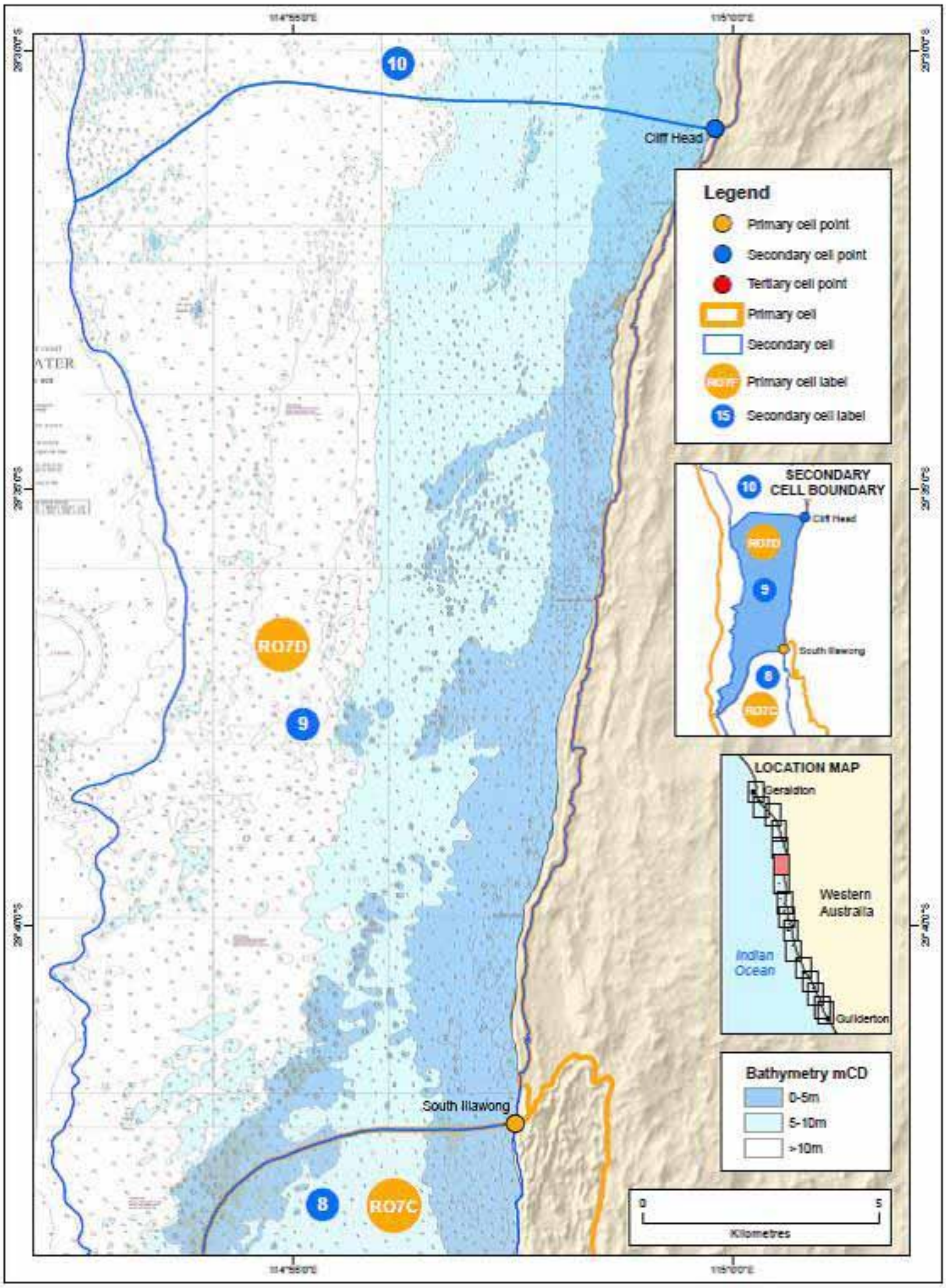

Figure 3.4: Secondary cells and tertiary cell points from Cliff Head to South Illawong

(Source: Coastal Sediment Cells for the Mid-West Coast, 2014)

3.2 Selected Coastal Stretch for Inundation and Erosion Modelling

A 75 km long continuous stretch of land from Illawong in the south, through to Bookara (Near to Nine Mile Beach) which belongs to Mid-West region of Western Australia is selected as the spatial domain of the study. This coast is located approximately between latitude (29^0 08’) S and (29^0 42’) S on the west facing the coast of the Australia and exposed to wave generation from the Indian Ocean. The twin towns of Dongara and Port Denison are located on either side of the Irwin River mouth (Landvision, 2000) and are important as an administrative centre and economic accomplishment (harbour and associated foreshore facilities) respectively. Figure 3.5 illustrates the study area and main important landmark locations. The blue shading area on Table 3-1 and Figure 3.2 , Figure 3.3, and Figure 3.4 shows the sediment cells of the selected coastal stretch in the study area

3.2.1 Climate

The study area experiences with mild wet winters and hot, dry summers climate (Damara, 2011, Peter, 2000). Tropical cyclones occasionally bring heavy rains to the area and hot days of the summer are moderated by strong southerly sea breeze (Peter, 2000). Average maximum temperature for the month of February is higher, 32.4^0 C in summer. Dominant wind directions indicated at Dongara are from the north east in the morning and from south and south west in the afternoon (Damara, 2011). Wave generate principally over the extended fetch of the southern Indian Ocean. Background swell is relatively varying at a lower frequency, which combine with locally generated windwave to make it varying at a higher frequency.

Figure 3.5: The study area

3.2.2 Oceanography

Understanding the status of the ocean is very important for the study. In the study area, the nearshore water is extending seaward from the shoreline to the 30 meter isobath, which is approximately 10 kilometres offshore (Peter, 2000). The 20 meter isobath is approximately 6.5 kilometres off the mouth of the Irwin River at Dongara (Damara, 2012). Between the offshore limestone reefs and the shoreline, it consists of a series of marine basins or lagoonal features themselves separated by irregular ridges of limestone reef (Damara, 2012, Peter, 2000). Inshore exposure is low to moderate in the protection of the Leander reef (Damara, 2012). The study area consist of sandy and rocky coast (Damara & GSWA, 2012). Port Denison Harbour is exposed to sandy beaches. The study area is characterised as a microtidal environment where the tidal ranges are less than 2 meters in height based on the tidal data from Geraldton tide station (Peter, 2000).

3.2.3 Geology

Tamala limestone and Quindalup dunes are dominant along the coast (Landvision, 2000), for an example, especially the coast of south of Cliff Head consist of Tamala limestone. Tamala limestone is noticeable in a nearshore platform and as offshore reefs along this part of the coast. The height and the extent of the cliffs vary from less than one meter to 10 meters on major headlands like Knobby Head, Cliff Head and Freshwater Point (Peter, 2000).

Holocene coast (Quindalup dunes) along the coast, had formed over the past 6000 to 10,000 years (Peter, 2000). Between Cliff head to Port Denison, Quindalup sands form more widespread beach ridge deposits and fields of parabolic dunes which may overlie the beach ridges (Landvision, 2000). Approximately forty mobile parabolic dunes and blowouts have been found along the coast margin between Cliff Head and Bookara (Peter, 2000). Between Knobby Head and Dongara, parabolic dunes contain a high content of calcareous sediments that are suitable as a source of limesands for industrial and agricultural purposes. The Quindalup sands are calcareous, with a pH up to 9.5 (Landvision, 2000).

3.2.4 Recorded Costal Hazards in the Study Area

The following sections present the coastal issues recorded in the literature and other historical records. Following figures show the erosion occurred in 2011 at Freshwater point.

Figure 3.6: Freshwater Point in 2011

(Source: Monitoring of Coastal Erosion in 2013)

The beach adjacent to the Dongara, Denison Holiday Park which is located at the immediate north of the Port Denison Boat Harbour has been eroded by storm conditions. In 2001, Investigation was done for coastal erosion in Port Denison foreshore. The worst erosion was extend about 12m in the foreshore and erosion has occurred over a period of 24 years (from 1977 to 2001), i.e. at an average erosion rate of 0.5m per year (Paul, 2001). The land form pattern of the sediment cell from Leander Point (Port Denison) to Dongara North influences the coastal processes and the stability of further north through discharge from the Irwin River and erosion of the beach immediately north of the Port Denison Harbour (Damara, 2011).

The first recorded major erosion problem was in October 2009 in between Granny's Beach and Surf Beach. The footpath was damaged after winter storm events and extensive erosion occurred at Surf Beach in May 2011 (SoI, 2013).

Figure 3.7: Granny's Beach in 2009

(Source: Monitoring of Coastal Erosion in 2013)

Based on observed trends in the historical shoreline movement, two major contributors to the erosion are the construction of Port Denison in 1978, which increased reflected wave energy to the north and the large number of extreme water level events that have occurred since the mid 1990's, increasing cross-shore transport of sediment to deeper water (Rogers, 2012).

Figure 3.8: Granny's/Surf Beach in 2011

(Source: Monitoring of Coastal Erosion in 2013)

River sand replenishment was undertaken to reduce the erosion problems on Surf Beach. After the erosion problems in 2010/2011, sea wall was constructed to prevent further erosion, under guidance from the Department of Transport. These impacts are well proven during a recent field visit to study area by Curtin University. The following photos were taken at different locations provide a good overview of the present status of the study area.

Figure 3.9: Recent observation at Surf Beach (23rd April 2015)

(Source: Field visit, 2015)

Figure 3.10: Recent observation at Port Denison (23rd April 2015)

(Source: Field visit, 2015)

Figure 3.11 : Recent observation at Freshwater Point (23rd April 2015)

(Source: Field visit, 2015)

Figure 3.12: Recent observation at Cliff Head (23rd April 2015)

(Source: Field visit, 2015)

Figure 3.13: Recent observation at Seaspray Beach (23rd April 2015)

(Source: Field visit, 2015)

Seaspray Beach is considered to have a high vulnerability due to the influence of the Irwin River and modifications as a result of the Harbour (constructed in 1979). (Damara & GSWA, 2012).

Figure 3.14: Recent observation at Seven Mile Beach (23rd April 2015)

(Source: Field visit, 2015)

In addition to the issues due to natural reasons, the available literature also recorded some anthropogenic impacts on the coastal zone which are: (SoI, 2000)

- Off-road vehicle use;
- Uncontrolled pedestrian activity;
- Stock and feral animal grazing;
- Inappropriate placement of infrastructure, such as carpark, boat launching areas, buildings (including squatters shacks) which interrupt natural processes; and
- Destruction of vegetation by fire.

4 Data Collection and Analysis

4.1 Introduction

Based on the objectives of the research, the methodology mainly includes an extensive literature survey to identify the historical hazards and potential coastal hazards in the study area, method of extreme value analysis and the suitable numerical model to the research. Also a data collection process is important to collect all the necessary data required for the modelling. Analysis of extreme events has been conducted using the collected data.

Following steps were followed to successfully complete the data analysis;

1. Literature review - Collected all available information about the modelling study area, the data and the relevant literature to find extreme analysis and modelling method and its requirements.
2. Field visits and monitoring – gathered missing data and additional information where necessary.
3. Developed a comprehensive inventory of historical coastal hazards to identify the past and the present coastal hazards and to predict/identify future hazards.

Based on the above information, the following data collection and analysis methods were proposed;

- Collected the required data from the internet, the government organisations and from the literature.
- Identified the sea level rise trends for the next 100 years using literature review.
- Analysed the extreme value for selected ARI events to design scenarios using statistical analysis method.

4.2 Data Collection

Data requirement depends on the model (MIKE 21). In this study, the data availability was checked according to the user guide of the model. It showed that most of the data is limited in the study area. Therefore several assumptions were made to achieve the most reliable model outcomes. In this study, the coastal inundation and erosion was assessed by using a dynamic (MIKE 21) model. Mainly water level, wave and wind data and sediment data were used for MIKE 21 modelling. Bathymetry and topography data were required to develop the model grid /mesh to run the model. Following sections provide more information on data collection, analysis method and the results from the analysis.

4.2.1 Water Level Data

According to the study area water level data was collected from tide gauges of the Department of Transport (DoT) at two main stations; Geraldton and Jurien Bay. Geraldton data was from 1986 to 2014 and Jurien Bay provided data from 1991 to 2014. Figure 4.1 illustrates the location of the tide gauges managed by DoT. Water level data were recorded every five minutes interval and every fifteen minutes interval before year 2000. According to the Submergence Curve from DoT, the tidal levels are shown on the Table 4-1 and Table 4-2 for Geraldton and Jurien Bay tide gauges. Using tidal details, all the water levels were converted in to AHD for the model.

Figure 4.1: Location of tide gauges managed by DoT

Source: Sea Level Change in Western Australia (Bicknell, 2010)

Table 4-1: Tidal levels for Geraldton tide gauge

Tidal Level	DATUM (Chart Datum)(m) Which is 2.608m below tidal benchmark DOT 301
Highest Astronomical Tide (HAT)	1.21
Mean Higher High Water (MHHW)	0.95
Mean Lower High Water (MLHW)	0.81
Mean Sea Level (MSL)	0.57
Australian Height Datum (AHD=0)	0.55
Mean Higher Low Water (MHLW)	0.36
Mean Lower Low Water (MLLW)	0.21
Lowest Astronomical Tide(LAT)	0.01

(Source: Department of Transport-Western Australia, 20th March 2012)

Table 4-2: Tidal levels for Jurien Bay tide gauge

Tidal Level	DATUM (Chart Datum) (m) Which is 2.608m below tidal benchmark DOT 301
Highest Astronomical Tide (HAT)	1.41
Mean Higher High Water (MHHW)	1.12
Mean Lower High Water (MLHW)	1.06
Mean Sea Level (MSL)	0.8
Australian Height Datum (AHD=0)	0.88
Mean Higher Low Water (MHLW)	0.54
Mean Lower Low Water (MLLW)	0.48
Lowest Astronomical Tide(LAT)	0.25

(Source: Department of Transport-Western Australia, 12th July 2012)

4.2.2 Wave Data

The wave data was collected from National Ocean and Atmospheric Administration's (NOAA) WAVEWATCH III (WWIII) global wave model, archived data set which provides hindcast significant wave heights, peak wave periods, and peak wave directions at each grid point. Two grid points (long 113.75^0, lat -29^0), (long 113.75^0, lat -30^0) were selected to extract data from the WWIII model. These were used to calculate extreme waves for each scenario from 1997 to 2010.

Fourteen years of data were collected from WWIII for wave analysis. Wave data was recorded in three hour intervals. As seen in Figure 4.2 and Figure 4.3 waves were predominately from the south west direction. The Wave Rose Diagrams were drawn by using available data at grid points (long 113.75^0, lat -29^0) and (long 113.75^0, lat -30^0).

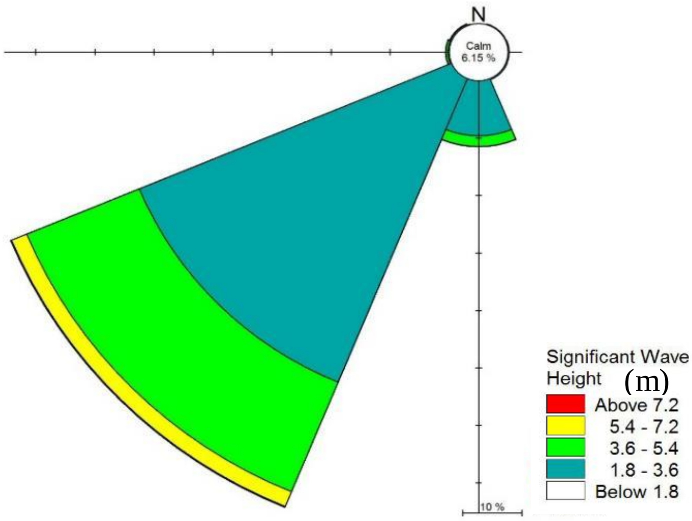

Figure 4.2: Wave rose diagram at grid point (long 113.75^0, lat -29^0)

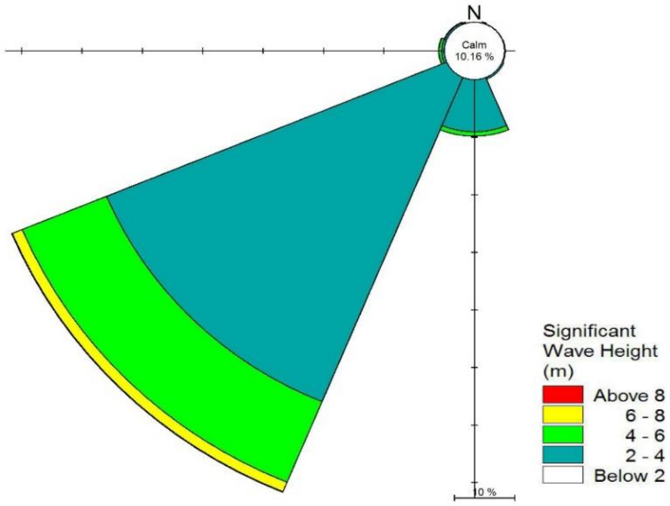

Figure 4.3: Wave rose diagram at grid point (long 113.75^0, lat -30^0)

4.2.3 Wind Data

Wind data was obtained from the Bureau of Meteorology's wind station located at Geraldton airport and is ranging from 2002 to 2014. Data was recorded at minute intervals. Wind was predominantly from the south. The wind rose diagram was drawn by using the available data at Geraldton airport.

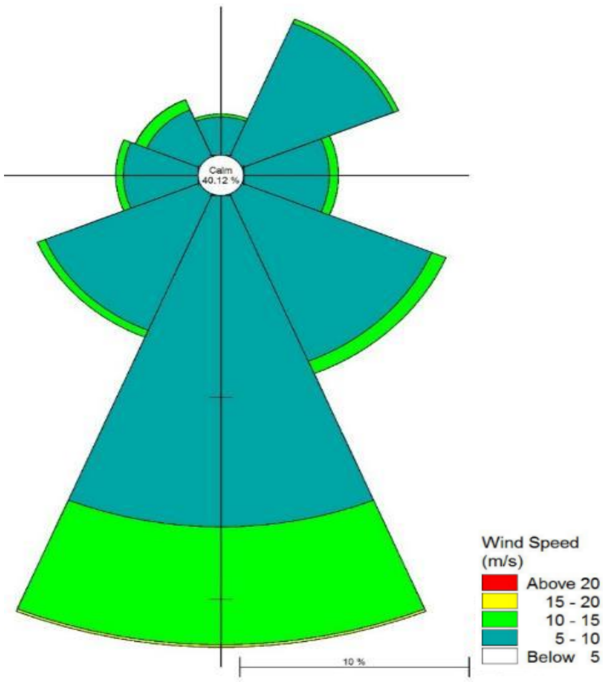

Figure 4.4: Wind rose diagram, wind station at Geraldton Air Port

4.2.4 Bathymetry Data

Bathymetry and coast line data were obtained from the DoT. The bathymetry had been collected using the airborne laser method (LADS Mk II) which was done in 2003 for Port Denison area. Data obtained is of high resolution where the horizontal resolution is less than 10m. Other data sets for further north near the Seven Mile Beach and further south close to the Freshwater Point were collected using hydrographic surveying (sounding) done in 1973, 1981, 1991, 1992 and 1994. The offshore bathymetry was obtained from Geoscience Australia and was a data set of 250m horizontal resolution.

There was no any source which contained bathymetry data for the whole study area for the same time frame. The bathymetry data of different regions were measured in different timeframes. This was one of the major drawbacks of the data which directly affects the model results. To create a data inventory of the bathymetry of the entire study area, the study integrated the whole collection of data without considering it's timeframe to develop a single domain of data for the study area. This process introduces some uncertainty as the coastal process may be significantly different during different timeframes. The study ignores any possible error due to the fact that the data are related to different time frames. It is also assumed that all the bathymetry data were in Australian Height Datum (AHD).

4.2.5 Coastline Data

Coastline is one of the key important data of this study. All the inundation and erosion measurements were decided based on the coastline. Therefore accurate and recent data on coastline is of prime importance for coastal inundation and erosion studies. As the data is not available for recent measurements of coastline around the study area, this study used measurements conducted in 1990 to draw the coastline. The coastline may have significantly changed over the past 25 years, therefore the coastline used for this study does not represent the exact location of the coast. The study assumes that there is no any error due to this assumption.

4.2.6 Topography

Topography data was collected from NACC which was developed using Light Detection and Ranging (LiDAR) survey in 2013. Digital Terrain Models (DTM) maps were used to define the ground surface elevations. Data was of high resolution which has less than 2m horizontal resolution, however due to the limitations of the capacity of the computer, the data was interpolated for 10m resolution for the model. All topography data were in AHD.

4.2.7 Sediment Data

4.2.7.1 Particle Size Distribution Test

As the sand particle size is one of the main parameters (Table 5-4: ST model setup parameters) in erosion modelling, sand samples were collected along the coastline to identify the correct sand particle sizes. Beach sand samples were collected from seven locations in the study area which are follows:

- South Knobby Head;
- Freshwater Point;
- Cliff Head;
- Surf Beach;
- Seaspray Beach;
- Seven Mile Beach; and
- North to Seven Mile Beach.

Figure 4.5 illustrates the sampling locations.

Figure 4.5: Sampling locations for particle size distribution test

Collected samples (Figure 4.6) were analysed at the Geotechnical lab at the Curtin University to estimate the particle size distribution curves for each sample. The following standard procedure was followed to estimate the particle size distribution (AS 1289.3.6.1—2009).

- Written down the weight of each sieve as well as the bottom pan to be used in the analysis;
- Samples were dried in oven for 24 hrs (Figure 4.8);
- Recorded the weight of the given sand sample(Figure 4.9);
- Sieves were assembled in the ascending order of the sieve numbers and carefully poured the soil sample into the top sieve and place the cap over it (Figure 4.10);
- Placed the sieve stack in the mechanical shaker and shook for 10 minutes; and
- Removed the stack from the shaker and carefully weigh and record the weight of each sieve with its retained sand and recoded the weight of the bottom pan with its retained fine sand.

Figure 4.6: Sand samples collected from the coast

Figure 4.7: Wet sand samples

Figure 4.8: Ready to measure dried sand samples

Figure 4.9: Taking weight for a dried sand sample

Figure 4.10: Sieve analysis test rig

4.2.7.2 Results of the Particle Size Distribution Test

Sand particle size is one of the main parameters in the Sand Transport module for erosion modelling, Figure 4.11 illustrates particle size distribution curves for selected sand samples. Table 4-3 shows median grain Size (D_{50}) extract from the Figure 4.11.

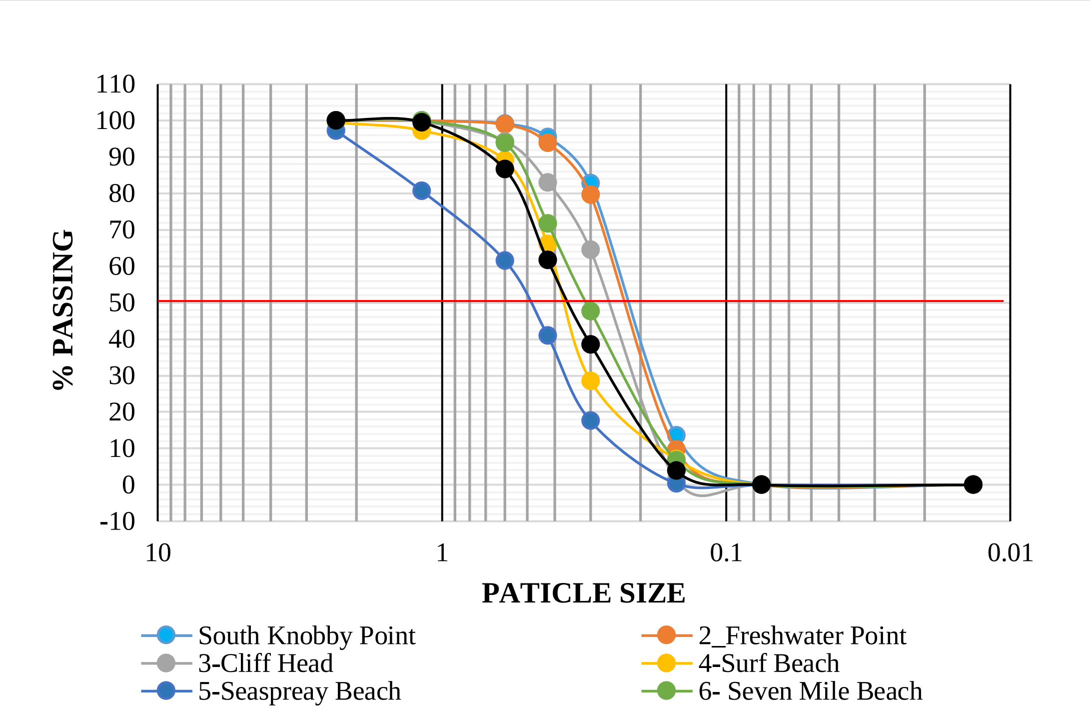

Figure 4.11: Particle size distribution curves for sea sand

Table 4-3: Particle size distribution results; Median Grain Size (D_{50})

Sample No	Location	Particle Size (D_{50})mm
1	South Knobby Head	0.225
2	Freshwater Point	0.23
3	Cliff Head	0.26
4	Surf Beach	0.375
5	Seaspray Beach	0.49
6	Seven Mile Beach	0.31
7	North to Seven Mile Beach	0.36

Further using Figure 4.11, Grading Coefficient ($\sqrt{D84}/\sqrt{D16}$) was taken as 1.35 for Sand Transport module.

According to the results, the south beaches to the Port Denison have finer sand than that of the north. Sand nourishment and replenishment had been done at the Surf Beach, the Seven Mile Beach and the Freshwater Point. The particle size of the sand sample collected at the Seaspray Beach was relatively higher. This could have been due to the fact that it is closer to the Irwin River. There has not been any sand nourishment or replenishment at the South Knobby Head and the particle size was considered to be the finest. According to the Irwin River beach erosion investigation report in April 2001, median grain size, D_{50} was 0.45mm at Port Denison Irwin River Mouth on Ocean side of Beach Berm was 0.4mm, Irwin River Mouth-on River side of Beach Berm was 0.7mm and South Beach was 0.14mm. Finer material would be much more readily eroded.

Historical information states that Granny's beach sand replenishment was taken place in 2008/2009. Sand from River mouth was used for sand nourishment at Granny's Beach (SoI, 2013). Figure 3.9 shows the sand replenishment at Surf Beach. Therefore the sand particle size at Surf Beach was not the original sand particle size in the coast. Therefore based on the sieve analysis results, this study assumes the average sand particle size of the study area is 0.225mm. The value taken for the model was D50 =0.225mm to represent the particle size of the original coast sand South Knobby Head.

Table 4-4 : Summary of the collected data for the numerical modelling

Data	Source	Time period	remarks
Bathymetry	DoT	1973	Seaspray to above
		1981	Freshwater Point
		1991/1992	Nine Mile Beach to Geraldton
		1994	Seven Mile Beach
		2003	Port Denison south to Freshwater Point extends from the coastline to the 30m contour
	Geoscience Australia		Deep Ocean- 250m horizontal resolution
Coast line	DoT	1990	All the estimation and relevant discussion were made based on 1990 coastline
Topography	NACC	2013	10m horizontal resolution was used for the model
Wave	WAVEWATCH- III	1997-2010	Data was in three hour intervals
	DoT		From 1998 to 2009- 1 hour intervals From 2010-2014- 30 minute intervals
Water Level-Geraldton	DoT	1986-2014	From 1986 to 1999- 15minute intervals From 2000-2014- 5minute intervals
Water Level-Jurien Bay	DoT	1991-2014	From 1991 to 1999- 15minute intervals From 2000-2014- 5minute intervals
Wind field data	BoM	2002-2014	Data was in every minute
Sediment data	Geotechnical lab -Curtin University	2015	Sample locations: South Knobby Head, Freshwater Point, Cliff Head, Surf Beach, Seaspray Beach, Seven Mile Beach and North to Seven Mile Beach

4.3 Extreme Analysis

The calculation of extreme events was done using Weibull Distribution and Gumbel (FT-I) distribution based mathematical analysis method. Weibull Distribution is a well-known mathematical analysis especially for coastal data analysis (Goda, 2010; Kamphuis, 2010; Filho, 2013) and Gumbel distribution mostly used for extreme water level analysis (Haigh et. al., 2012, You, 2012). In section 2.5 it discuss about examples of different distribution functions in detail. The following section briefly explains the first principles of the Weibull Distribution concept and Gumbel distribution.

Weibull Distribution function is as follows (Goda, 2010)

$$F(X) = 1 - exp^{[-(\frac{x-B}{A})^k]} \qquad k > 0,\ B \leq x < +\infty \qquad \text{Equation 4.1}$$

Based on the Weibull Distribution function, Probability Density Function can be defined as;

$$f(X) = \frac{k}{A}\left(\frac{x-B}{A}\right)^{(k-1)} exp^{[-(\frac{x-B}{A})^k]} \qquad \text{Equation 4.2}$$

Where;

k - Shape parameter, A - Scale Parameter and B - Location Parameter

Weibull distribution was treated as two parameter distribution by fixing the value of shape parameter (k). Shape parameter (k) was fixed with pre-selected values (k =0.75, 1.0, 1.4, and 2).

Gumbel Distribution function is as follows (Goda, 2010)

$$F(X) = exp^{[-exp^{(-\frac{x-B}{A})}]} \qquad -\infty < x < \infty \qquad \text{Equation 4.3}$$

Based on the Gumbel Distribution function, Probability Density Function can be defined as;

$$f(X) = \frac{1}{A} exp^{[-\frac{x-B}{A} - exp^{\left(-\frac{x-B}{A}\right)}]} \qquad \text{Equation 4.4}$$

A - Scale Parameter and B - Location Parameter

For the present study, data sample was selected using peaks over threshold (POT) method (Goda, 2010; Filho, 2013). Data in the sample was sorted in the descending order ($x_{(m)}$), selected around sixty number of maximum storm events from the sample. Assign the non-exceedance probability ($F_{(m)}$) by using following equation (Unbiased plotting position formula).

$$F_{(m)} = 1 - \frac{m-\alpha}{N-\beta} \qquad m= 1, 2, 3 \ldots n \qquad \text{Equation 4.5}$$

N - Total Number selected events, m - The order number

Constants of unbiased plotting position formula (α and β) were chosen from Table 13.2 in section 13 from Goda, Y. 2010. Constants for Weibull and Gumbel distribution are tabulated below.

Table 4-5: Constants of unbiased plotting position formula

Distribution	α	β	Authors
Gumbel	0.44	0.12	Gringorten[21]
Weibull	$0.20+ 0.27/\sqrt{k}$	$0.20+ 0.23/\sqrt{k}$	Goda[13,20]

(Source: Random Seas and Design of Maritime Structures, (Goda, 2010))

k - Shape parameter

Next step is calculate the reduce variate (y_m). It is a dimensionless variate. Reduce variate was found using following equations.

Weibull Distribution: $y_{(m)} = [- \ln (1- F(m))]^{1/k}$ Equation 4.6

Gumbel Distribution: $y_{(m)} = - \ln [-\ln F(m)]$ Equation 4.7

After that Least Square method was used to find the scale and location parameters (Goda, 2010). Apply the lest Square method by assuming a linear relation between ordered statistic (x_m) and reduce variate (y_m) of following equation

$$x_m = \hat{B} + \hat{A} y_m \qquad \text{Equation 4.8}$$

Using $\hat{A}$ (Scale Parameter) and $\hat{B}$ (Location Parameter) Calculated values (X_m) were calculated.

Using x_m and y_m, Correlation Coefficient (C) and Root-Mean –Square –Error (RMSE) were calculated using Excel functions.

$$C = \frac{\sum(x_m - \bar{x})(X_m - \bar{X})}{\sqrt{\sum(x_m - \bar{x})^2 \sum(X_m - \bar{X})^2}} \qquad \text{Equation 4.9}$$

$$\text{RMSE} = \sqrt{\frac{\sum(x_m - X_m)^2}{N}} \qquad \text{Equation 4.10}$$

X_m - Calculated values $\qquad$ x_m – Ordered statistic data in the sample

Estimation of return value $\hat{x}_R$ for a given return period R is made using the reduced variate y_R as

$$\hat{x}_R = \hat{B} + \hat{A}\, y_R \qquad \text{Equation 4.11}$$

The reduce variate y_R is calculated as a function of the return period R and the mean rate λ as follows:

Weibull Distribution: $\quad y_{(m)} = [\ln(\lambda R)]^{1/k} \qquad$ Equation 4.12

Gumbel Distribution: $\quad y_{(m)} = -\ln\{-\ln[1 - (1/\lambda R)]\} \qquad$ Equation 4.13

For this study return periods were selected as 1, 100 and 500 year ARIs.

$$\lambda = \frac{N}{K} \qquad \text{Equation 4.14}$$

N - Total Number selected events $\qquad$ K = Period (no of years)

Matlab and Excel software were used for data sorting and calculation purposes.

The Geraldton tide gauge provided 29 years of recorded digital data for water levels and the Jurien Bay tide gauge has 24 years of water level data. According to the above method, sixty number of maximum water levels data were selected for each location (Appendix A). Then the Weibull and Gumbel distributions were used to find extreme water levels for selected ARI events.

The same method that is mentioned above was used for wave analysis and wind data analysis. As discussed in the section 4.2.2, wave data collected over 14 years was considered for the wave analysis which was recorded in three hours intervals. The dominant direction of the wave data was from the southwest (225^0), (Figure 4.2 and Figure 4.3) and the data set was selected according to this direction (Appendix A).

Wind data collected over a period of 12 years was considered, with the data being recorded in minute intervals. The wind direction was predominantly from the south (Figure 4.4) however the wave data was predominantly from the southwest. Therefore available data was taken from south to southwest directions. The data sample was selected from the south to southwest direction data set (Appendix A). Therefore the wind direction was taken as an average direction which was southwest (225^0).

4.4 Results of Extreme Value Analysis

This section presents the results of Extreme Value Analysis of sea levels, wind and wave. Extreme value analysis theory is a one of the most important statistical disciplines (Coles, 2001). In Particular, the aim is to estimate what future extreme levels of an environmental process is expected based on a historical series of observations: for example, sea-levels, wind speeds, wave heights.

The frequency of extreme sea levels occur has practical importance to coastal areas for coastal protection (Tsimplis, 1997) and for studying of extreme value of sea levels is to predict inundation risks, and especially how these might change in the future. In addition, raised up coastal water levels accelerate beach erosion and further damage of coastal ecosystems (You, 2012). Therefore, accurate prediction of extreme water levels is important for environment, economy, ecology and social aspects.

In this study, 1, 100 and 500 year ARI events were selected for extreme value estimation. Extreme sea level, wind and wave were analysed using two probability distribution function which were Weibull and Gumbel distributions. According to the Section 4.3, using peak over threshold method data samples were selected and parameters of the distribution functions were calculated using least square method.

4.4.1 Estimated Extreme Water Levels

The data was taken from two DoT tide gauges which are located in Geraldton and Jurien bay. The sixty number of maximum recorded values were selected from each tide gauge (Appendix A). Weibull and Gumbel distributions were applied for each data set and 1,100 and 500 ARI values were calculated without sea level rise. Table 4-6 shows the results for each distribution for selected ARI events. Correlation coefficient and root mean square error (RMSE) were calculated to find the best fit to the sample.

Table 4-6: Summary of the estimated extreme water level data

ARI Event	Water Level (m) AHD			
	Geraldton		Jurien Bay	
	Weibull (k=0.75)	Gumbel	Weibull (k=2)	Gumbel
1	1.08	1.10	0.93	0.93
100	1.54	1.40	1.07	1.10
500	1.75	1.50	1.11	1.16
Correlation Coefficient	0.91	0.81	0.99	0.98
RMSE	0.04	0.05	0.01	0.01

From Geraldton results, Correlation Coefficient for Weibull and Gumbel distributions were 0.91 and 0.81 and RMSE were 0.04 and 0.05 respectively. From these values 0.91 was selected, because it is close to the value one and 0.04 was selected for RMSE, because it is close to the Zero value. From Jurien bay results, Correlation Coefficient for Weibull and Gumbel distributions were 0.99 and 0.98 and RMSE were 0.01 for the both distributions respectively. The value 0.99 and 0.01 were selected from Jurien Bay results. Further, Figure 4.12 and Figure 4.13 show the comparison of the results from Weibull distribution for each k values and Gumbel distribution values with the observed values from sample data set. Therefore, according to the graph and the values from correlation coefficient and RMSE, the Weibull distribution was fitted to the measured data to obtain extreme water levels for the selected return periods for Geraldton and Jurien Bay.

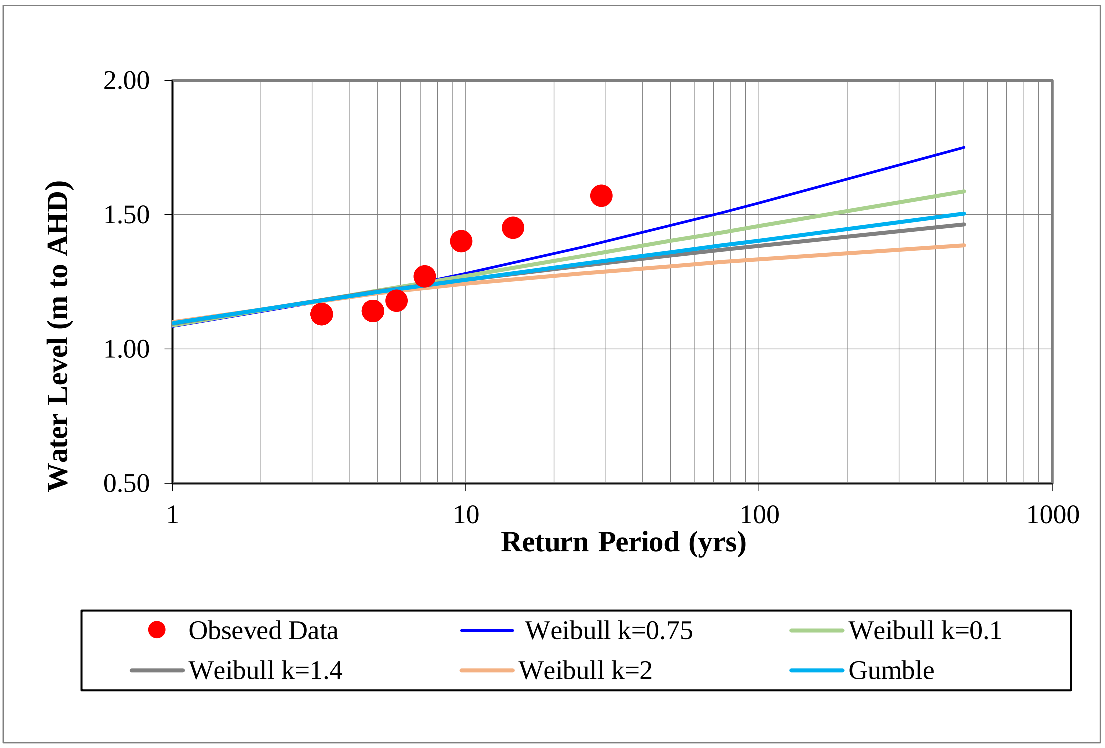

Figure 4.12: The estimated extreme water levels and observed data at Geraldton tide gauge

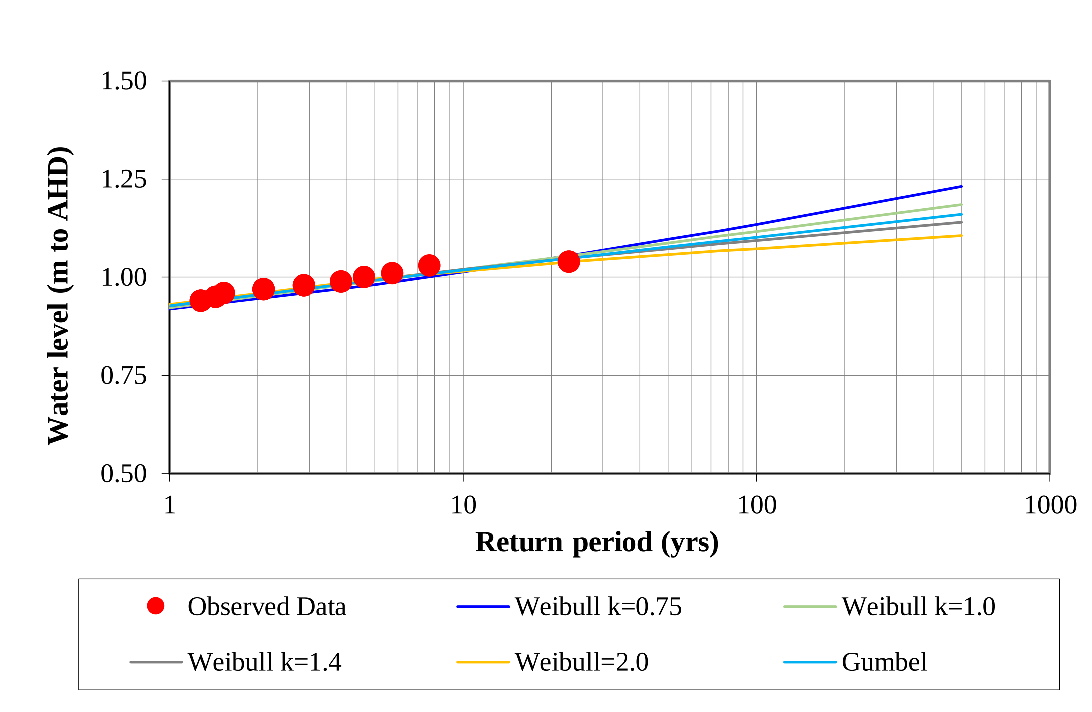

Figure 4.13: Estimated extreme water levels and observed data at Jurien Bay tide gauge

Extreme values for each ARI events were used to select the forcing data for the model. As an example, the following section explains the application of 1 year ARI event to the model.

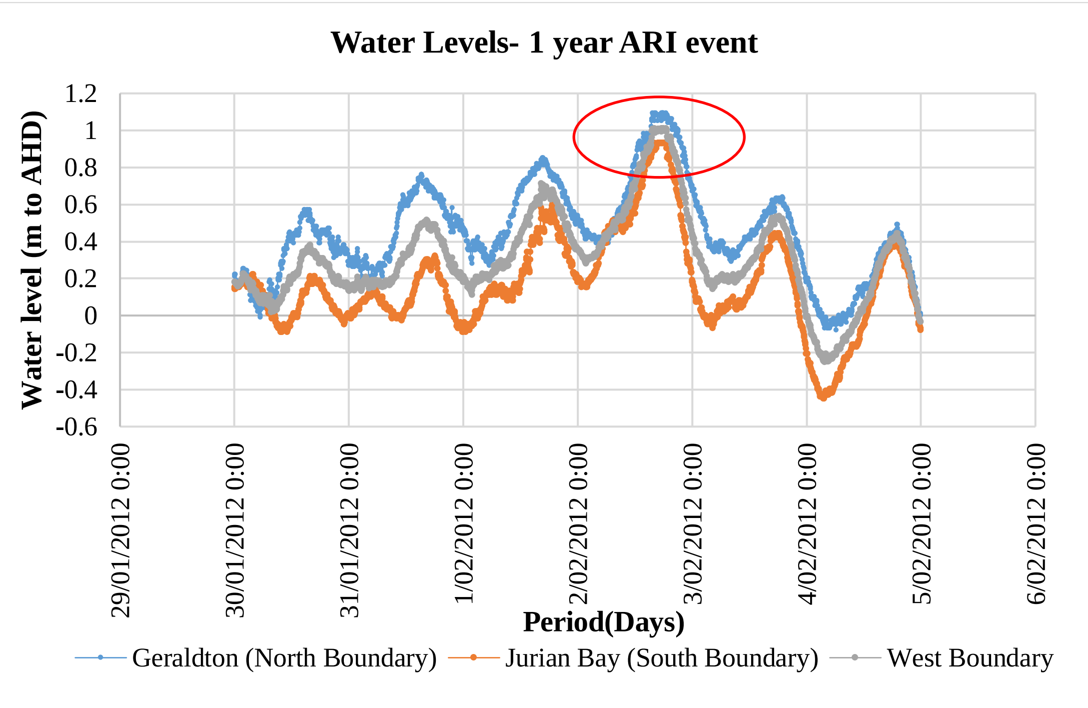

Figure 4.14: Water levels –boundary condition for 1year ARI

Whenever available, the extreme values from the actual past events were selected from observed data set, for an example: The actual past event was selected for 1 year ARI event within the observed data by using the value 1.08m. Figure 4.14 illustrates that past event for Geraldton. In the same way, the actual past event was selected for 1 year ARI event within the observed data by using the value 0.93m for Jurien bay. Geraldton and Jurien bay are the North and the South boundaries respectively for the model domain. Even though there were measured data available for the North and the South boundaries, there were no measured data available for the West boundary. Hence the water level at the west boundary was taken by averaging the data of North and the South boundaries.

The time series of water levels for 100 and 500 year ARI events were calculated by multiplying a factor which was calculated by dividing 100 and 500 year extreme values by the 1 year extreme value.

Table 4-7: Calculation of the multiplication factors for water levels

	1 Year ARI	100 Year ARI	500 Year ARI
Geraldton			
Water level (m)	1.08	1.54	1.75
Factor	1	1.391	1.423
Jurien Bay			
Water level(m)	0.93	1.07	1.11
Factor	1	1.153	1.188

4.4.2 Estimated Extreme Wave

The data was collected from National Ocean and Atmospheric Administration's (NOAA) WAVEWATCH III (WWIII) global wave model. Figure 4.2 & Figure 4.3 illustrate the dominant direction of the wave data, which was from the southwest (225^0). Therefore the sixty number of maximum recorded significant wave height values were selected from the southwest direction data set which were extracted from the WWIII data set at the location of (long 113.75^0, lat -30^0) (Appendix A). Weibull and Gumbel distributions were applied for the data set and 1,100 and 500 ARI values were calculated for significant wave height.

Table 4-8 shows the results for each distribution for selected ARI events. Correlation coefficient and root mean square error (RMSE) were calculated to find the best fit to the sample.

From the results, Correlation Coefficient for Weibull and Gumbel distributions were 0.99 and 0.98 and RMSE were 0.05 and 0.06 respectively. From these values 0.99 was selected, because it is close to the value one and 0.05 was selected for RMSE, because it is close to the Zero value.

Table 4-8: Summary of the estimated extreme wave

ARI Event	**Wave data**		
	Sig. Wave Height (m)		Wave Direction (degree)
	Weibull (k=1)	Gumbel	
1	8.53	8.53	225
100	9.83	9.89	225
500	10.21	10.36	225
Correlation Coefficient	0.99	0.98	
RMSE	0.05	0.06	

Further, Figure 4.15 shows the comparison of the results from Weibull distribution for each k values and Gumbel distribution values with the observed values from sample data set. Therefore, according to the graph and the values from correlation coefficient and RMSE, the Weibull distribution (k=1) was fitted to the measured data to obtain extreme significant wave heights for the selected return periods.

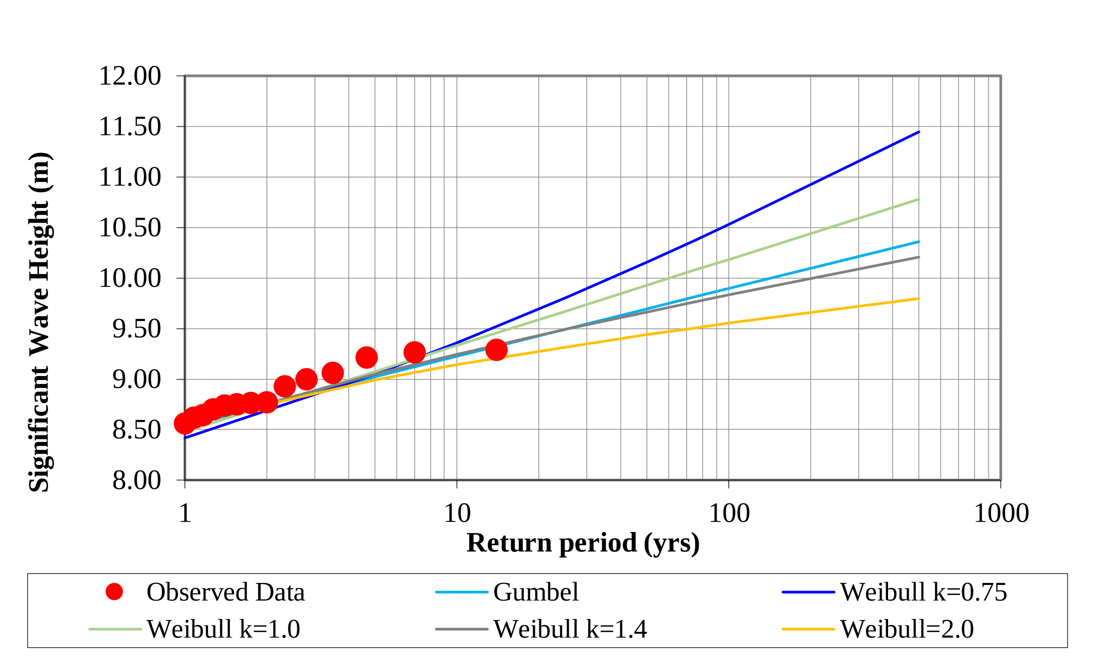

Figure 4.15: Estimated extreme significant wave height and observed data

Extreme values for each ARI events were used to select the forcing data for the model. As an example, the following section explains the application of 1 year ARI event to the model.

The extreme wave height from the actual past events were selected from global data set, for an example: The actual past event was selected for 2 year ARI event within the global data by using the value 8.77m. While selecting the 2 year ARI event, peak wave period was taken from same selected past event. All three boundaries of the model domain were applied same wave event in 1 year ARI for stimulation.

Time series of wave heights and wave periods for 100 and 500 year ARI events were calculated by multiplying a factor which was calculated by dividing 100 and 500 year extreme values by 2 year extreme value. Figure 4.16 illustrates that 1 year ARI event which was calculated by multiplying 0.973 into 2 year extreme event data.

Table 4-9: Calculation of the multiplication factors for waves

	1 Year ARI	2 Year ARI	100 Year ARI	500 Year ARI
Significant wave Height(m)	8.53	8.77	9.83	10.21
Wave Period	14.41	14.81	16.60	17.22
Factor	0.973	1	1.121	1.163

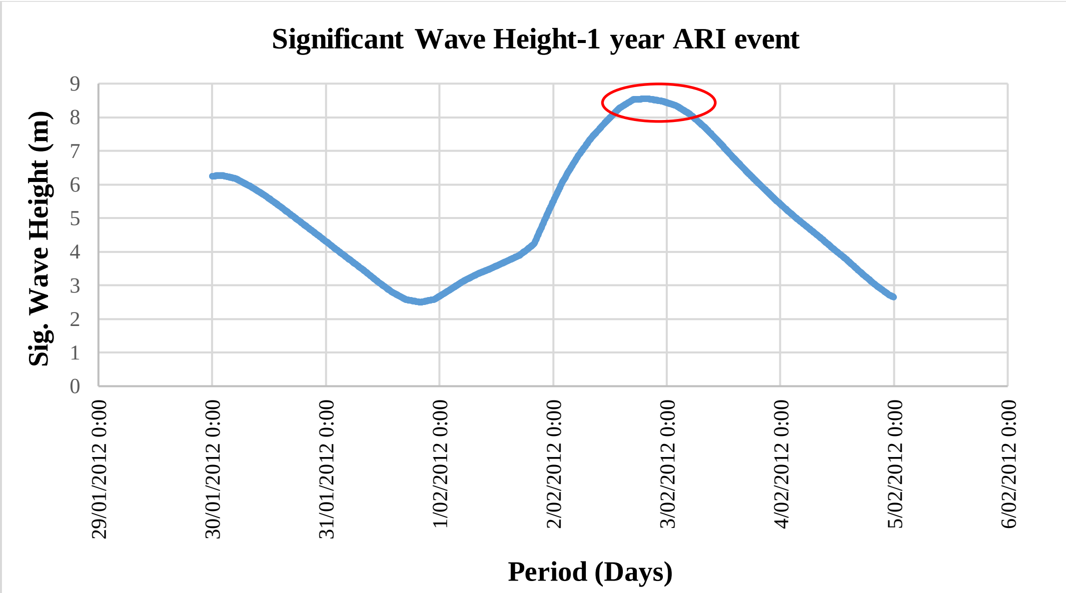

Figure 4.16: Significant wave height-boundary condition for 1 year ARI

4.4.3 Estimated Extreme Wind

The data was obtained from the Bureau of Meteorology's wind station located at Geraldton airport. Figure 4.4 illustrates the dominant direction of the wind data and the wind direction was taken as an average direction which was southwest (225^0). Therefore the sixty number of maximum recorded wind speed values were selected from south to southwest direction data set which extract from measured data set (Appendix A). Weibull and Gumbel distributions were applied for the data set and 1,100 and 500 ARI values were calculated for wind speed. Table 4-10 shows the results for each distribution for selected ARI events. Correlation coefficient and root mean square error (RMSE) were calculated to find the best fit to the sample.

Table 4-10: Summary of the estimated extreme wind

ARI Event	**Wind data**		
	Wind Speed (m/s)		Wind Direction (degree)
	Weibull (k=1)	Gumbel	
1	19.02	19.06	225
100	20.55	20.39	225
500	21.08	20.84	225
Correlation Coefficient	0.99	0.97	
RMSE	0.06	0.09	

From the results, correlation coefficient for Weibull and Gumbel distributions were 0.99 and 0.97 and RMSE were 0.06 and 0.09 respectively. From these values 0.99 was selected, because it is close to the value one and 0.06 was selected for RMSE, because it is close to the Zero value. Further, Figure 4.17 illustrates the comparison of the results from Weibull distribution for each k values and Gumbel distribution values with the observed values from sample data set. Even though height observed value closed to the k=0.75 line, the second height value is deviate from the line, but it close to k=1 line. Therefore, according to the graph and the values from correlation coefficient and RMSE, the Weibull distribution (k=1) was fitted to the measured data to obtain the extreme wind speed for the selected return periods.

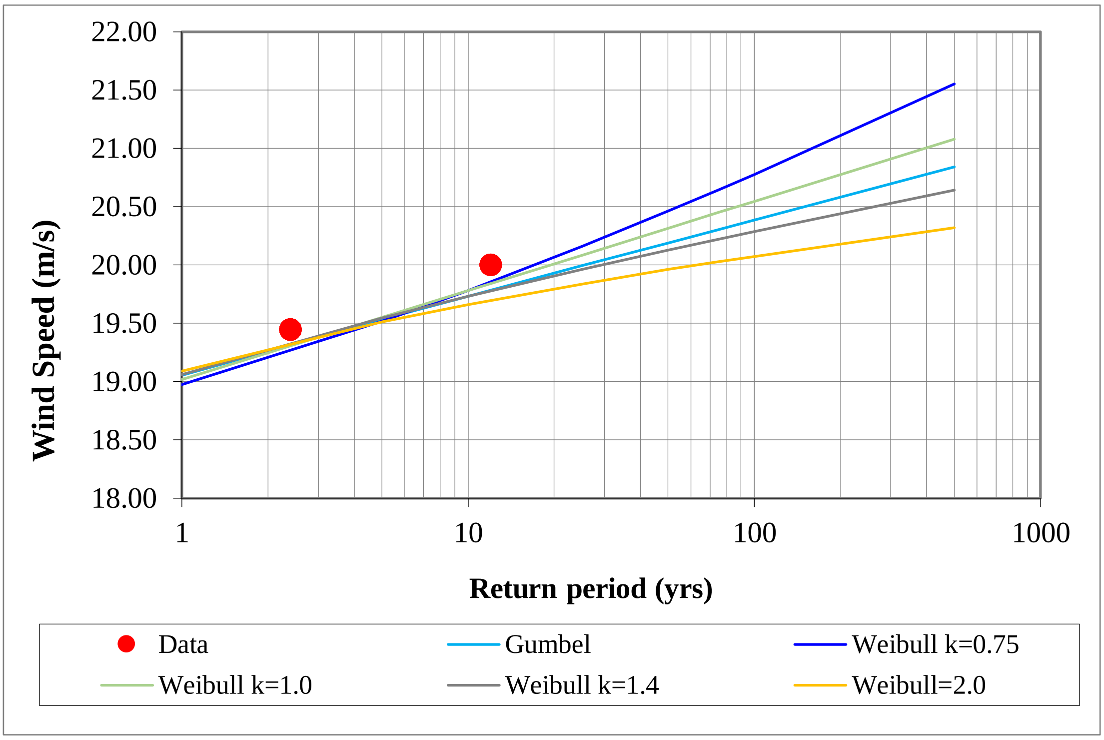

Figure 4.17: Estimated extreme wind speed and observed data

Extreme values for each ARI events were used to select the forcing data for the model. As an example, the following section explains the application of 1 year ARI event to the model.

The extreme wind speed from the actual past events were selected from observed data set, for an example: The actual past event was selected for 1 year ARI event within the observed data by using the value 19.02m. All three boundaries of the model domain were applied same wind event in the 1 year ARI simulation. Time series of wind speeds for 100 and 500 ARI events were calculated by multiplying a factor in Table 4-11 which was calculated by dividing 100 and 500 year extreme values by 1 year extreme value. Figure 4.18 illustrates that 1 year ARI event which was selected from observed data.

Table 4-11: Calculation of the multiplication factors for wind speed

	1 Year ARI	100 Year ARI	500 Year ARI
Wind Speed(m/s)	19.02	20.55	21.08
Factor	1	1.080	1.108

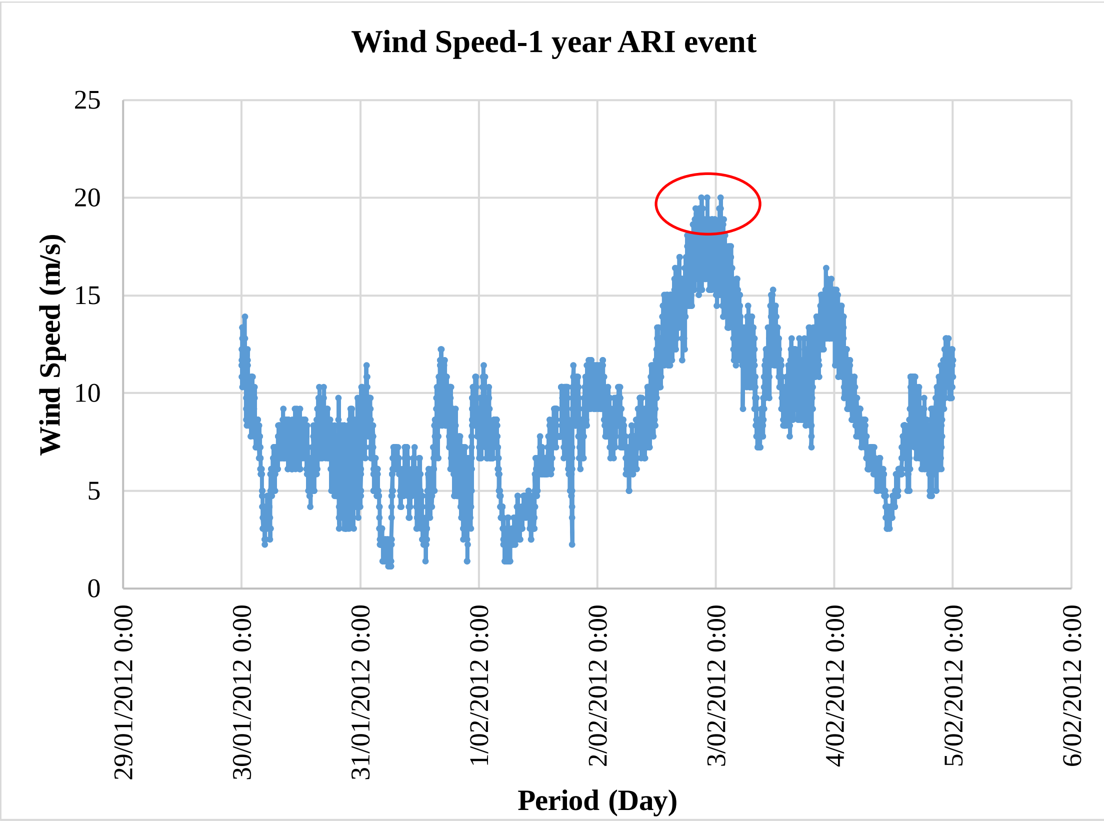

Figure 4.18: Wind speed-boundary condition for 1 year ARI

5 Inundation and Erosion Numerical Model

5.1 Introduction

Inundation and erosion models are important to assess the coastal hazards risk due to the sea level rise, storm surge, wave setup and wave run-up. Development of the inundation and erosion models are the key tasks of the research. The numerical modelling for inundation and erosion process with the sea level rise is conducted using the analysed data according to the Chapter 4.

Following steps were followed to successfully conduct the coastal process modelling using MIKE 21.

- Select the model scenarios.
- Development of a flexi mesh grid representing bathymetry and topography of the study area using MIKE 21/FM.
- Arrange the model grid to portray fine resolution (condensed grids) for the areas shown as high risk and other important locations (such as town of Dongara, Port Denison and other highly interested locations)
- Calibration and validation of the model using MIKE 21 global tide data in to MIKE 21 Hydrodynamic Model (HD).
- Conduct the inundation and erosion modelling using MIKE 21/3 integrated model with Hydrodynamic Module (HD), Spectral Wave (SW) module and Sand Transport (ST) module.

5.2 Model Scenarios

Flowing Table 5-1 describes the model scenarios. The water levels for future were calculated by adding each Average Recurrence Interval (ARI) water level and sea level rise. There extreme events were considered for this study. Sea level rise allowance and the year were taken from Figure 2.6 in section 2.3. Additionally, a sea level rise of 1.5m at Year 2110 was also adopted to determine high-end (worst case) sensitivity.

Table 5-1: Model scenarios

Scenarios	Inputs	SLR allowance (m AHD)	Year
Extreme Event (1year ARI)	1 year ARI water level with 1 year ARI Wind and Wave	0 +0.5 +0.9 +1.5	Present (2014) 2070 2110(Medium) 2110(High)
Extreme Event (100 year ARI)	100 year ARI water level with 100 year ARI Wind and Wave	0 +0.5 +0.9 +1.5	Present(2014) 2070 2110(Medium) 2110(High)
Extreme Event (500 year ARI)	500 year ARI water level with 500 year ARI Wind and Wave	0 +0.5 +0.9 +1.5	Present(2014) 2070 2110(Medium) 2110(High)

5.1 Mesh Generation (Model Domain)

The model domain should be selected in such a way that it encloses locations where the data are available to force the model and validation. Therefore the North and the south boundaries were selected based on the locations of the tide gauges. The north boundary was defined as the Geraldton tide gauge and the south boundary as the Jurien Bay tide gauge. As the topography data was available around 2km from the coastline, the land boundary was selected 2kms towards the land from the coast line (based on 1990 coast line). West boundary was selected allowing enough distance from the coast line to force the data in the model domain. Figure 5.1 illustrates the boundaries of the model domain. The open boundaries are located on the offshore edges of the model domain which are Northern, Western and Southern boundaries. Water level and wave climate parameters were forced on the open boundaries in the HD and SW model respectively.

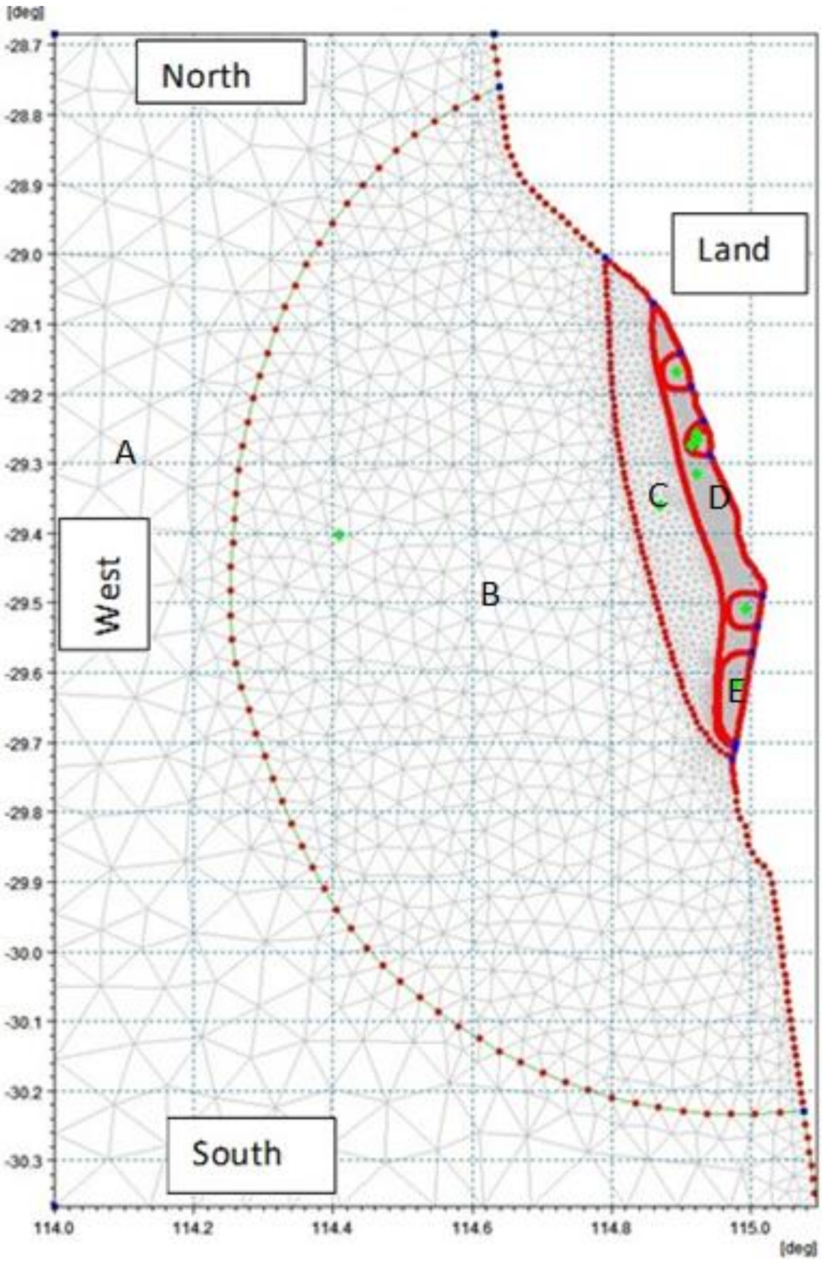

Figure 5.1: Model boundaries

Flexible mesh (FM) allows for coarse resolution for offshore area and high-resolution mesh in particular interest area at the coastline. The mesh sizes (length of the sides of the triangle) were defined to achieve the best results. The final mesh elements were divided in to five sizes. The largest triangle in Deep Ocean (section A) varies from

7km to 10km a side. In Section B, triangle sizes vary from 4km to 5.5km a side. The nearshore was divided into three sections. In section C sizes vary from 1km to 2km a side and In Section D, the triangle size is from 200m to 300m a side. The finer mesh was used for the selected points, which are Seven Mile Beach, Seaspray Beach, Port Denison, Cliff Head and Freshwater Point. The results were focused in these six locations (Section E). In these high resolution fine mesh areas, triangles sizes vary from the 30m to 50m.

Figure 5.2 illustrates a close up view of the defined mesh at Cliff Head, where sections C, D and E are clearly presented.

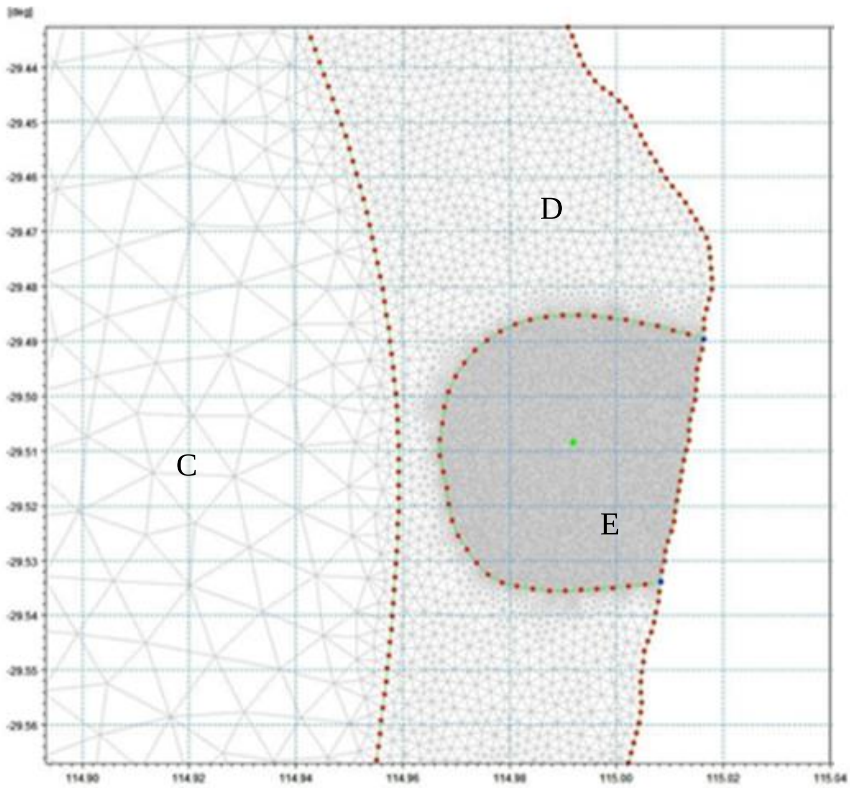

Figure 5.2: Model mesh grid: the close up view of nearshore region (Cliff Head)

The grid and data were projected according to Longitude and Latitude of the study area. After finalising the mesh sizes, the bathymetry and topography data were applied into the model. Data were obtained as described in section 4.2.4 and 4.2.6. Bathymetry and topography data were linearly interpolate over the mesh grid to construct the initial domain bathymetry. Figure 5.3 and Figure 5.4 illustrate interpolated bathymetry for nearshore area and the mesh with bathymetry for the domain respectively. The same domain is used for Hydrodynamic, Spectral Wave and Sand Transport models. According to the Figure 5.5 bathymetry was upgraded at every time step, once start to run the model.

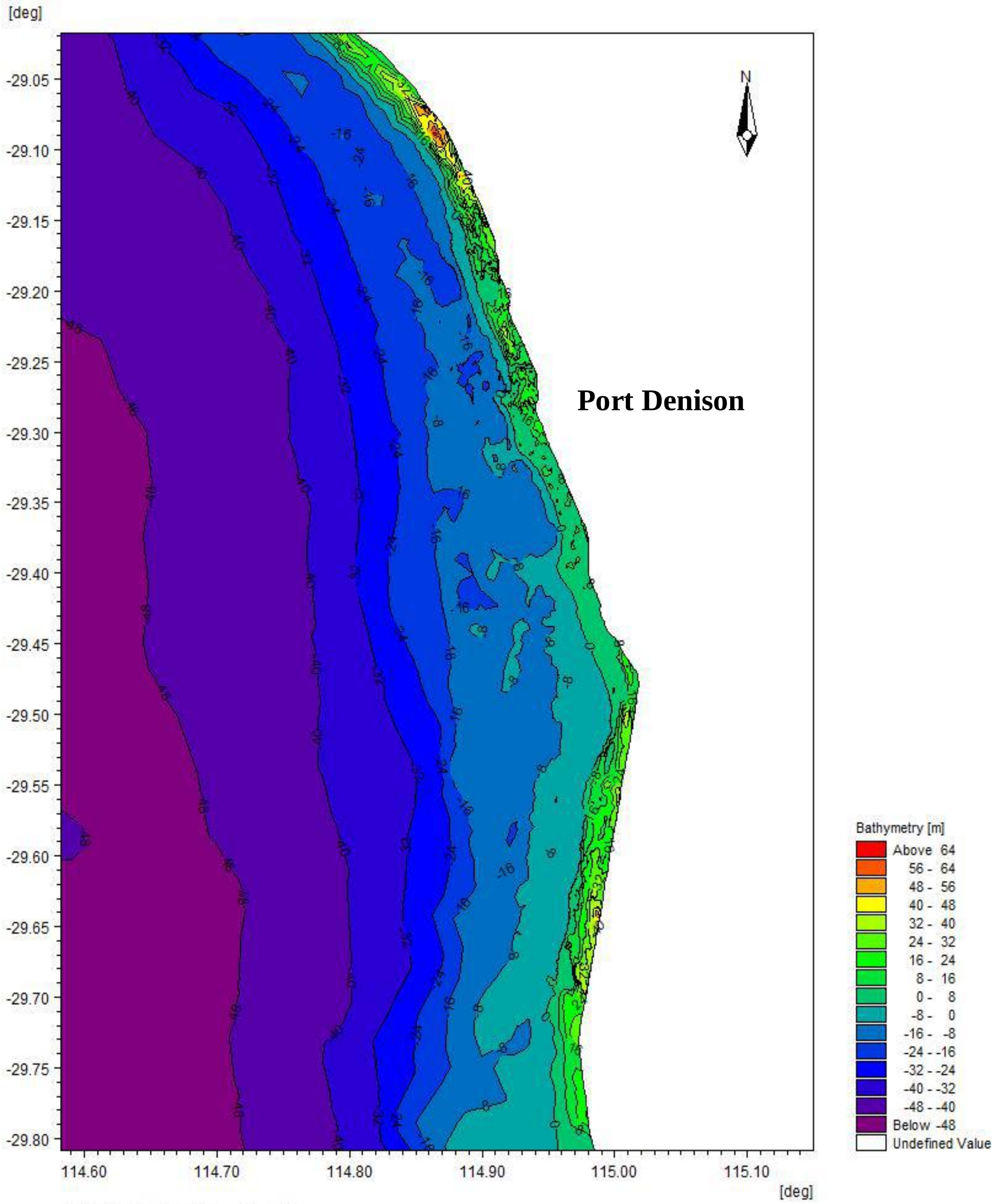

Figure 5.3: Initial model bathymetry and topography for nearshore area

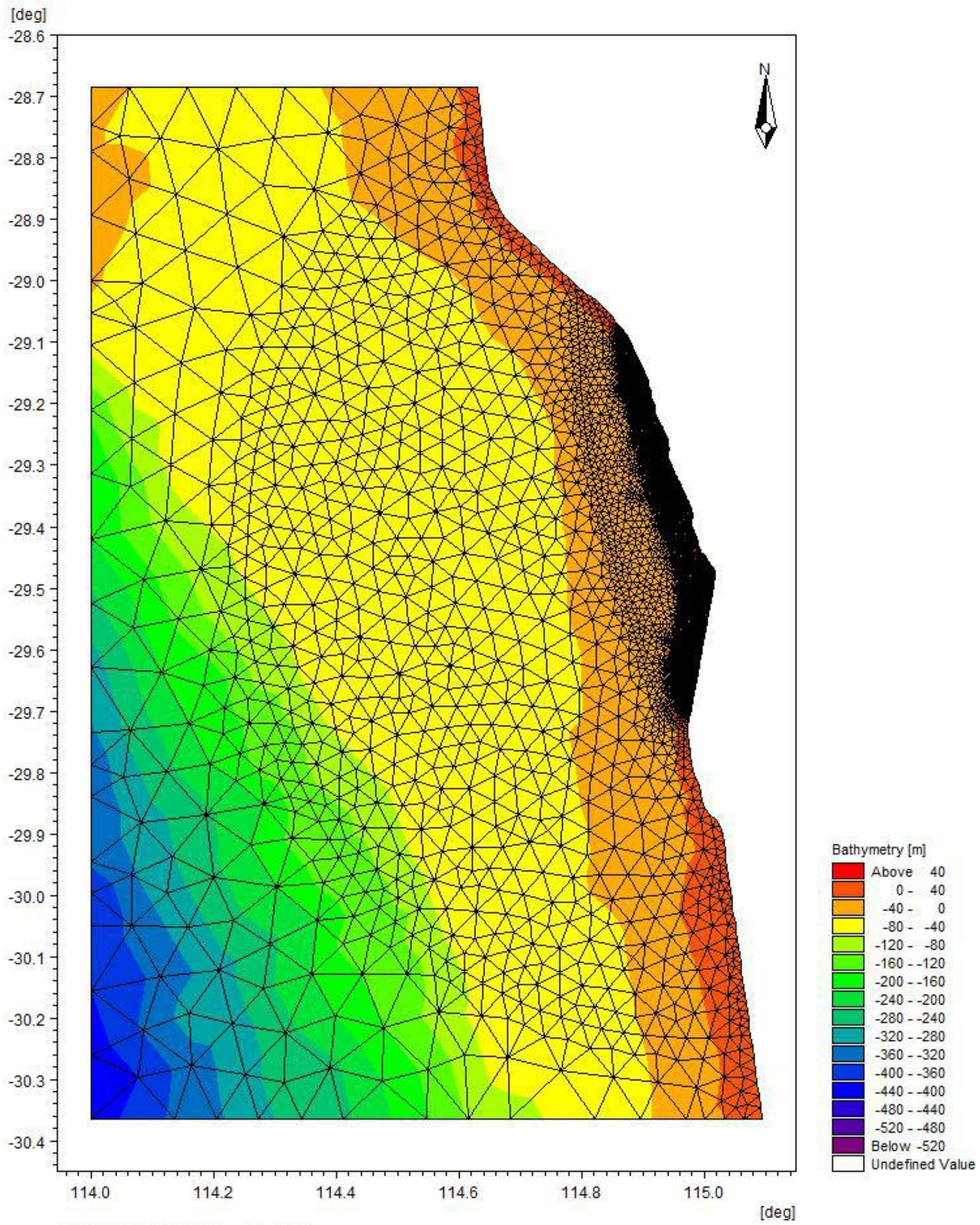

Figure 5.4: The model mesh with bathymetry and topography

5.2 Numerical Modelling

MIKE 21 flow model FM and MIKE 21/3 Couple Model FM are comprehensive and versatile modelling systems for two-dimensional coastal and marine modelling developed by Danish Hydraulic Institute (DHI). MIKE 21/3 is integrated model which is further improvement of MIKE 21 and MIKE 3 Flow Model FM. The type of the model grid is a Flexible Mesh (FM) (DHI, 2011). The modelling system was developed for complex applications within oceanographic, coastal and estuarine environments. MIKE 21/3 Couple Model FM takes account of the impact of waves and tides on each other, by using dynamically coupled versions of MIKE 21/3 FM HD and MIKE 21 SW within the single interface (Flood, 2015). The impact of the sediment transport processes on the overall system can be found by adding sand or mud transport modules.

In this study, MIKE21/3 Couple model FM (flexible mesh) is used to generate a model with a combination of Hydrodynamic (HD) module, Spectral Wave (SW) module and Sand Transport (ST) module. Figure 5.5 illustrates the diagram of the model.

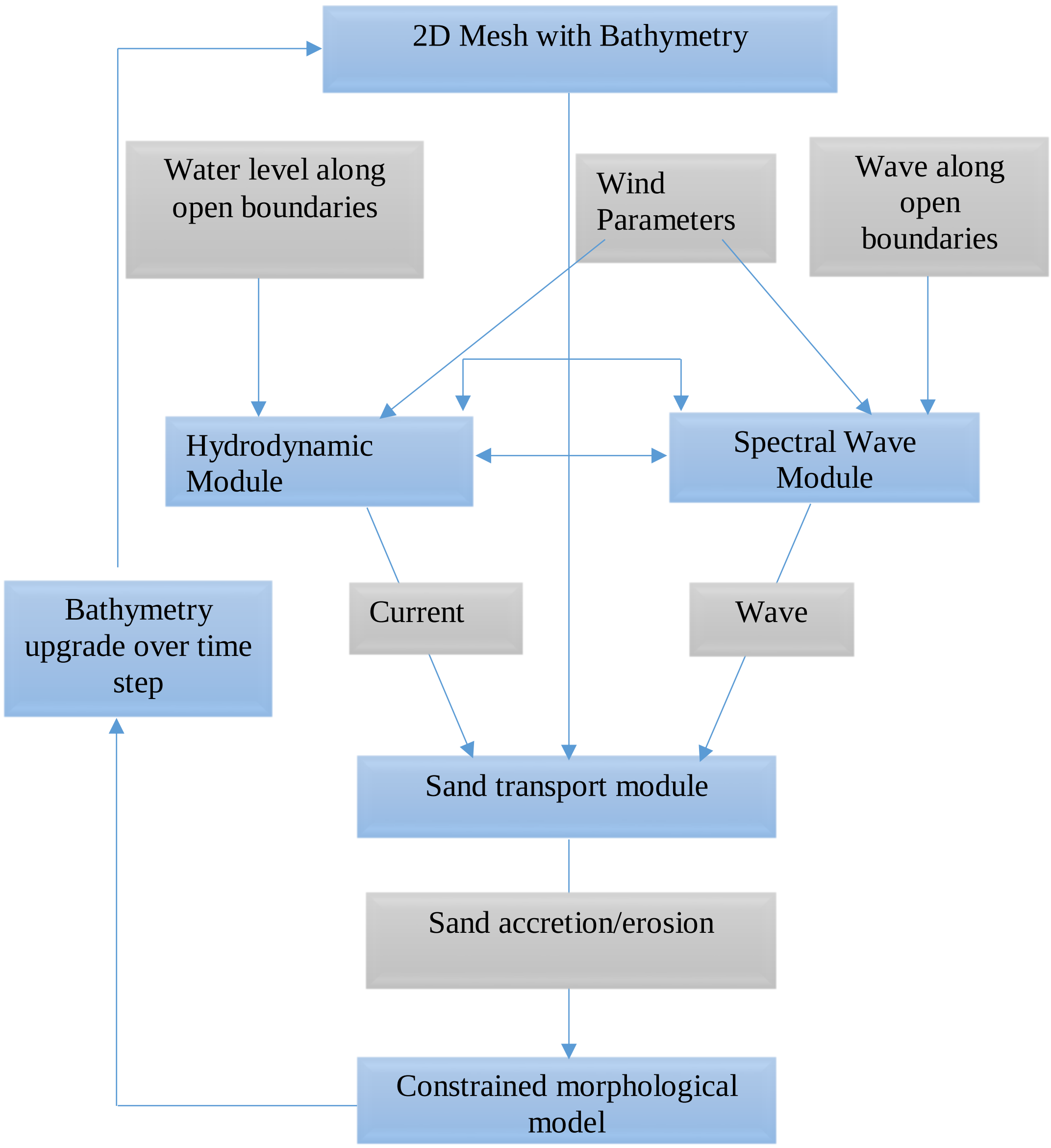

Figure 5.5: Schematic of HD, SW and ST modules in MIKE 21/3 couple model FM

The model allows dynamic simulation of connections between the waves and the current at every time step, also upgrades the bathymetry over the time step. It is a continuous process under the combined action of wind, waves, and tides. The model period was selected to cover the extreme events and sufficient data were available to force and validation the model.

5.2.1 Hydrodynamic Module (HD)

The Hydrodynamic module provides the basis for computations performed in many other modules, but can also be used alone. It simulates the water level variations and flows in response to a variety of forcing functions on flood plains, in lakes, estuaries and coastal areas (DHI, 2011a). The Hydrodynamic module is based on the numerical solution of the two dimensional shallow water equations (the depth integrated equations) (DHI, 2011b). Therefore, the model consist of continuity, momentum, temperature, salinity and density equations. Water levels, waves and winds are the model forcing data out of which the water levels and the waves apply along the open boundary and the wind applies on the surface. Model set up parameters are as follows.

Table 5-2: HD model setup parameters

Parameters	Setup as
Eddy viscosity	Smagorinsky formulation: Constant value over the domain
Bed resistance	Manning number: constant over the domain
Wind forcing	Varying in time, constant in domain
Wave radiation	Wave radiation from spectral wave (SW module) simulation
Initial Conditions	Water levels and velocities: set to zero
Structures	Break waters (Port Denison Harbor) set as culvert to avoid erosion in ST module
Boundary Condition	Open boundary: Water level variation over the time and constant along the boundary
Model time step	5 minutes
Model outputs	Sea levels, U and V velocity components: In 5 minute intervals

5.2.2 Spectral Wave Module (SW)

MIKE21 Spectral Wave (SW) module is a state-of-the art numerical modelling tool. The model is based on flexible mesh and therefore is mainly applicable for simultaneous wave prediction and analysis both on regional and local scale (DHI, 2007a). Flexible mesh allows for coarse resolution for offshore area and high-resolution mesh in shallow water and at the coastline. HD model was coupled with SW model to simulate wave and current interaction. The model simulates wave growth by the action of wind and includes all relevant wave phenomena such as shoaling, breaking, refraction and swells. (DHI, 2011c). Significant wave height, peak wave period and mean wave direction were used for wave boundary data for the model simulation. The set-up parameters of the SW model:

Table 5-3: SW model setup parameters

Parameters	Setup as
Spectral formulation	Directionally decupled parametric formulation
Spectral discretization	360 degree rose
Water level condition	From HD simulation
Wind forcing	Varying in time, constant in domain
Wave braking	Specified gamma
Bottom friction	Nikuradse roughness: constant over the domain
Boundary condition	Open boundary: Wave parameters variation over the time and constant along line: Significant wave height, Peak wave period and mean wave direction
Outputs	Significant wave height, peak wave period and mean wave direction

5.2.3 Sand Transport Module (ST)

MIKE 21 ST module can simulate sand transport rates in a wide selection of settings, including tidal inlets, estuaries and coast lines and manmade constructions like harbours and bridges (DHI, 2007b). Optimum precision in the simulations of the model is determined by the consideration of tide, wind, wave and current. The MIKE 21 ST model calculates the rate of sand transport in combine with waves and currents and pure currents methods (DHI, 2015). The ST model calculates sand transport rates on the flexible mesh covering the area of concern of the hydrodynamic data obtain from a simulation with the HD model and wave data from SW model together with the information about the characteristics of the bed material.

Table 5-4: ST model setup parameters

Parameters	Setup as
Model definition	Wave and current
Sediment properties	Constant
Wave forcing	Wave field from SW simulation
Boundary condition	Zero sediment flux gradient
Outputs	Bed level, Bed level change, Rate of bed level change

5.3 Assumptions and limitations

Three sources of uncertainty affect the vertical accuracy of the inundation models presented here: (1) uncertainty in tidal elevations, (2) uncertainty in topographic elevations, and (3) uncertainty in wave-driven set-up and run-up values (Storlazzi et al, 2013).

The following are the main assumptions for the modelling.

- Effects from other methods of catchment flooding (Rainfall, River flow and ground water level and connectivity) were not considered for the modelling.

- Calibration of the model was done using MIKE21 global tide data, due to lack of data in the study area.
- Even though bathymetry data was over 20 years old, it was assumed that the data and levels are still valid. Please note that as some of the bathymetry data near the study area was more than 20 years old, it might affect the final results.
- The coastline data which was considered in the model had been collected in 1990. The model assumes that the coast line still exists at the same location.

6 Calibration and Validation of the Numerical Model

The accuracy and the quality of the results is an important part of a Numerical modelling. Therefore the calibration and validation of a numerical model is essential to obtain a correct output from the model. The calibration consisted of iterative adjustment to model parameters until the model results agreed with the measured data. In this study the model boundaries were selected based on the available tide gauges. Within the domain, there is no any additional observed tide data to calibrate the model, but in this study, global data was used to calibrate the model. Therefore the calibration and the validation were done using MIKE 21 predicted tidal data.

6.1 Calibration of the Hydrodynamic Model

Calibration of the hydrodynamic model (HD) was carried out by using the global tide data set extract from MIKE 21 tool box for twenty days from 1st January 2005 to 20th January 2005. Tide data was extract from the mid-point of the boundaries of the domain for above time period. Those boundary data was used as forcing data to run the model. A point was selected within the domain which was (long 114.915^0, lat -29.265^0) and extracted the tide level for the point. After that, the model parameters were selected for the hydrodynamic model.

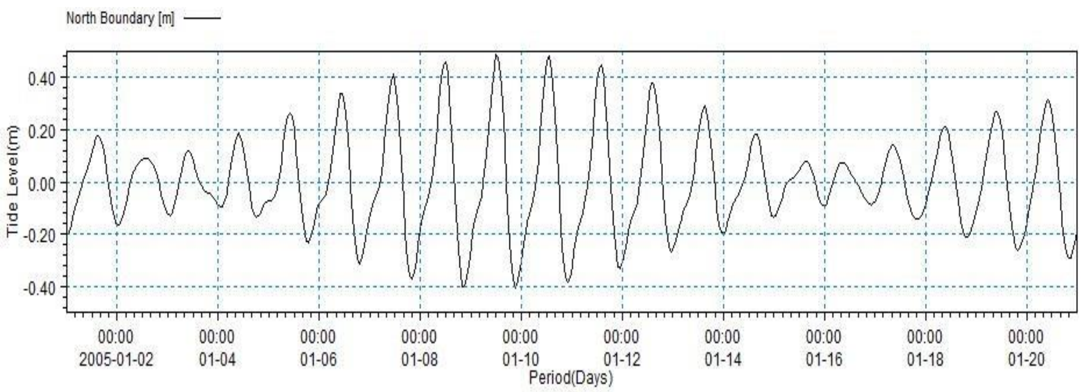

Figure 6.1: Forcing data (tide level) at north boundary for model calibration

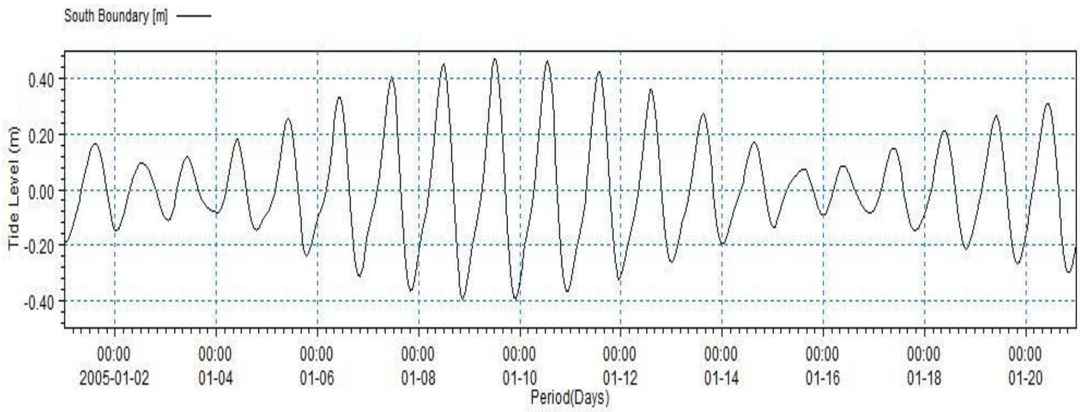

Figure 6.2: Forcing data (tide level) at south boundary for model calibration

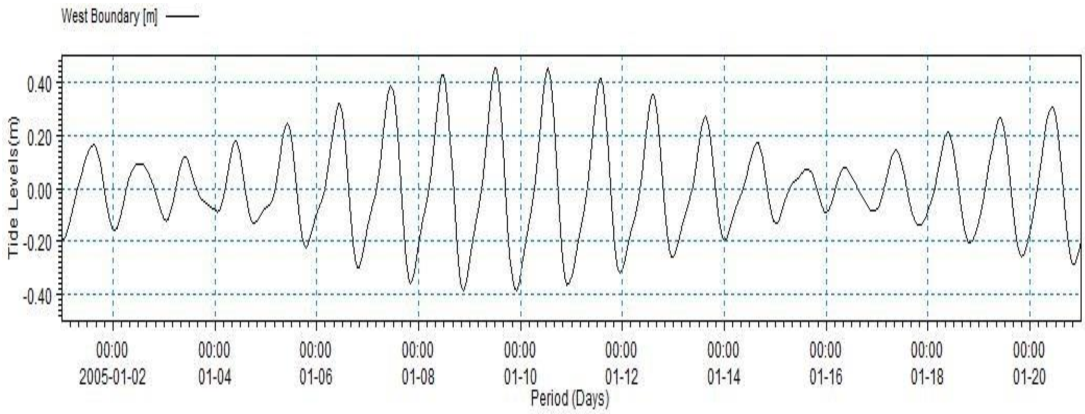

Figure 6.3: Forcing data (tide level) at west boundary for model calibration

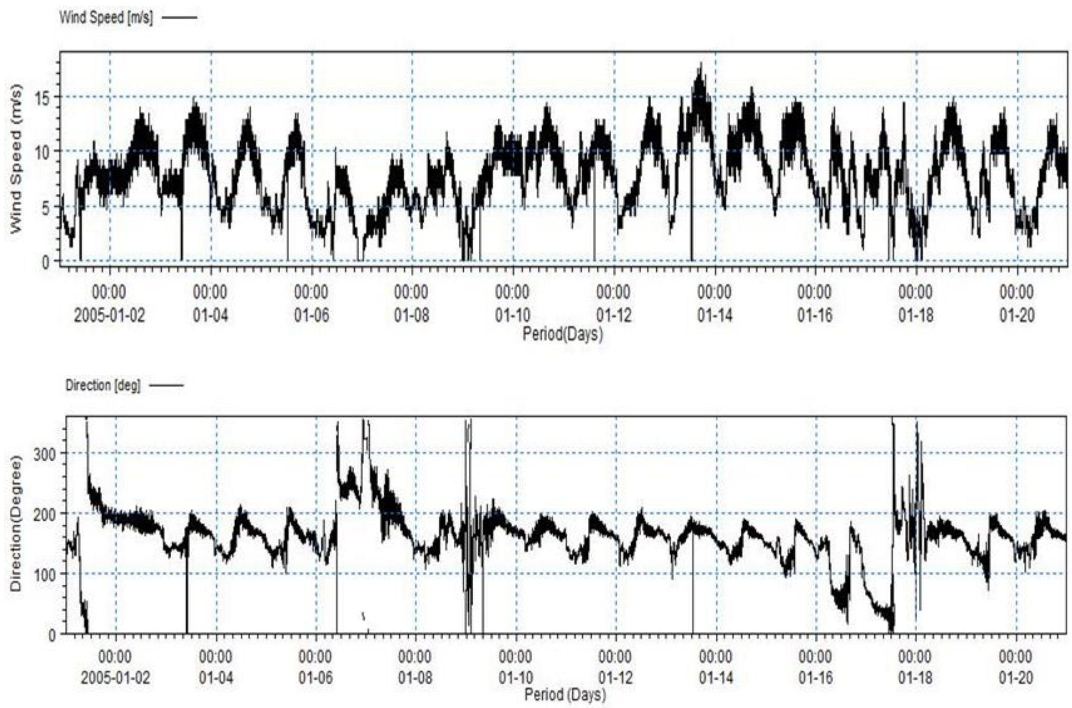

Figure 6.4: Wind data for model calibration

The low order, fast algorithm was selected as shallow water equation. The maximum time step was 30 second and critical CFL number was 0.8. Flood and dry depth was selected as default values which fulfilled $h_{dry}(0.005m) < h_{flood}\ (0.05m) < h_{wet}(0.1m)$. Barometric option was selected as the density type. Wind frictions were selected as 0.002 and 0.0035 for 7m/s and 25m/s respectively. Smagorinsky formulation was used for Eddy Viscosity and Manning Number was selected bed resistance. Eddy Viscosity and Manning Number were used as the variables and kept the constant values for one parameter, while changing the value for other variable to calibrate the hydrodynamic model. First the model was simulated without wind speed and wave radiation.

Figure 6.5 illustrates the calibration graph for global data and model result at the point (long 114.915^0, lat -29.265^0) in the domain.

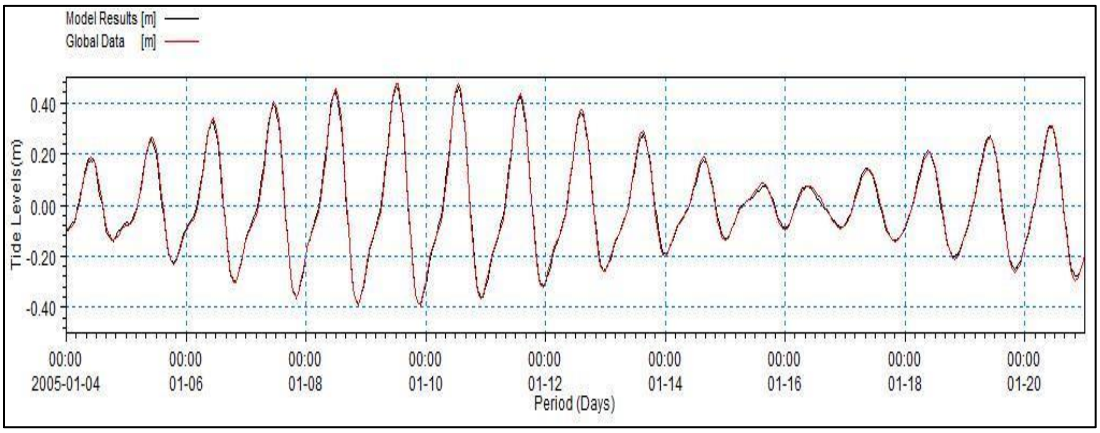

Figure 6.5: Calibration of the hydrodynamic module without wind (Model results and global data set from MIKE 21)

After that, the model was simulated with wind data. Figure 6.6 illustrates the calibration graph for global data and model result at the point (long 114.915^0, lat -29.265^0) in the domain.

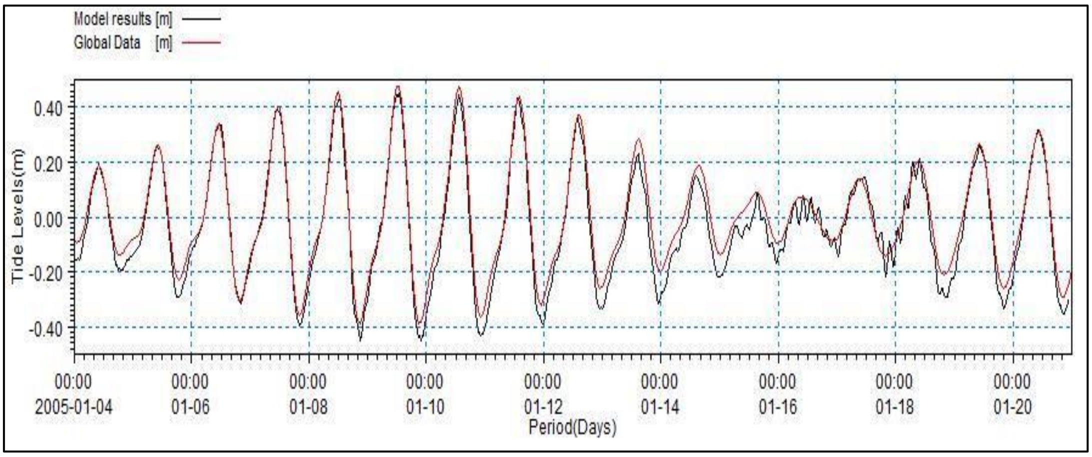

Figure 6.6: Calibration of the hydrodynamic Module with wind (Model results and global data set from MIKE 21)

The accuracy of the model is defined using Correlation Coefficient and RMS Error.

Table 6-1: Calibration statistics comparing simulated and global tide levels during calibration period

	RMS Error	Correlation Coefficient
Calibrate without wind	0.98	0.04
Calibrate with wind	0.97	0.06

The above calibration model result were obtained by setting the Eddy Viscosity coefficient and the Manning Number as 0.28 and 32 $m^{1/3}/s$ respectively during the model simulation. The result matched with the global data at the selected point.

6.2 Validation of the Hydrodynamic Model

Using calibrated parameters, validation of the model was done for another data set. Validation of the hydrodynamic model was carried out by using the global tide prediction data set extracted from MIKE 21 tool box for twenty days from 1st to 20th July 2010. Same as that of the calibration, the tide data was extract from the mid-point of the boundaries of the domain for the above time period. The same point which was used for calibration was selected within the domain (114.915, -29.265) and extract the tide levels for the defined time period.

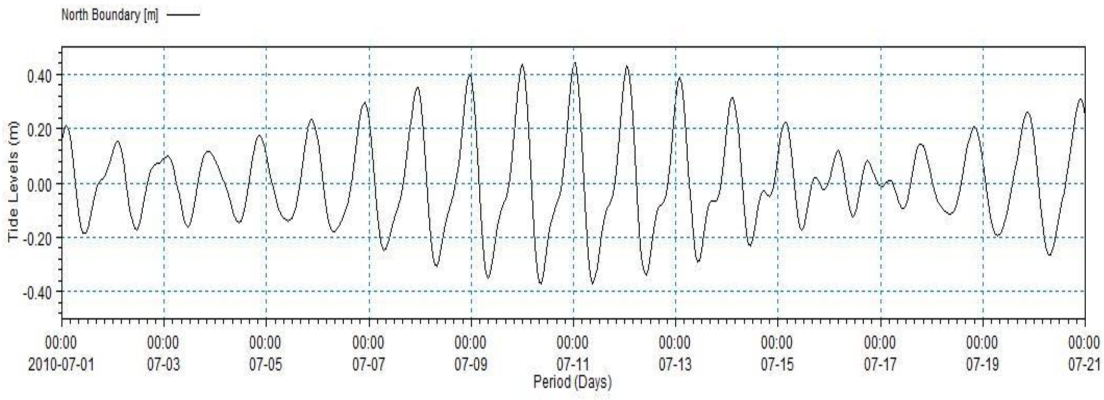

Figure 6.7: Forcing data (tide level) at north boundary for model validation

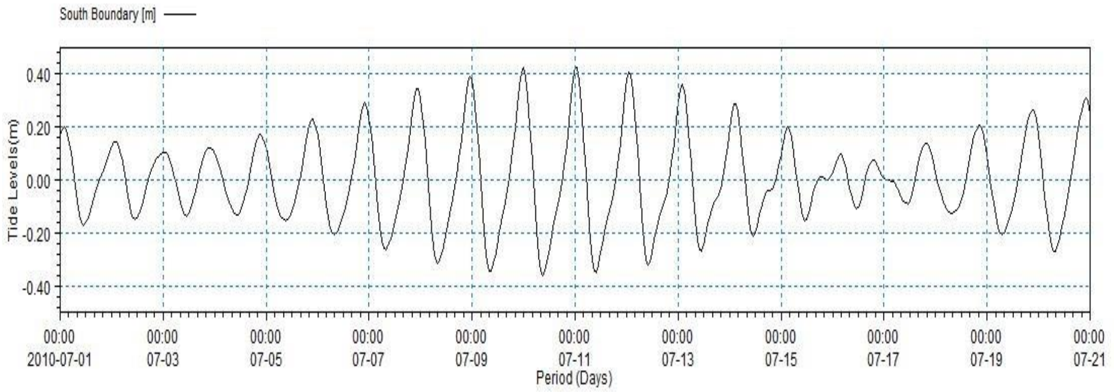

Figure 6.8 : Forcing data (tide level) at south boundary for model validation

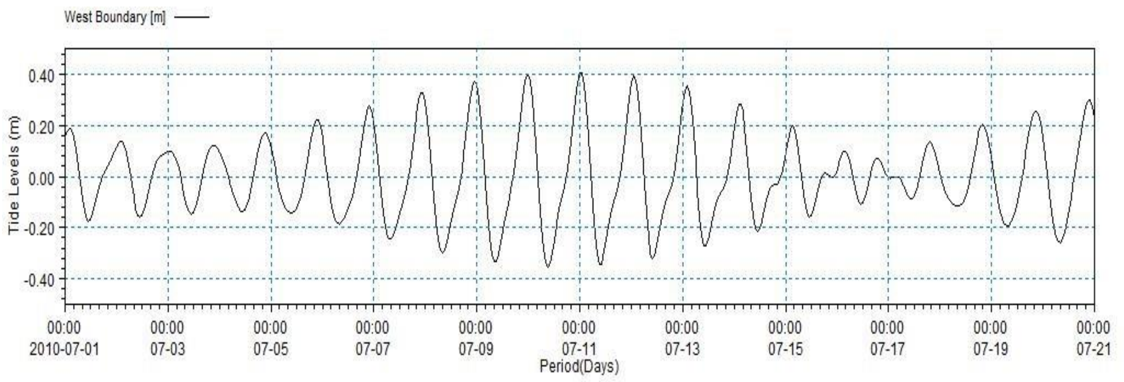

Figure 6.9: Forcing data (tide level) at west boundary for model validation

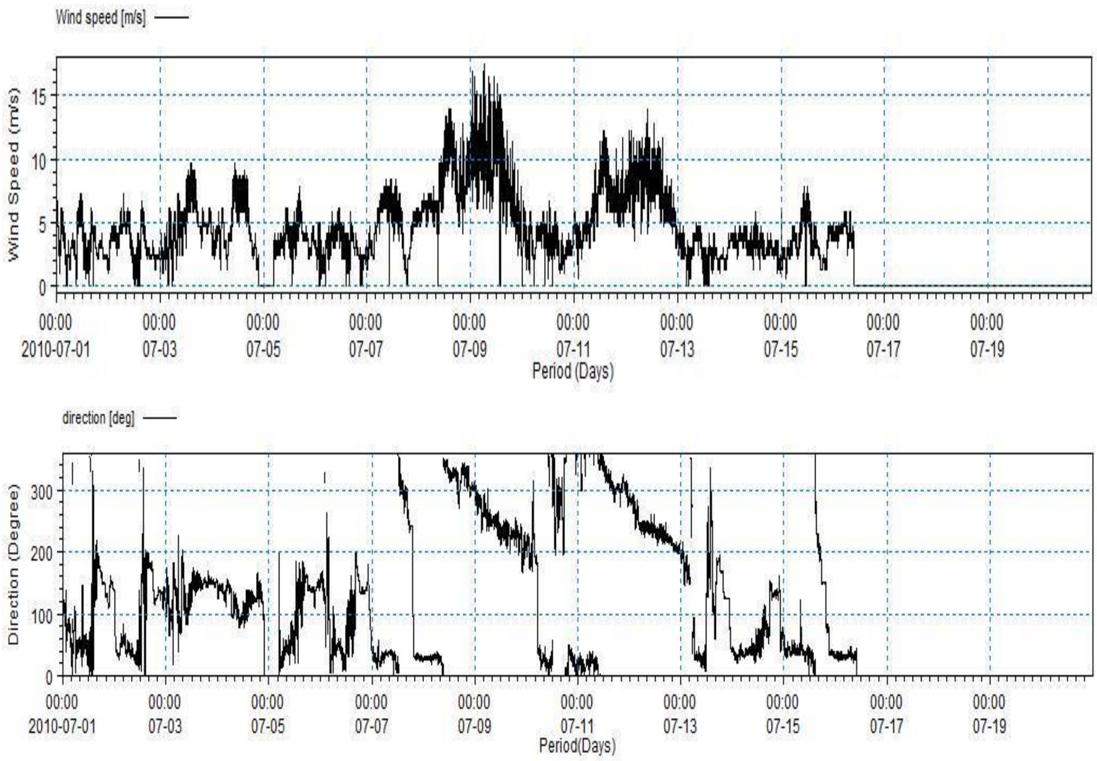

Figure 6.10: Wind data for model validation

The model was simulated using above data and without wind speed and wave radiation. Further the values at the selected point extract from the model result. Figure 6.11 illustrates the validation graph and the global data at the selected point.

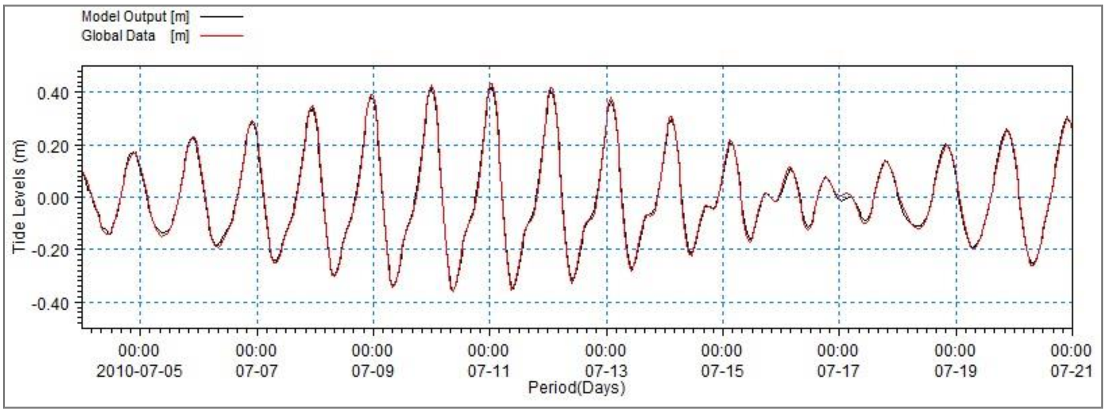

Figure 6.11: Validation of the hydrodynamic module without wind (Model results and global data set from MIKE 21)

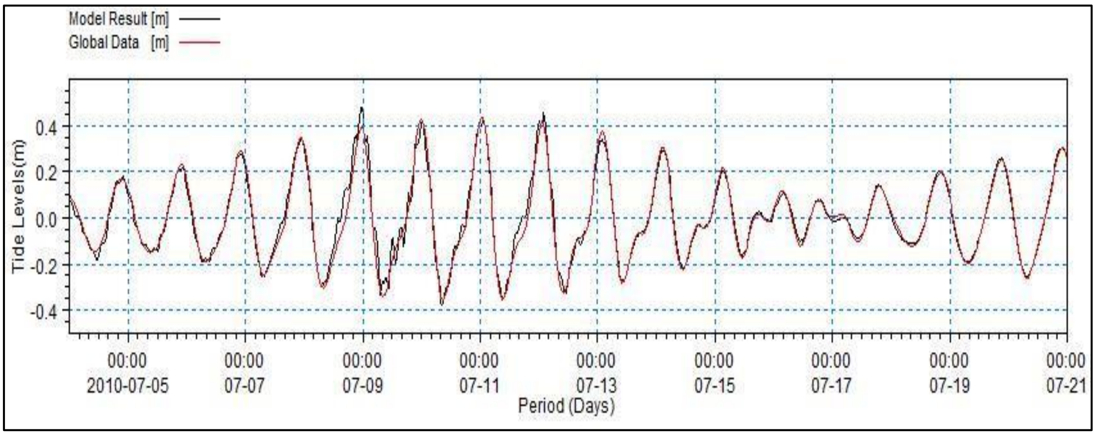

Figure 6.12: Validation of the hydrodynamic module with wind (Model results and global data set from MIKE 21)

Table 6-2: Validation statistics comparing simulated and global tide levels during validation period

	RMS Error	Correlation Coefficient
Validation without wind	0.98	0.03
Validation with wind	0.97	0.04

In this study, the calibration data period was in mid-summer and the validation data was in mid-winter season. Each of these data set captured a range of weather conditions, including summer conditions during the calibration data period and winter condition in validation data collection period. The calibration and subsequent validation of the model provides the means for assessment of coastal process at the coastal zone in the study area. After comparing calibration and validation results, the model parameters were defined as 0.28 for Eddy Viscosity coefficient and 32 $m^{1/3}/s$ Manning Number for the hydrodynamic model.

7 Spatial and Temporal Variation of Coastal Inundation

This chapter presents the final results of the inundation model in terms of the inundation maps. The inundation maps are important as they show the spatial and temporal distribution of inland inundation as well as the water depth at given locations. These inundation maps only represent the impacts of the coastal flooding and do not take into account of the flooding that occurs as a result of issues related to surface run off, river flow and ground water level.

The maps are categorised based on locations which are considered as highly important areas and maps were produced using ArcGIS software:

- Port Denison, Granny's Beach/Surf Beach;
- Seaspray Beach/Irwin River;
- South Beach (North);
- South Beach (South);
- Seven Mile Beach;
- Cliff Head (North);
- Cliff head (South); and
- Freshwater Point.

Inundation maps were developed for each location based on the considered sea level rise scenarios and extreme events (ARI). Therefore 12 maps were developed for each identified locations (Four sea level rise – 0, 0.5, 0.9 and 1.5m; three ARI: 1, 100, and 500). Following sections explain the detailed results of the inundation maps for each location. (A set of maps for one selected location is included in the main manuscript and the rest of the maps are placed in Appendix B).

1990 coastline is used as the baseline for the mapping process. The results are presented in the summary tables which is clear to understand the comparison for each event. Even though the inundation depth is not mentioned in the ArcGIS maps, the model results include the surface elevation levels and the inundation depths. Considering the results, it is possible to summarize above areas where inundation is likely to be an issue at the present time as well as additional areas where inundation is likely to become a problem in the future where sea level rise is adversely affected.

7.1 Port Denison/Granny's Beach/Surf Beach

Port Denison contains a harbour and associated foreshore facilities which are of great economic importance to the region. The Dongara town is also located close to Port Denison and this area is highly populated compared to the other locations of the study area. Further, the Granny's Beach and the Surf Beach are considered to be important recreational locations by the community. There is also a popular caravan park between these two beaches. Even though the topography readings were taken in 2013, the bathymetry was taken in 2003. Therefore the seawall located in front of the Caravan Park may not be considered in the model due to the unavailability of recent bathymetry data in that area. The following table summarises the inundation risk at Port Denison/Granny's Beach/Surf Beach coastal area and Figure 7.1-Figure 7.8 portray the inundation distribution.

Table 7-1: Inundation hazards according to the model results- Port Denison/Granny's Beach and Surf Beach

The location	Present Inundation Hazards (0.0m SLR)	Future Inundation Hazards (0.5m,0.9m and 1.5m SLR)	Reference
Port Denison/Granny's Beach and Surf Beach	Port Denison Harbour and the footpath in the embankment in front of the Caravan Park may be inundated slightly for 1 year ARI. Inundation may be extended > 15m landward at the Caravan Park for 1 year ARI. Port Denison Jetty and boat ramp, Harbour foreshore, the section of the Breakwaters, Caravan Park, and Fishermen's Drive may be inundated for 100 and 500 year ARI events and also Granny's Beach and Surf Beach.	Part of the Caravan Park, along the Harbour foreshore and Fishermen's Drive may be inundated for 1, 100 and 500 year ARI at 0.5m SLR. Inundation may be extended > 30m landward at the Caravan Park and >60m at harbour foreshore for 1 year ARI at 0.5mSLR. The variation may be affected due to the elevation difference between these two locations. Further inundation may be extended >5m for 100 year ARI with respect to 1 year ARI and >3m for 500 year ARI with respect to 100 year ARI. Water depth may be varied < 0.5m for 1 year ARI and < 0.6m and < 0.7m for 100 and 500 ARI events respectively at 0.5m SLR. (From the model results).	Figure 7.1 to Figure 7.8

	Further inundation may be extended >10m in 100 year ARI with respect to 1 year ARI and >5m in 500 year ARI with respect to 100 year ARI. Water depth may be varied < 0.3m for 1 year ARI and <0.5m and < 0.6 for 100 and 500 ARI events respectively. (From the model results).	Potential shift of inundation zones due to 0.9m SLR along the coast at Port Denison, Granny's beach and Surf Beach affects a relatively small area from the inundation boundary of 0.5m SLR, but the inundation zone between 0.9 to 1.5m SLR may be considerably increased towards the harbour foreshore and Granny's Beach to Surf Beach area. Section of the Caravan Park, Granny's Beach, Surf Beach, buildings in the harbour foreshore, Fishermen's Drive and section of the Point Leander Drive may be inundated at 0.9m SLR Inundation may be extended > 40m landward at the Caravan Park and >90m at harbour foreshore for 1 year ARI at 0.9m SLR. Further inundation may be extended > 4m for 100 year ARI with respect to 1 year ARI and > 4m for 500 year ARI with respect to 100 year ARI.	

		According to the model results water depth may be diverse < 0.5m for 1 year ARI and <0.6m and < 0.7 for 100 and 500 ARI events respectively at 0.9m SLR. Caravan Park, Granny's Beach, Surf Beach, buildings in the harbour foreshore, Fishermen's Drive, Point Leander Drive, Ocean Drive and some residential buildings near to the harbour may be inundated at 1.5m SLR. Inundation may be extended > 70m landward at the Caravan Park and > 100m at harbour foreshore for 1 year ARI at 1.5m SLR. Further inundation may be extended > 7m for 100 year ARI with respect to 1 year ARI and >10m for 500 year ARI with respect to 100 year ARI. According to the model results, water depth may be diverse < 1m for 1 year ARI and < 2m and < 2.5 for 100 and 500 ARI events respectively at 1.5m SLR.	

Figure 7.1: Inundation map of Port Denison – 1,100 and 500 year ARI event at Present (2014) 0m SLR

Figure 7.2: Integrated inundation map of Port Denison at present (0.0m SLR)

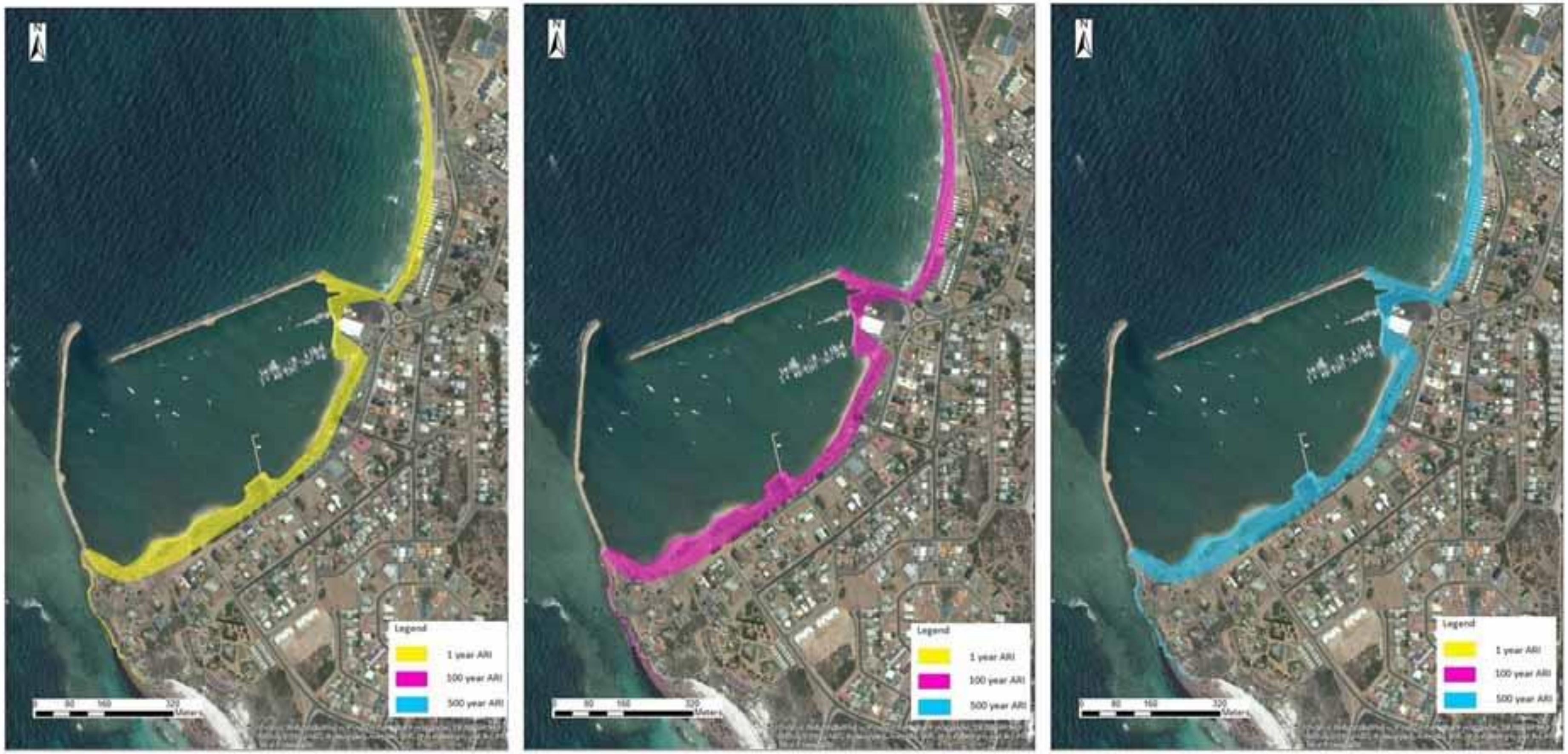

Figure 7.3: Inundation map of Port Denison – 1,100, 500 year ARI event in 2070 (0.5 m SLR)

Figure 7.4: Integrated inundation map of Port Denison in 2070 (0.5m SLR)

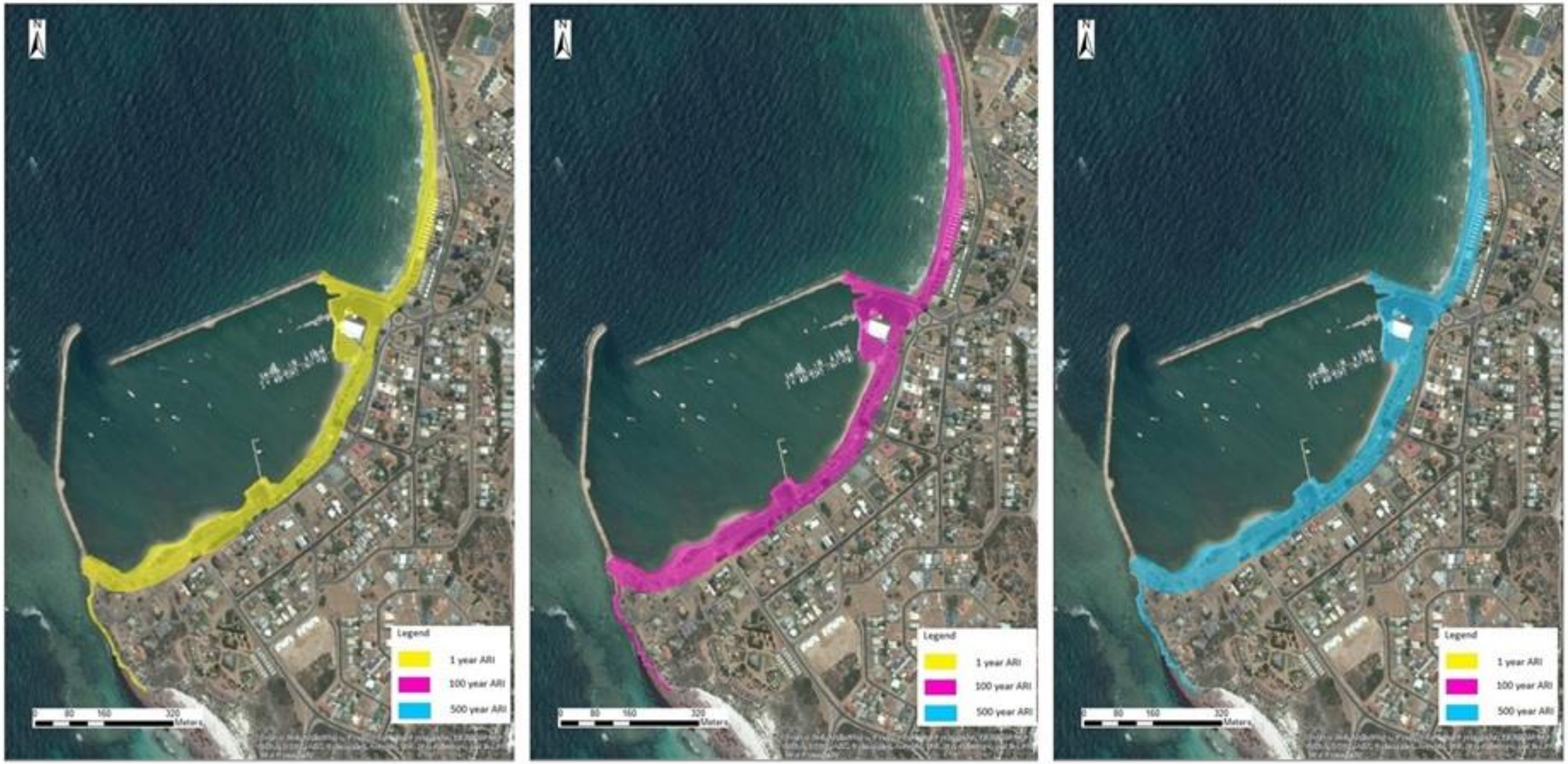

Figure 7.5: Inundation map of Port Denison -1,100 and 500 year ARI event in 2110 (0.9m SLR)

Figure 7.6: Integrated inundation map of Port Denison in 2110 (0.9m SLR)

Figure 7.7: Inundation map of Port Denison -1,100 and 500 year ARI event in 2110 (1.5m SLR)

Figure 7.8: Integrated inundation map of Port Denison in 2110 (1.5m SLR)

7.2 South Beach (North)

South Beach (North) is adjacent to the Port Denison Harbour. This is an economically and socially important location for future development in the study area. There is no any control structures facing the coastline at South Beach (North). This area includes the beach and adjacent dunes and scrubland, a caravan park, a public road, a cafe and the Surf Lifesaving Club's shed. All of the land is public land. The car park and the public road are experiencing inundation annually. The Table 7-2 summarises the inundation risk at South Beach (North) coastal area and Figure B. 1 -Figure B. 8 (Appendix B) show the inundation distribution.

Table 7-2: Inundation hazards according to the model results-South Beach (North)

The location	Present Inundation Hazards (0.0m SLR)	Future Inundation Hazards (0.5m,0.9m and 1.5m SLR)	Reference
South Beach (North)	Only the beach may be inundated.	Flood slightly may be reached to building premises for 100 and 500 year ARI at 0.5m SLR scenario. Inundation may be extended > 15m landward for 100 year ARI with respect to 1 year ARI and > 2m for 500 year ARI with respect to 100 year ARI.	Figure B. 1 to Figure B. 8

		Water depth may be varied < 0.5m for 1 year ARI and <0.6m and < 0.7 for 100 and 500 ARI events respectively at 0.5m SLR. (From the model results). The buildings and the car park at the end of the Wight-Tops Road may be partially inundated at 0.9m SLR. Inundation may be extended > 40m landward for 1 year ARI at 0.9m SLR, > 15m for 100 year ARI with respect to 1 year ARI and >3m in 500 year ARI with respect to 100 year ARI. According to the model results water depth varies < 0.6m for 1 year ARI and < 1m and < 2m for 100 and 500 ARI events respectively at 0.9m SLR. The majority of the area may be inundated for a 1.5m SLR scenario. The buildings, the car park and section of the Wight-Tops Road may be fully inundated at 1.5m SLR.	

		Inundation may be extended > 70m landward for 1 year ARI at 1.5mSLR. Further inundation may be extended >8m for 100 year ARI with respect to 1 year ARI and > 12m for 500 year ARI with respect to 100 year ARI. According to the model results, water depth varies < 0.7m for 1 year ARI and < 2m and < 2.5 for 100 and 500 ARI events respectively at 1.5m SLR.	

7.3 South Beach (South)

This area contains the community's most popular and well-used beach and adjacent dune systems. A little further inland, atop the dune systems is the runway, which is approximately 12m above the sea level. Apart from the runway, this area will remain undeveloped. The Table 7-3 highlight the inundation risk at South Beach (South) coastal area and Figure B. 9 - Figure B. 16 (Appendix B) depict the inundation distribution at South Beach (South) coastal zone.

Table 7-3: Inundation hazards according to the model results-South Beach (South)

The location	Present Inundation Hazards (0.0m SLR)	Future Inundation Hazards (0.5m,0.9m and 1.5m SLR)	Reference
South Beach (South)	Only the beach may be inundated.	Flood slightly may be reached to the land for 100 and 500 year ARI at 0.5m SLR scenario. Inundation may be extended > 120m landward for 1 year ARI (from 1990 coastline). Inundation may be extended > 5m landward for 100 year ARI with respect to 1 year ARI and > 5m for 500 year ARI with respect to 100 year ARI at 0.5m SLR. The land beyond the beach may be inundated at 0.9m SLR.	Figure B. 9 to Figure B. 16

		Inundation may be extended > 150m landward for 1 year ARI at 0.9m SLR (from 1990 coastline), > 10m for 100 year ARI with respect to 1 year ARI and >5m in 500 year ARI with respect to 100 year ARI. The land area may be significantly inundated for a 1.5m SLR scenario. Inundation may be extended > 450m landward for 1 year ARI at 1.5mSLR (from 1990 coastline). Further inundation may be extended >20m for 100 year ARI with respect to 1 year ARI and > 10m for 500 year ARI with respect to 100 year ARI.	

7.4 Seaspray Beach/Irwin River

This area consist of beaches and adjacent dune systems, a river mouth, a coastal wetland system, public roads, boardwalks, a car park and public toilet and a caravan park. Most of this area is public land, with the exception of a freehold lot containing buildings associated with the caravan park. Seaspray Beach and Irwin River are also important areas in this study. However the model did not consider the hydrological influence of the river flow. Therefore river inundation results might vary when river flow is added. The river bridge level was not considered for modelling. Approximate values of river bed levels were taken in to consideration for the model. The Table 7-4 summarises the inundation risk at Seaspray Beach and Irwin River coastal area. Inundation maps for this area is shown in Figure B. 17-Figure B. 32 (Appendix B).

Table 7-4: Inundation hazards according to the model results- Seaspray Beach / Irwin River

The location	Present Inundation Hazards (0.0m SLR)	Future Inundation Hazards (0.5m,0.9m and 1.5m SLR)	Reference
Seaspray Beach/Irwin River	The beach may be slightly inundated. The Irwin river may be flooded > 500m because of 1,100 and 500 ARI, but the river inundation may be changed significantly, once the river flow added to the model.	Seaspray beach may be inundated for 100 and 500 year ARI at 0.5m SLR scenario. The Irwin river may be flooded > 1.5km for 100 and 500 ARI events, but the river inundation may be changed significantly, once the river flow added to the model.	Figure B. 17 to Figure B. 32

		Inundation may be extended > 15m at Seaspray Beach for 1 year ARI at 0.5m SLR. Inundation may be extended >5m for 100 year ARI with respect to 1 year ARI and >10m for 500 year ARI with respect to 100 year ARI. Water depth may be varied < 1 m for 1 year ARI and <2m and < 2.5 for 100 and 500 ARI events respectively at 0.5m SLR. (From the model results). Seaspray beach may be totally inundated at 0.9m SLR and it could slightly reach the Seaspray Beach Holiday Park premises. South of the river, inundation may be extended up to Ocean Drive. Inundation may be extended > 50m at Seaspray Beach for 1 year ARI at 0.9m SLR, there is no much difference for 100 year ARI with respect to 1 year ARI and > 3m for 500 year ARI with respect to 100 year ARI. The river may be flooded > 1.5km for 100 and 500 ARI events.	

		According to the model results water depth may vary < 2m for 1 year ARI and < 2.5m and < 3m for 100 and 500 ARI events respectively at 0.9m SLR. A significant area of the river sides would be flooded for a 1.5m SLR scenario. Some residential buildings and Seaspray Beach Holiday Park premises and buildings may be significantly inundated at 1.5m SLR. The river flood would be extended up to Brand Highway. The section of the Ocean Drive may be inundated. Inundation may be extended > 80m landward for 1 year ARI at 1.5m SLR. Further inundation may be extended >10m for 100 year ARI with respect to 1 year ARI and > 4m for 500 year ARI with respect to 100 year ARI. Water depth may be varied < 2.5m for 1 year ARI and < 3m for 100 and 500 ARI events at 1.5m SLR.	

7.5 Seven Mile Beach

Seven Mile Beach consist of beaches and associated dunes systems, a public car park and public road. The car park is used for overnight camping and recreational fishing. Table 7-5 summarises the inundation risk at Seven Mile Beach coastal area and Figure B. 33 - Figure B. 40 (Appendix B) illustrate the inundation distribution at Seven Mile Beach.

Table 7-5: Inundation hazards according to the model results- Seven Mile Beach

The location	Present Inundation Hazards (0.0m SLR)	Future Inundation Hazards (0.5m,0.9m and 1.5m SLR)	Reference
Seven Mile Beach	Significant inundation would be happened at north side of the Seven Mile Road. Inundation may be extended >50m landward for 1 year ARI. Further inundation may be extended > 30m for 100 year ARI with respect to 1 year ARI and > 20m for 500 year ARI with respect to 100 year ARI.	Potential shift of inundation zones due to 0.5m SLR along the coast affects a relatively small area to the 0.0m SLR, but the inundation zone between 0.5 to 0.9m SLR may be considerably increased towards the land. North side of the Seven Mile Road is significantly inundated at all SLR scenario. The end of the road and parking area may be inundated in the most extreme scenarios. Inundation may be extended > 80m to the inland for 1 year ARI at 0.5m SLR. Further inundation may be extended >	Figure B. 33 to Figure B. 40

	Water depth would be varied < 0.3 m for 1 year ARI and < 0.5m and < 0.6m for 100 and 500 ARI events respectively. (From the model results).	6m for 100 year ARI with respect to 1 year ARI and > 3m in 500 year ARI with respect to 100 year ARI. Water depth may be varied < 0.5 m for 1 year ARI and < 0.6m and < 0.7m for 100 and 500 ARI events respectively at 0.5m SLR. (From the model results). Inundation may be extended > 80m landward for 1 year ARI at 0.9m SLR, further inundation is anticipated > 3m for 100 year ARI with respect to 1 year ARI and > 4m for 500 year ARI with respect to 100 year ARI. According to the model results water depth may vary < 0.7m for 1 and 100 year ARI < 1m for 500 ARI events at 0.9m SLR. Inundation may be extended > 100m landward for 1 year ARI at 1.5m SLR. Further inundation may be extended >10m for 100 year ARI with respect to 1 year ARI and >5m for 500 year ARI with respect to 100 year ARI. Water	

		depth may vary < 1m for 1, 100 and 500 ARI events at 1.5m SLR.	

7.6 Freshwater Point

This area consist of a limestone shoulder that protects a small bay, beaches and adjoining scrubland, a public access track and parking area, public toilet and a number of shacks and other structures associated with the fishing industry. A number of shacks and structure have been recently removed due to the shrinking coastline in this location. The area is used by overnight campers and fishermen. Table 7-6 highlight the inundation risk at Freshwater Point coastal area and Figure B. 41- Figure B. 48 (Appendix B) depict the inundation distribution.

Table 7-6: Inundation hazards according to the model results- Freshwater Point

The location	Present Inundation Hazards (0.0m SLR)	Future Inundation Hazards (0.5m,0.9m and 1.5m SLR)	Reference
Freshwater Point	Fisherman's shacks would be slightly inundated. Inundation may be extended > 40m landward for 1 year ARI. Further Inundation may be extended >10m for 100 year ARI with respect to 1 year ARI and > 4m for 500 year ARI with respect to 100 year ARI.	Fisherman's shacks may be partially inundated at 0.5m SLR. The majority of the area is flooded for the 0.9m and 1.5m SLR scenarios. Those shacks premises would be fully inundated the 0.9m and 1.5m SLR. Inundation may be extended > 50m to the inland for 1 year ARI at 0.5mSLR. Further inundation may be extended >5m for 100 year ARI with respect to 1 year ARI and >4m for 500 year ARI with respect to 100 year ARI.	Figure B. 41 to Figure B. 48

	Water depth would be varied < 0.4 m for 1 year ARI and < 0.7m for 100 and 500 ARI events. (From the model results).	Water depth may be varied < 0.5 m for 1 year ARI and < 1m for 100 and 500 ARI events at 0.5m SLR. (From the model results). Inundation may be extended > 60m landward for 1 year ARI at 0.9m SLR, further inundation is anticipated >5m for 100 year ARI with respect to 1 year ARI and >5m in 500 year ARI with respect to 100 year ARI. According to the model results water depth may vary < 0.7m for 1 year ARI and < 1m for 100 and 500 ARI events at 0.9m SLR. Inundation may be extended > 70m landward for 1 year ARI at 1.5m SLR. Further inundation may be extended > 7m for 100 year ARI with respect to 1 year ARI and > 8m for 500 year ARI with respect to 100 year ARI. Water depth may be varied < 1m for 1 and 100 ARI events < 2m for 500 ARI event at 1.5m SLR.	

7.7 Cliff Head (North)

This area is comprised of beaches and associated dune systems, public access tracks, camping areas and a public toilet. The area is used for recreation camping and fishing. The following table summarises the inundation risk at Cliff Head (North) coastal area. Inundation maps for this area is shown in Figure B. 49 - Figure B. 56 (Appendix B).

Table 7-7: Inundation hazards according to the model results- Cliff Head (North)

The location	Present Inundation Hazards (0.0m SLR)	Future Inundation Hazards (0.5m,0.9m and 1.5m SLR)	Reference
Cliff Head	All ARI events cause inundation through to the coastal access tracks (off road tracks). Inundation may be extended > 60m landward for 1 year ARI. Further Inundation may be extended > 10m for 100 year ARI with respect to 1 year ARI and > 8m for 500 year ARI with respect to 100 year ARI.	Potential shift of inundation zones due to 0.5m SLR along the coast affects a relatively small area to the 0.0m SLR, but the inundation zone between 0.9 to 1.5m SLR may be significantly increased towards the land. Inundation may be extended >100m to the inland for 1 year ARI at 0.5m SLR. Further inundation may be extended >10m for 100 year ARI with respect to 1 year ARI and >20m for 500 year ARI with respect to 100 year ARI.	Figure B. 49 to Figure B. 56

	Water depth would be varied < 0.7 m for 1 year ARI and < 1m for 100 and 500 ARI events. (From the model results).	Water depth may be varied < 1 m for 1, 100 and 500 ARI events at 0.5m SLR. (From the model results). Inundation may be extended > 100m landward for 1 year ARI at 0.9m SLR, further inundation is anticipated > 10m for 100 year ARI with respect to 1 year ARI and > 5m for 500 year ARI with respect to 100 year ARI. According to the model results water depth may be varied < 1m for 1 year ARI and < 2m for 100 and 500 ARI events at 0.9m SLR. Inundation may be extended > 150m landward for 1 year ARI at 1.5m SLR. Further inundation may be extended > 15m for 100 year ARI with respect to 1 year ARI and >8m for 500 year ARI with respect to 100 year ARI. Water depth may be varied < 2m for 1 year ARI, water depth would be varied< 2.5m for 100 and 500 ARI events at 1.5m SLR.	

7.8 Cliff Head (South)

Cliff Head South consist of beaches and associated dune systems, fishermen's shacks, public access tracks, camping areas and public toilets. The area is used by the fishing industry but is mostly used for recreational purposes. There is a mining tenement on the land (for the extraction of gypsum). The Table 7-8 summarises the inundation risk at Cliff Head (South) coastal area and Figure B. 57- Figure B. 64 (Appendix B) highlight the inundation distribution at Cliff Head (South).

Table 7-8: Inundation hazards according to the model results- Cliff Head (South)

The location	Present Inundation Hazards (0.0m SLR)	Future Inundation Hazards (0.5m,0.9m and 1.5m SLR)	Reference
Cliff Head South	Slightly inundate some residential areas for 100 and 500 ARI events. Inundation may be extended > 40m landward for 1 year ARI. Further Inundation may be extended >20m for 100 year ARI with respect to 1 year ARI and > 8m for 500 year ARI than 100 year ARI.	Residential buildings may be inundated partially for 100 and 500 ARI events at 0.5m. Potential shift of inundation zones due to 0.9m and 1.5m SLR along the coast affects a relatively small area to the 0.5m SLR Inundation may be extended > 70m to the inland for 1 year ARI at 0.5m SLR. Further inundation may be extended > 14m for 100 year ARI with respect to 1 year ARI and > 10m for 500 year ARI with respect to 100 year ARI.	Figure B. 57 to Figure B. 64

	Water depth would be varied < 0.2 m for 1 year ARI and < 0.5m for 100 ARI event and < 0.6m for 500 ARI events. (From the model results).	Water depth may be varied < 0.5m for 1 ARI event, < 0.6m and 0.7m for 100 and 500 ARI events respectively at 0.5m SLR. (From the model results). Inundation may be extended > 80m landward for 1 year ARI at 0.9m SLR, further inundation is anticipated >15m for 100 year ARI with respect to 1 year ARI and > 4m for 500 year ARI with respect to 100 year ARI. According to the model results water depth may be varied < 0.7m for 1 year ARI, < 1m for 100 ARI and < 2m for 500 ARI event at 0.9m SLR. Inundation may be extended > 100m landward for 1 year ARI at 1.5m SLR. Further inundation may be extended > 25m for 100 year ARI with respect to 1 year ARI and > 3m for 500 year ARI with respect to 100 year ARI. Water depth may be varied < 1m for 1 ARI, water depth would be varied < 2m and < 2.5m for 100 and 500 ARI events respectively at 1.5m SLR.	

7.9 Summary of the Coastal Inundation Results

Coastal inundation maps were developed based on the model results to show the spatial and temporal distribution of inundation risk in the study area. In this study, three ARI events of 1 year, 100 year and 500 year recurrence interval and present and future sea level rise scenarios of 0.5m 0.9m and 1.5m were considered to obtain the coastal inundation. The maps are based on locations which are considered as highly important areas in the selected study stretch.

Most of the areas in Port Denison, Granny's Beach and Surf Beach are likely to be significantly affected by coastal inundation over the next 96 years. The extreme inundation at present condition is more than 30m towards the land and more than 100m for with future sea level rise. Thus, there is an essential need for further studies and ongoing monitoring about the inherent uncertainties with climate change. Because Port Denison is very important location economically and socially.

In the South Beach North, the modelling shows that the caravan park will be unaffected by coastal inundation over the 96 years. The extreme inundation is more than 50m towards the land for with future sea level rise. With regards to the coastal modelling, the natural areas are shown to be the most affected by significant storm events for next 96 years at the South Beach South. The modelling shows the runway may not to be affected by inundation. The extreme inundation is more than 450m towards the land for with future sea level rise.

The most significant impacts for the Seaspray Beach area are likely to occur in 2110, where the 0.9m and 1.5m rises in sea levels were considered. The Irwin River mouth area is likely to be much more sensitive to significant inundation events across the next 96 year period. It is required to carry out flood modelling of the Irwin River, including an analysis of combined river flooding and coastal impacts.

The modelling shows the natural areas may be affected in most scenarios at Seven Mile Beach. The car park and public road are shown to be affected by inundation in the 2070 (0.5m sea level rise) and 2110 (0.9m and 1.5m sea level rise) scenarios. The extreme inundation at present condition is more than 50m towards the land and more than 100m for with future sea level rise.

In the Freshwater Point, the natural areas will be affected in most scenarios and that the private and public infrastructure would be threatened by the inundation scenarios.

In the Cliff Head North, modelling shows that the natural areas are likely to be affected across all scenarios, with inundation likely to have the most significant impacts. The public toilet and public access tracks are shown to be affected in the 2110 scenarios. In the Cliff Head South the natural areas are likely to be most affected across all modelling scenarios, with inundation likely to have the most significant impacts. The public toilets, shacks, public access tracks and camping areas are shown to be inundated in the 2110 scenarios.

8 Spatial and Temporal Variation of Coastal Erosion

Erosion modelling results provide indication to find the coastal vulnerability in the study area. This study was conducted with very limited data and site information. In the erosion mapping, there are four components to be considered to calculate the coastal erosion in sandy beaches (WAPC, 2013).

S1: Allowance for the current risk of storm erosion;
S2: Allowance for historical shoreline movement trend;
S3: Allowance for erosion caused by future sea level rise; and
In addition the estimation should include 0.2m per year allowance for uncertainty.

In this study, all measurements were taken from the horizontal shoreline datum which was the 1990 coastline (as previously discussed). S3 was added to the S1 and used the total of both values as an input water level in the model. According to the Beach Concept Development report (Rogers, 2012), historical shoreline movement (S2) for Granny's Beach/Surf Beach was 25m towards the land from 1965 to 2010. Therefore the rate of erosion per year was 0.55m (25m/45 years). There are no available data for shoreline movement at other locations. Therefore 0.55m /year was used as S2 for the entire study area (Figure 8.1).

The following table shows the values used for S1, S2 and S3 for erosion mapping for each selected time frame.

Table 8-1: Calculation for Erosion Mapping

Location	Present(2014) (0.0m)	2070(0.5m)	2110(0.9m)	2110 (1.5m)
S1+S3	Model Output			
S2 (0.55m/year)	0m	30.8 m	52.8m	52.8m
Uncertainty (0.2m/year)	0m	11.2m	19.2m	19.2m
Total erosion	Model output + 0m	Model output + 30.8m+11.2m	Model output + 52.8m+19.2m	Model output + 52.8m+19.2m

Figure 8.1: Shoreline Movement (recorded value and assumed values)

The erosion model was conducted taking SLR and extreme water levels into account. Each modelling was conducted for the present for 0.5, 0.9 and 1.5 SLR scenarios and

1, 100 and 500 year ARI events. In addition as per SPP2.6, additional scenario S2 and uncertainty rate were considered for erosion mapping of sandy beaches.

The investigation was done quite conservatively, without any geotechnical investigation to locate existence of rock on shore or nearshore which will disrupt erosion pattern. In addition, erosion model uses sediment property of the study area, which assumed a homogeneous sand properties along the entire study area and neglected the heterogeneity of the sand properties due to different sand nourishment and other activities such as sediment deposition from river flow etc.

Final model output is shown and discussed in the following sections. Erosion hazard is presented as a series of colour polygons in mode of aerial maps, where the anticipated coastal response to present and future erosive pressures has been converted into a horizontal distance of shoreline recession. Maps were produced for the following locations using ArcGIS software:

- Granny's Beach/Surf Beach;
- Seaspray Beach/Irwin River;
- South Beach (North);
- South Beach;
- Seven Mile Beach;
- Freshwater Point;
- Cliff Head; and
- Cliff Head South.

Series of erosion maps are developed for each location based on the considered SLR scenarios and ARI. Therefore 12 maps were developed for each identified locations (Four SLR – 0, 0.5, 0.9 and 1.5m; three ARI: 1, 100, and 500). All measurements are taken from the horizontal shoreline datum which is the 1990 coastline.

8.1 Granny's Beach/Surf Beach

This area consist of fairly significant levels of public infrastructure, a caravan site, beaches and adjacent residential and commercial properties. The main assumption affects the results of the Granny's Beach and Surf Beach (Dongara Port) region is that the seawall located in front of the Caravan Park was not consider in the model due to the unavailability of bathymetry data in that area. The Table 8-2 summarises the erosion risk at Port Denison/Granny's Beach/Surf Beach coastal area and Figure 8.2 - Figure 8.9 portray the erosion distribution at Granny's Beach/Surf Beach.

Table 8-2: Erosion hazards according to the model results- Granny's Beach and Surf Beach

The location	Present Erosion Hazards (0.0m SLR)	Future Erosion Hazards (0.5m,0.9m and 1.5m SLR)	Reference
Granny's Beach and Surf Beach	The footpath in the embankment in front of the Caravan Park may be affected slightly for 1 year ARI. Erosion may be extended > 30m landward from the (1990) coastline for 1 year ARI.	The Caravan Park and section of the Ocean Drive may be affected for 1, 100 and 500 year ARI at 0.5m SLR. Erosion may be extended > 90m landward at the Caravan Park for 1 year ARI at 0.5mSLR. Further erosion may be extended >8m for 100 year ARI with respect to 1 year ARI and >5m for 500 year ARI with respect to 100 year ARI. Potential shift of erosion zones due to 0.5m SLR along the coast at Granny's beach and Surf Beach affects a relatively larger	Figure 8.2 to Figure 8.9

	Section of the Caravan Park may be eroded for 100 and 500 year ARI events and also the Granny's Beach. Further erosion may be extended >15m in 100 year ARI with respect to 1 year ARI and >2m in 500 year ARI with respect to 100 year ARI.	area to the 0.0m SLR, but the erosion zone between 0.9 to 1.5m SLR may be relatively small at the same location. The coast between Granny's Beach and Surf Beach and further to south along the beach, The Caravan park, Ocean Drive and the residential building next to the Ocean Drive may be affected at 0.9m and 1.5mSLR Significantly susceptible to increased sea level rise in 2110 Erosion may be extended > 150m landward at the Caravan Park for 1 year ARI at 0.9m SLR. Further erosion may be extended > 1m for 100 year ARI with respect to 1 year ARI and > 2m for 500 year ARI with respect to 100 year ARI. Erosion may be extended > 180m landward at the Caravan Park for 1 year ARI at 1.5m SLR. Further erosion may be extended > 7m for 100 year ARI with respect to 1 year ARI and >10m for 500 year ARI with respect to 100 year ARI.	

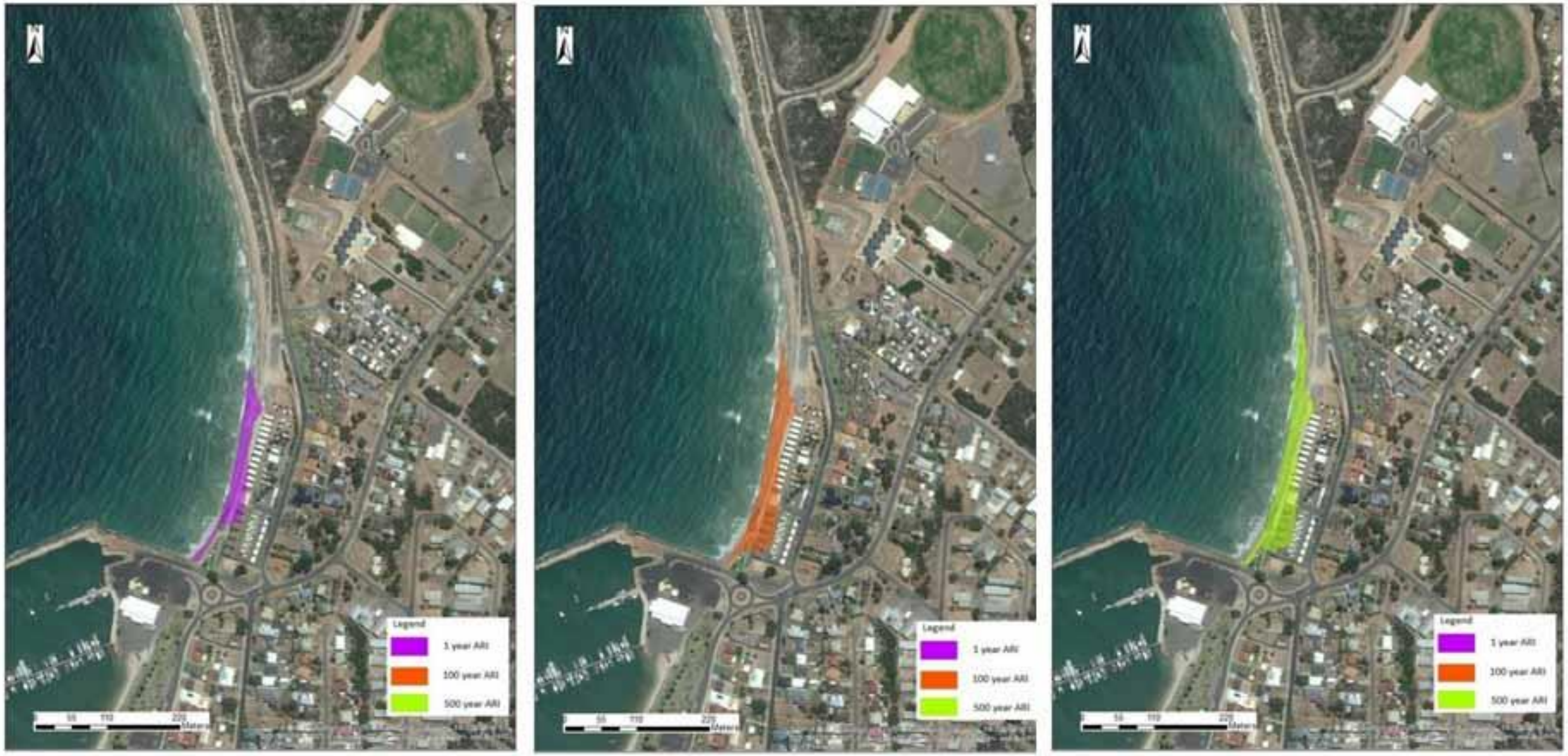

Figure 8.2: Erosion map of Granny's Beach / Surf Beach- 1, 100 and 500 year ARI at present (0.0m SLR)

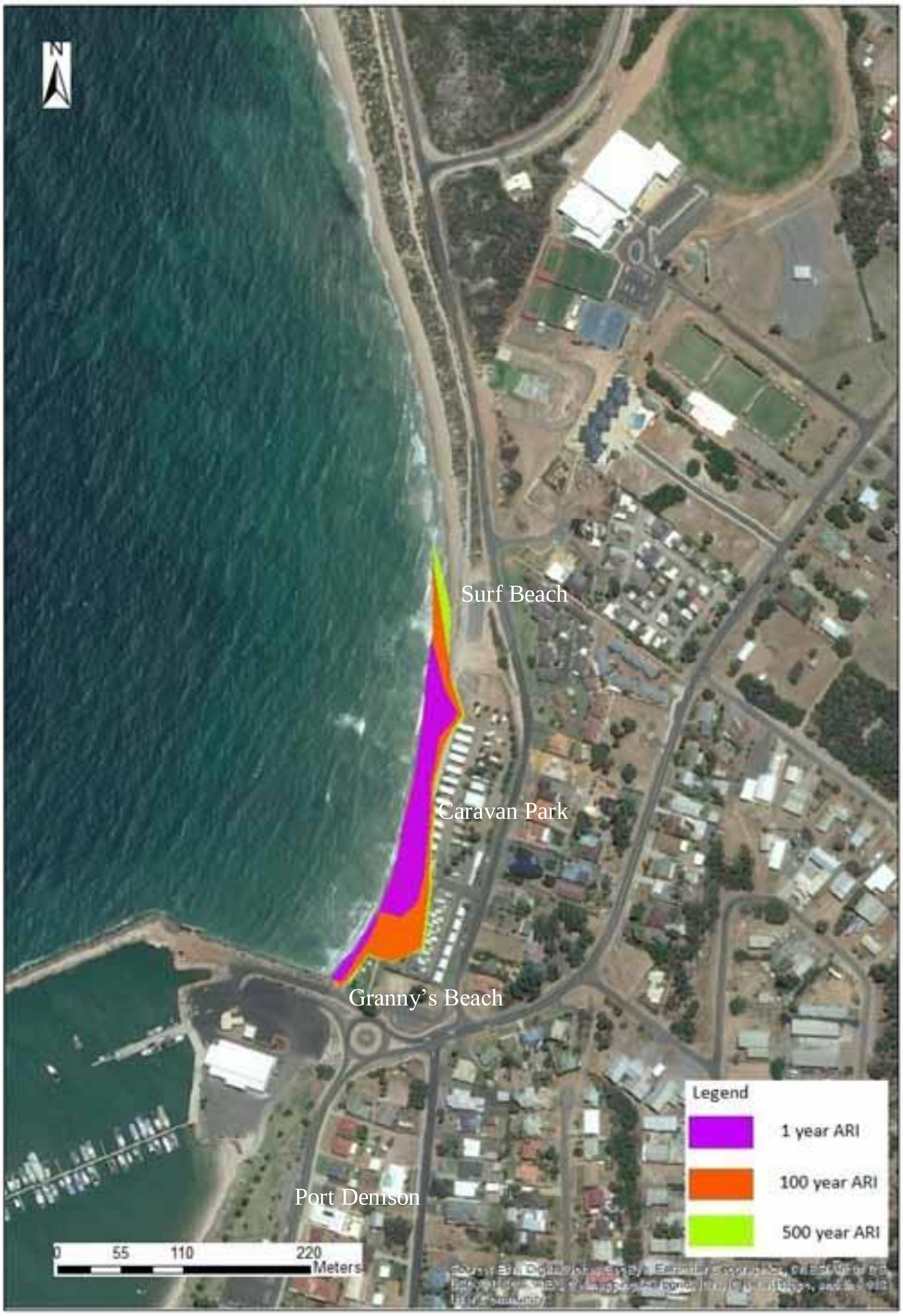

Figure 8.3: Integrated erosion map of Granny's Beach /Surf Beach at present (0.0m SLR)

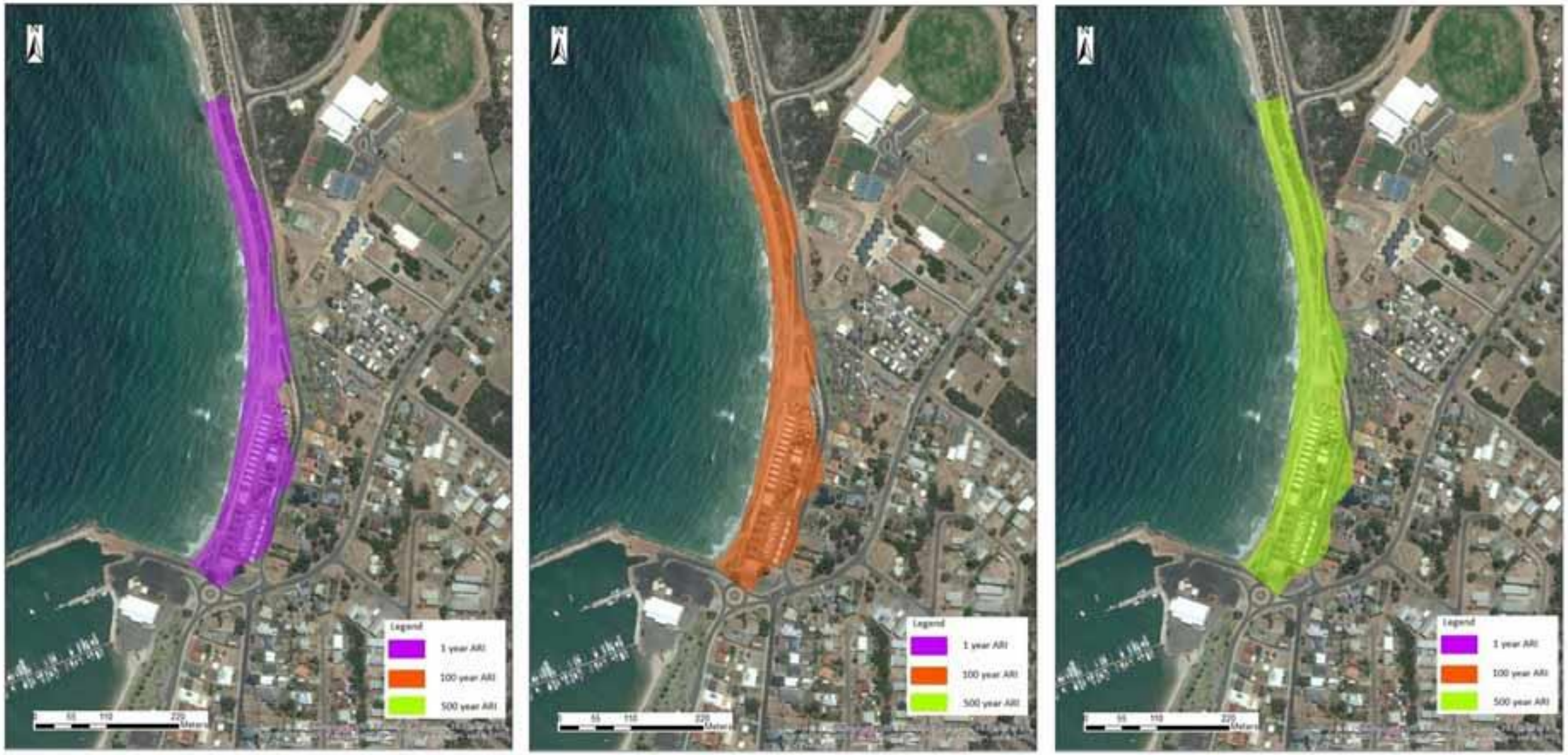

Figure 8.4: Erosion map of Granny's Beach /Surf Beach-1, 100 and 500 year ARI in 2070 (0.5m SLR) + (Shore line movement + allowance for uncertainty)

Figure 8.5: Integrated erosion map of Granny's Beach /Surf Beach in 2110 (0.5m SLR) + (Shore line movement + allowance for uncertainty)

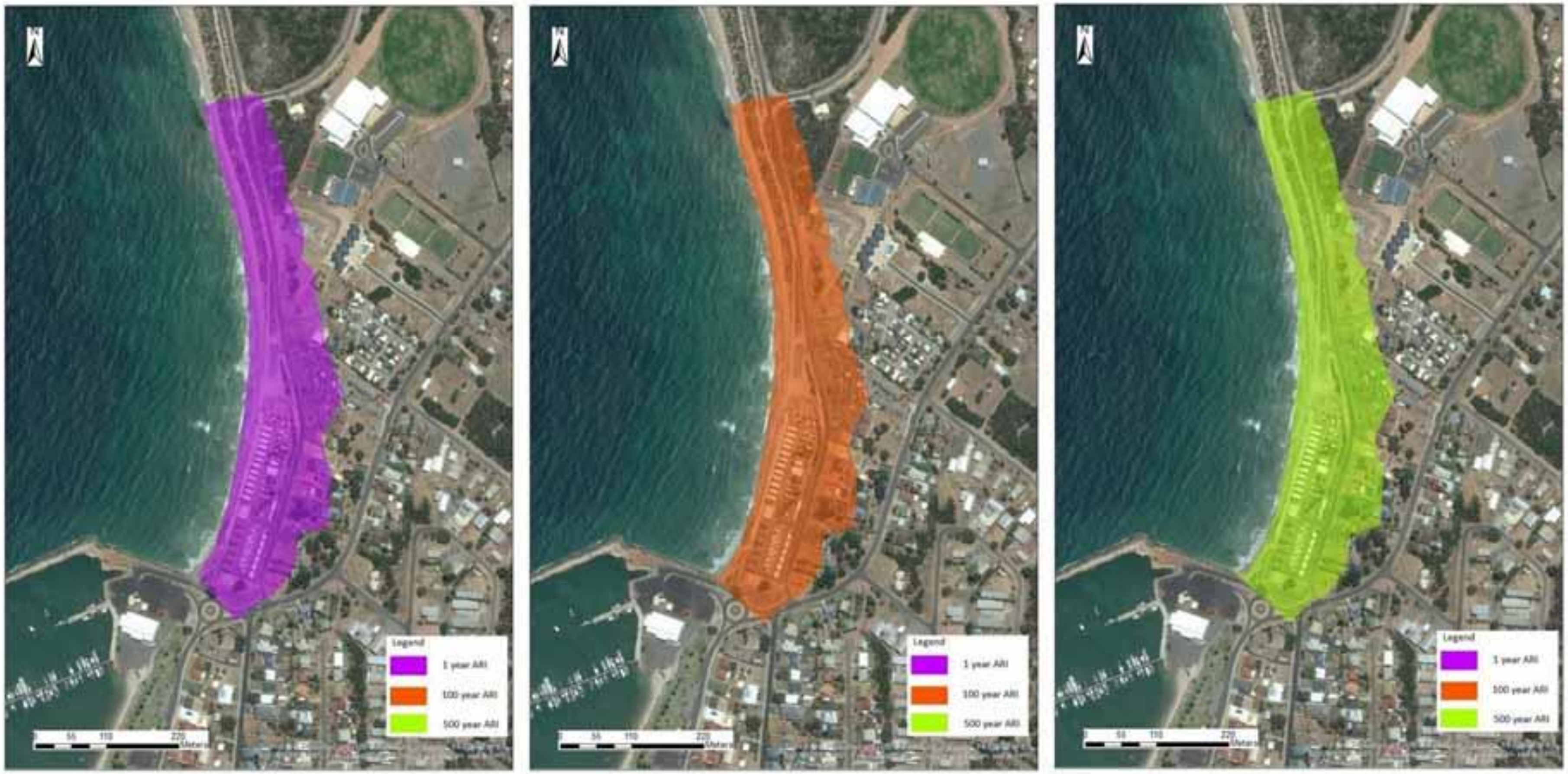

Figure 8.6: Erosion map of Granny's Beach/Surf Beach-1, 100 and 500 year ARI in 2110 (0.9m SLR) + (Shore line movement + allowance for uncertainty)

Figure 8.7: Integrated erosion map of Granny's Beach /Surf Beach in 2110 (0.9m SLR) + (Shore line movement + allowance for uncertainty)

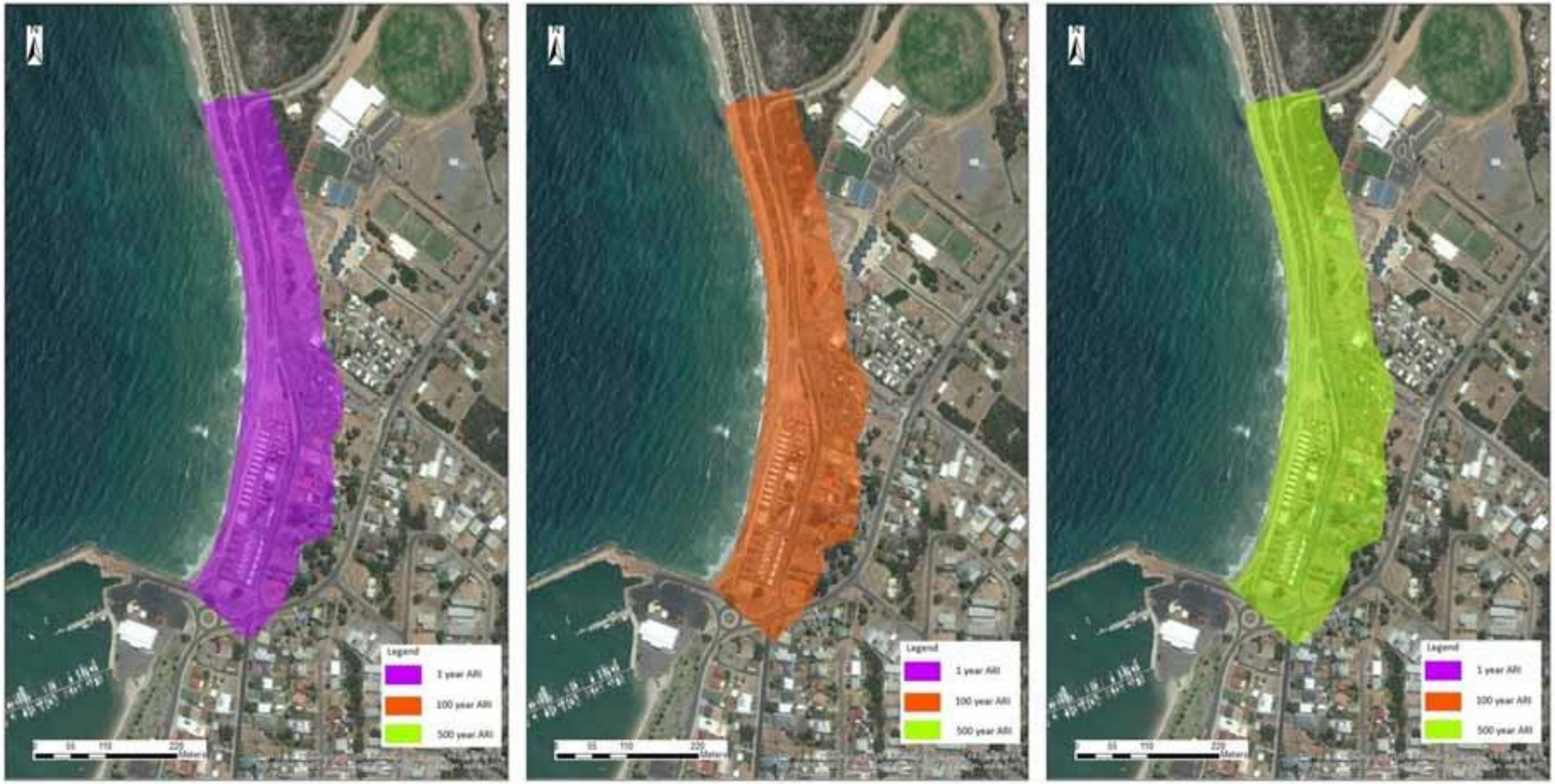

Figure 8.8: Erosion map of Granny's Beach/Surf Beach-1, 100 and 500 year ARI in 2110 (1.5m SLR) + (Shore line movement + allowance for uncertainty)

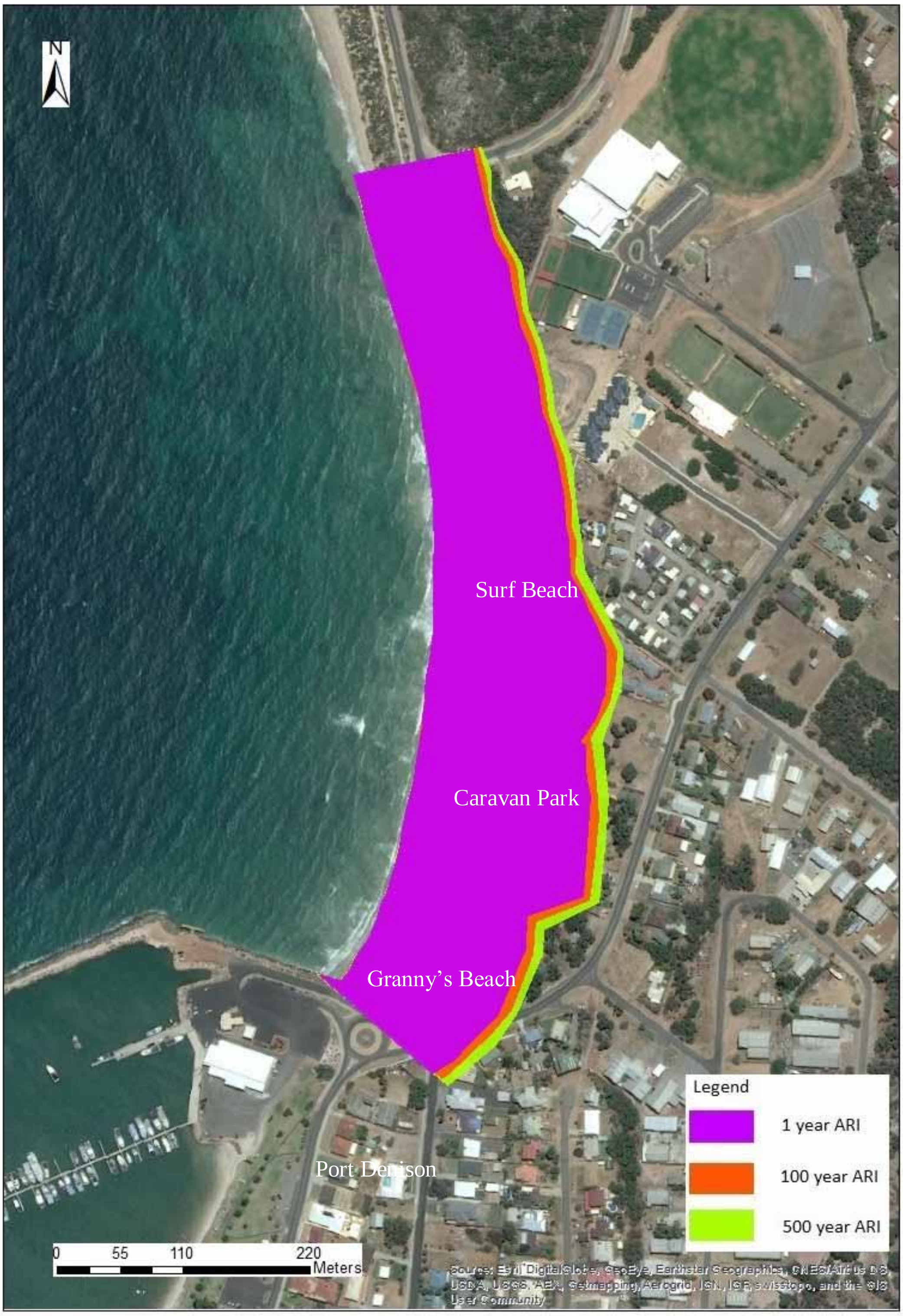

Figure 8.9: Integrated erosion map of Granny's Beach/Surf Beach in 2110 (1.5m SLR) + (Shore line movement + allowance for uncertainty)

8.2 South Beach (North)

This area includes the beach and adjacent dunes and scrubland, a caravan park, a public road, a cafe and the Surf Lifesaving Club's shed. All of the land is public land. There is no significant coastal erosion events have been recorded in this area. The Table 8-3 summarises the erosion risk at South Beach (North) coastal area and Figure C. 1 - Figure C. 8 (Appendix C) show the erosion distribution.

Table 8-3: Erosion hazards according to the model results- South Beach (North)

The location	Present Erosion Hazards (0.0m SLR)	Future Erosion Hazards (0.5m,0.9m and 1.5m SLR)	Reference
South Beach (North)	Only the beach may be eroded.	The buildings and the car park at the end of the Wight-Tops Road and the section of the Wight-Tops road may be affected for 1, 100 and 500 year ARI at 0.5m SLR. Erosion may be extended > 70m landward for 1 year ARI at 0.5mSLR. Further erosion may be extended >10m for 100 year ARI with respect to 1 year ARI and >5m for 500 year ARI with respect to 100 year ARI. Significantly susceptible to increased sea level rise in 2110. The buildings and the car park at the end of the Wight-Tops Road , the section of the Wight-Tops road and Section of the Dongara Tourist	Figure C. 1 to Figure C. 8

		Park may be affected for 1, 100 and 500 year ARI at 0.9m and 1.5m SLR. Erosion may be extended > 120m landward for 1 year ARI at 0.9m SLR. Further erosion may be extended > 5m for 100 year ARI with respect to 1 year ARI and > 5m for 500 year ARI with respect to 100 year ARI. Erosion may be extended > 140m landward for 1 year ARI at 1.5m SLR. Further erosion may be extended > 5m for 100 year ARI with respect to 1 year ARI and >10m for 500 year ARI with respect to 100 year ARI.	

8.3 South Beach (South)

This area contains popular and well-used beach and adjacent dune systems. A little further inland, the runway is located approximately 12m above the sea level. The area suffers from some anthropogenic hazards associated with erosion caused by off-road vehicles and other human activity. No significant coastal erosion events have been recorded in this area, although the extent of the beach varies due to natural coastal processes. The Table 8-4 highlight the erosion risk at South Beach (South) coastal area and Figure C. 9 -Figure C. 16 (Appendix C) depict the erosion distribution at South Beach (South) coastal zone.

Table 8-4: Erosion hazards according to the model results- South Beach

The location	Present Erosion Hazards (0.0m SLR)	Future Erosion Hazards (0.5m,0.9m and 1.5m SLR)	Reference
South Beach	Only the beach may be eroded.	The land may be slightly affected for 1, 100 and 500 year ARI at 0.5m SLR. Erosion may be extended > 150m landward for 1 year ARI at 0.5mSLR (From 1990 coastline). Further erosion may be extended >2m for 100 year ARI with respect to 1 year ARI and >8m for 500 year ARI with respect to 100 year ARI. Significantly susceptible to increased sea level rise in 2070 and 2110.	Figure C. 9 to Figure C. 16

		The land may be significantly affected for 1, 100 and 500 year ARI at 0.9m and 1.5m SLR. Erosion may be extended > 175m landward for 1 year ARI at 0.9m SLR (From 1990 coastline). Further erosion may be extended > 10m for 100 year ARI with respect to 1 year ARI and > 5m for 500 year ARI with respect to 100 year ARI. Erosion may be extended > 185m landward for 1 year ARI at 1.5m SLR (From 1990 coastline). Further erosion may be extended > 5m for 100 year ARI with respect to 1 year ARI and >5m for 500 year ARI with respect to 100 year ARI.	

8.4 Seaspray Beach/Irwin River

This area consist of beaches and adjacent dune systems, a river mouth, a coastal wetland system, public roads, boardwalks, a car park and a public toilet and a caravan park. Most of this area is public land, with the exception of a freehold lot containing buildings associated with the caravan park. Erosion issues at the Seaspray Beach have unearthed infrastructure placed during the days of the crayfish factory. Pipes and cabling were washed out of the sand dune and rusted off star pickets, which were used to secure the pipes in place. A suction pipe was exposed by erosion and was rusted and unsafe in May 2013(SoI, 2013). The Table 8-5 summarises the erosion risk at Seaspray Beach and Irwin River coastal area. Erosion maps for this area is shown in Figure C. 17 - Figure C. 24 (Appendix C).

Table 8-5: Erosion hazards according to the model results- Seaspray Beach

The Location	Present Erosion Hazards (0.0m SLR)	Future Erosion Hazards (0.5m,0.9m and 1.5m SLR)	Reference
Seaspray Beach / Irwin River	The Seaspray beach may be eroded for 1and 100 ARI. Erosion may be extended >30m from the coastline (1990) for 500 ARI.	Seaspray beach may be affected at 0.5m SLR and it could partially reach the Seaspray Beach Holiday Park premises. South of the river, erosion may be extended up to Ocean Drive for 1, 100 and 500 year ARI at 0.5m SLR. Erosion may be extended > 70m landward at the Seaspray Beach for 1 year ARI at 0.5m SLR. Further erosion may be extended >	Figure C. 17 to Figure C. 24

		10m for 100 year ARI with respect to 1 year ARI and > 7m for 500 year ARI with respect to 100 year ARI. Significantly susceptible to increased sea level rise in 2110. Seaspray Beach Holiday Park premises and buildings may be significantly eroded at 1.5m SLR. The section of the Ocean Drive may be erode for 1, 100 and 500 year ARI at 0.9m and 1.5m SLR. Erosion may be extended > 130m landward at Seaspray Beach for 1 year ARI at 0.9m SLR. Further erosion may be extended > 20m for 100 year ARI with respect to 1 year ARI and > 9m for 500 year ARI with respect to 100 year ARI. Erosion may be extended > 170m landward for 1 year ARI at 1.5m SLR. Further erosion may be extended > 9m for 100 year ARI with respect to 1 year ARI and > 8m for 500 year ARI with respect to 100 year ARI.	

8.5 Seven Mile Beach

Seven Mile Beach consist of beaches and associated dunes systems, a public car park and a public road. The car park is used for overnight camping and recreational fishing. In October 2103, the car park was eroded leaving 1.5m drop to the beach (SoI, 2013). The dune heading south has undergone extensive erosion through the winter months. The area suffers from some anthropogenic hazards associated with erosion caused by off-road vehicles, uncontrolled pedestrian activity, stock and feral animal grazing and bushfire hazards. The Table 8-6 summarises the erosion risk at Seven Mile Beach coastal area and Figure C. 25 - Figure C. 32 (Appendix C) illustrate the erosion distribution at Seven Mile Beach.

Table 8-6: Erosion hazards according to the model results- Seven Mile Beach

The Location	**Present Erosion Hazards (0.0m SLR)**	**Future Erosion Hazards (0.5m,0.9m and 1.5m SLR)**	**Reference**
Seven Mile Beach	Significant erosion would be happened at north side of the Seven Mile Road. All ARI events cause erosion through to the coastal access tracks (off road tracks). Erosion may be extended >50m landward for 1 year ARI. Further erosion may be extended > 30m for 100 year ARI with	North side of the Seven Mile Road is significantly eroded at all SLR scenario. The end of the road and parking area may be eroded in the most extreme scenarios. Erosion may be extended > 160m to the inland for 1 year ARI at 0.5m SLR. Further erosion may be extended > 9m for 100 year ARI with respect to 1 year ARI and > 6m in 500 year ARI with respect to 100 year ARI.	Figure C. 25 to Figure C. 32

	respect to 1 year ARI and > 15m for 500 year ARI with respect to 100 year ARI.	Significantly susceptible to increased sea level rise in 2070 and 2110. Erosion may be extended > 200m landward at Seaspray Beach for 1 year ARI at 0.9m SLR. Further erosion may be extended > 8m for 100 year ARI with respect to 1 year ARI and > 8m for 500 year ARI with respect to 100 year ARI. Erosion may be extended > 240m landward for 1 year ARI at 1.5m SLR. Further erosion may be extended > 9m for 100 year ARI with respect to 1 year ARI and > 8m for 500 year ARI with respect to 100 year ARI.	

8.6 Freshwater Point

This area consist of limestone shoulder that protects a small bay, beaches and adjoining scrubland, a public access track and parking area, public toilet and a number of shacks and other structures associated with the fishing industry. A number of shacks and structure have been recently removed due to the shrinking coastline in this location. The area is used by overnight campers and fishermen. The Table 8-7 highlight the erosion risk at Freshwater Point coastal area and Figure C. 33-Figure C. 40 (Appendix C) depict the erosion distribution.

Table 8-7: Erosion hazards according to the model results- Freshwater Point

The Location	Present Erosion Hazards (0.0m SLR)	Future Erosion Hazards (0.5m,0.9m and 1.5m SLR)	Reference
Freshwater Point	Fisherman's shacks would be slightly eroded. Erosion may be extended >30m landward for 1 year ARI. Further erosion may be extended >10m for 100 year ARI with respect to 1 year ARI and > 4m for 500 year ARI with respect to 100 year ARI.	Fisherman's shacks may be partially affected at 0.5m SLR. The majority of the area is eroded for the 0.9m and 1.5m SLR scenarios. Those shacks premises would be fully eroded the 0.9m and 1.5m SLR. Erosion may be extended > 100m to the inland for 1 year ARI at 0.5mSLR. Further erosion may be extended > 9m for 100 year ARI with respect to 1 year ARI and > 10m for 500 year ARI with respect to 100 year ARI.	Figure C. 33 to Figure C. 40

		Significantly susceptible to increased sea level rise in 2070 and 2110. Erosion may be extended > 160m landward at Seaspray Beach for 1 year ARI at 0.9m SLR. Further erosion may be extended > 10m for 100 year ARI with respect to 1 year ARI and > 10m for 500 year ARI with respect to 100 year ARI. Erosion may be extended > 200m landward for 1 year ARI at 1.5m SLR. Further erosion may be extended > 20m for 100 year ARI with respect to 1 year ARI and > 10m for 500 year ARI with respect to 100 year ARI.	

8.7 Cliff Head (North)

This area consist of beaches and associated dune systems, public access tracks, camping areas and a public toilet. The area is used for recreational camping and fishing. There are few historical records of significant erosion events for Cliff Head north. The following table summarises the erosion risk at Cliff Head (North) coastal area. Erosion maps for this area is shown in Figure C. 41- Figure C. 48 (Appendix C).

Table 8-8: Erosion hazards according to the model results- Cliff Head (North)

The Location	Present Erosion Hazards (0.0m SLR)	Future Erosion Hazards (0.5m,0.9m and 1.5m SLR)	Reference
Cliff Head	All ARI events cause erosion through to the coastal access tracks (off road tracks). Erosion may be extended > 60m landward for 1 year ARI. Further erosion may be extended > 10m for 100 year ARI with respect to 1 year ARI and > 8m for 500 year ARI with respect to 100 year ARI.	Potential shift of erosion zones due to 0.5m SLR along the coast affects a relatively large area to the 0.0m SLR, but the erosion zone between 0.9 to 1.5m SLR may be relatively small at the same location. Erosion may be extended >130m to the inland for 1 year ARI at 0.5m SLR. Further erosion may be extended >10m for 100 year ARI with respect to 1 year ARI and >10m for 500 year ARI with respect to 100 year ARI.	Figure C. 41 to Figure C. 48

		Significantly susceptible to increased sea level rise in 2070 and 2110. Indian Ocean Drive may affected at 0.9m and 1.5m SLR Erosion may be extended > 200m landward at Seaspray Beach for 1 year ARI at 0.9m SLR. Further erosion may be extended > 5m for 100 year ARI with respect to 1 year ARI and > 9m for 500 year ARI with respect to 100 year ARI. Erosion may be extended > 230m landward for 1 year ARI at 1.5m SLR. Further erosion may be extended > 20m for 100 year ARI with respect to 1 year ARI and > 10m for 500 year ARI with respect to 100 year ARI.	

8.8 Cliff Head (South)

Cliff Head South consist of beaches and associated dune systems, fishermen's shacks, public access tracks, camping areas and public toilets. The area is used by the fishing industry but is mostly used for recreational purposes. There is a mining tenement on the land (for the extraction of gypsum). Table 8-9 summarises the erosion risk at Cliff Head (South) coastal area and Figure C. 49- Figure C. 56(Appendix C) highlight the erosion distribution at Cliff Head (South).

Table 8-9: Erosion hazards according to the model results- Cliff Head (South)

The Location	Present Erosion Hazards (0.0m SLR)	Future Erosion Hazards (0.5m,0.9m and 1.5m SLR)	Reference
Cliff Head South	Slightly erode some residential areas for 100 and 500 ARI events. Erosion may be extended > 40m landward for 1 year ARI. Further erosion may be extended >20m for 100 year ARI with respect to 1 year ARI and > 8m for 500 year ARI than 100 year ARI.	Residential buildings may be eroded for 1, 100 and 500 ARI events at 0.5m. Erosion may be extended > 100m to the inland for 1 year ARI at 0.5m SLR. Further erosion may be extended > 10m for 100 year ARI with respect to 1 year ARI and > 10m for 500 year ARI with respect to 100 year ARI. Significantly susceptible to increased sea level rise in 2070 and 2110. Erosion may be extended > 160m landward at Seaspray Beach for 1 year ARI at 0.9m SLR. Further erosion may be extended	Figure C. 49 to Figure C. 56

		> 20m for 100 year ARI with respect to 1 year ARI and > 5m for 500 year ARI with respect to 100 year ARI. Erosion may be extended > 190m landward for 1 year ARI at 1.5m SLR. Further erosion may be extended > 15m for 100 year ARI with respect to 1 year ARI and > 5m for 500 year ARI with respect to 100 year ARI.	

8.9 Summary of the Coastal Erosion Results

The erosion model was conducted taking Sea Level Rise and extreme water levels into account. Each modelling was conducted for the present, 0.5, 0.9 and 1.5 SLR scenarios and 1, 100 and 500 year ARI events. In addition as per SPP2.6, additional scenario S2 and uncertainty rate were considered for erosion mapping of sandy beaches. The maps are based on locations which are considered as highly important areas in the selected study stretch.

The Port Denison area has experienced significant levels of erosion between Granny's Beach and Surf Beach and minor levels of erosion on the foreshore within the harbor. Most of the areas likely to be significantly affected by coastal erosion over the next 96 years are likely to be public land.

The modelling shows that the caravan park in South Beach north may be affected by erosion in the 2110 scenarios, which considers the potential impact of 0.9m and 1.5m sea level rises. The buildings near the public car park may be affected by erosion over the next 50 years. There is no significant coastal erosion events have been recorded in the South Beach South area, although the extent of the beach varies due to natural coastal processes. With regard to the coastal modelling, the natural areas are shown to be most affected by significant storm events. In some scenarios, the modelling shows the runway to be affected by erosion.

The modelling indicates that the most significant impacts for the Seaspray Beach area are likely to occur in the 2110 scenarios, where the 0.9m and 1.5m rises in sea levels were considered. However the model did not consider the hydrological influence of the river flow. Therefore river erosion results is not included in the maps. The Irwin River mouth area is likely to be much more sensitive to significant erosion events across the 96 year period.

The modelling shows the natural areas may be affected in most scenarios at the Seven Mile Beach. The car park and the public road are shown to be affected by erosion in the 2070 (0.5m sea level rise) and 2110 (0.9m and 1.5m sea level rise) scenarios. The modelling shows the natural areas in the Freshwater Point will be affected in most scenarios and that the private and public infrastructure would be most threatened by the erosion scenarios.

The modelling shows that the natural areas are in the Cliff Head North likely to be affected across all scenarios, with erosion likely to have the most significant impacts. The public toilet and public access tracks are shown to be affected in the 2110 scenarios. In the Cliff Head South the natural areas are likely to be most affected across all modelling scenarios, with erosion likely to have the most significant impacts. The public toilets, shacks, public access tracks and camping areas are shown to be affected in the 2110 scenarios.

9 Overview of Future Coastal Vulnerability and Recommendation for Adaptation

This chapter describes the impacts of future coastal inundation and erosion on the assets along the coastal zone and recommendation for adaptation and mitigation process.

Most of the areas in Port Denison, Granny's Beach and Surf Beach are likely to be significantly affected by coastal inundation and erosion over the next 96 years. Thus, there is an essential need for further studies and ongoing monitoring about the inherent uncertainties with climate change, the coastal processes and the inundation of urban drainage systems due to sea level rise. Investigate potential inundation impacts, determine the need and feasibility for improving the inundation resilience of public infrastructure in this area, investigate the necessity of coastal protection structures to protect areas from erosion and future relocation of public infrastructures are some recommendations for adaptation.

In the South Beach (North), the modelling shows that the caravan park will be unaffected by coastal inundation over the 96 years, but may be affected by erosion in the 2110 scenarios, which consider the potential impact of 0.9m and 1.5m sea level rises. The buildings near the public car park may be affected by inundation and erosion over the next 50 years. Educate the public about values of the beach and environmentally sound recreational enjoyment, ensure that all approved buildings are relocatable, continuous monitoring of the coastal processes and ensure the public are kept informed and plan for the movement of public infrastructure around the south beach car park, when inundation and erosion threats happen in the future are some recommendations for adaptation.

With regards to the coastal modelling, the natural areas are shown to be the most affected by significant storm events at the South Beach South. In the 2110 scenarios, the modelling shows the runaway to be slightly affected by erosion. Educate the public about environmentally sound recreational enjoyment of the area, continuous monitor of the coastal processes and ensure the public are kept informed and plan for the future relocation of the runaway by 2110, or sooner if threats happen are some of the options for adaptation plan.

The modelling indicates that the most significant impacts for the Seaspray Beach area are likely to occur in the 2110 scenarios. The Irwin River mouth area is likely to be much more sensitive to significant inundation and erosion events across the next 96 year period. It is required to carry out flood modelling of the Irwin River, including an analysis of combined river flooding and coastal impacts, monitoring of the coastal processes and ensuring that the public are kept informed and all approved buildings within the caravan park are relocatable and plan for the movement of public and private infrastructure when threats occur in the future, are some of the adaptation options for the Seaspray Beach and the Irwin River mouth.

The modelling shows the natural areas may be affected in most scenarios at Seven Mile Beach. Educate the public about environmentally sound recreational enjoyment of the area, continuous monitoring of the coastal processes and ensuring the public are kept informed about hazards in the future are some recommendations for the adaptation plan.

The modelling shows the natural areas will be affected in most scenarios and that the private and public infrastructure would be most threatened by the erosion scenarios in Freshwater Point. Ensuring that the approved buildings are relocatable, educate the public about environmentally sound recreational enjoyment of the area, continuous monitoring of the coastal processes and ensuring that the public are kept informed about hazards in the future and plan for the future relocation of public infrastructure when threats occur are some recommendations for adaptation in Freshwater Point.

The modelling shows that the natural areas in the Cliff Head North are likely to be affected across all scenarios, with erosion likely to have the most significant impacts. The public toilet and public access tracks are shown to be affected in the 2110 scenarios. Educate the public about environmentally sound recreational enjoyment of the area, continuous monitoring of the coastal processes and ensure the public are kept informed about hazards in the future are some recommendations for adaptation.

The natural areas in the Cliff Head South are likely to be most affected across all modelling scenarios, with erosion likely to have the most significant impacts. The public toilets, shacks, public access tracks and camping areas are shown to be affected in the 2110 scenarios. By ensuring that the approved buildings are relocatable, educate the public about environmentally sound recreational enjoyment of the area, continuous monitoring of the coastal processes and ensuring the public are kept informed about hazards in the future and plan for the future relocation of public infrastructure when threats occur are some recommendations for adaptation.

10 Conclusions and Recommendations

10.1 Conclusions

This research aims to evaluate the coastal process in the Mid-West Coast of Western Australia to assess the impacts of sea level rise on coastal inundation and erosion. The literature review was carried out prior to the study to understand the coastal process, climate change (sea level rise) and impact of them to the coastline. As numerical modelling methods are the most appropriate approach for such studies, study aimed to use suitable numerical model for the assessment. Several literature suggested that MIKE 21 is appropriate to be used to model the coastal inundation and erosion process and is ideal to finish the study within a relatively shorter period of time. Therefore MIKE 21 was selected as the modelling tool for this study and was used for 2D simulation. Thus, the literature review provided the guidance by ensuring the study's scope and the methodology was appropriate to continue the research. Finally, deferent scenarios were simulated to demonstrate the spatial and temporal variation of inundation and erosion process in the study area.

Before simulating the model, the extreme values were found for 1, 100 and 500 year ARI events. Weibull and Gumbel distributions were used to find the extreme values and values were selected according to the correlation coefficient and the root mean square error. Storm events were selected within measured data to match the extreme values. The model domain was decided by covering the study area and the water level data. Interpolating available bathymetry and topography data finalised the model domain. The Hydrodynamic model was calibrated using tide data for selected time period (Twenty days) in the summer. The model parameters were finalised by calibrating the model and validation was done for another set of tide data for twenty days which was in the winter period. After verify the model parameters, modelling was conducted for the selected sea level rise scenarios which were the present situation (2014), 0.5m for 2070, and 0.9m and 1.5m correspond to medium and high sea level rises respectively in year 2110.

The final results from the numerical modelling of coastal inundation and coastal erosion were presented in terms of spatial maps. Maps were developed for several sea level rise and water level scenarios. For the user reference, the maps are categorised based on locations which are highly important regions;

- Port Denison, Granny's Beach/Surf Beach
- Seaspray Beach/Irwin River
- South Beach (North)
- South Beach (South)
- Seven Mile Beach
- Freshwater Point
- Cliff Head (North)
- Cliff Head (South)

Series of inundation and erosion maps were developed for each location based on the considered sea level rise scenarios and ARIs. Therefore twenty four maps were developed for each identified locations; two coastal processes (inundation and erosion), four sea level rise (0, 0.5m, 0.9m and 1.5m); three ARI event (1, 100, and 500). Each map was discussed using the identified inundation/erosion extend, water depth and potential risk on identified assets.

Overall modelling results clearly show that future climate change and sea level rise have adverse impacts on the selected coastal region. Inundation will be expanded inland creating more areas inundated by severe weather conditions. Erosion will be more active and erode the beach at most of the locations, especially where extreme wave conditions occurs. Among the selected locations, all the locations predict higher degree of inundation and erosion under sea level rise in the future. Specially integrated impact of extreme water levels (1 in 100 year extreme events and 1 in 500 year extreme events), would create more vulnerable situation. Regions such as Port Denison, Seaspray Beach, South Beach (North) and Cliff Head South are highly populated areas with residential and commercial establishments. Other areas such as Seven Mile beach, Freshwater Point and Cliff Head are environmentally valuable regions as higher diversity of ecological and environmental assets are located at these regions.

It is highlighted that model results were highly dependent on the accuracy of the available data. Therefore the results of the study should be used as indicators and preliminary findings for further detailed studies. Therefore the defined erosion and inundation extents should be treated as a preliminary indication on potential erosion in an area where data and previous studies are very limited needs to be communicated. The investigation was done quite conservatively, without any geotechnical investigation to locate existence of rock on shore or nearshore which will disrupt erosion pattern. In addition, this study assumed a homogeneous sand properties along the entire study area and neglected the heterogeneity of the sand properties due to different sand nourishment and other activities such as sediment deposition from river flow.

10.2 Recommendations (for Further Study and Implementation)

The findings of this study would be very useful for authorities such as local city councils and coastal management organizations to develop their future coastal management and adaptation plans. Also these results give very good information for coastal communities in understanding the future coastal changes and behaviours. Anyway any application, implementation to the specific coastal areas, should be alerted that the present study is a preliminary level study conducting a first pass analysis with very limited data and site information, results of the study are highly dependent on the accuracy of the available data. Therefore the results of the study should be used as indicators and preliminary findings for further detailed studies.

With the experience gained during the study, the following recommendations are made to guide to conduct a detailed study in the future.

- This results can used for developing risk management and adaptation plan. Significant attention should be paid towards socially, environmentally and economically important locations during developing risk mitigation and adaptation processes.

- Data availability for a detailed analysis is the main drawback. The principle data used for the analysis is bathymetry data, coastline data, topography data, wave and water level data and wind data. Availability of all of these data sets is very limited in the study area;

- Collection of latest field data in the study area is highly recommended. High technological approached such as airborne laser method (LADS Mk II) or Light Detection and Ranging (LiDAR), or other methods to obtain high resolution bathymetric and topographic data is essential for a detailed study;

- More data from more observation locations will definitely enhance the quality of any study. Water level and wave data observation from locations such as Port Denison will allow to calibrate and verify the model against field data. Such information is highly recommended for future studies;

- Wave data combined with mean wave directional component is another missing data set at present. A detailed monitoring scheme to obtain complete wave data is also recommended.

- Recent coastline data and shoreline movement data along the entire study area is one of the most important factors for accurate results. Monitoring programs to collect this data is highly recommended.

- Geotechnical investigations to define the geotechnical and geological properties of the coastal region is very important to conduct a detailed erosion model. Collection of geotechnical data is another important task to be proposed for future actions.

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Appendix A

Table A. 1: Geraldton Tide Gauge: Water Level: Sample Data Set

No	Date	Water Level (AHD)m	No	Date	Water Level (AHD)m
1	2010.07.09	1.57	31	2011.01.29	1.1
2	2010.07.09	1.45	32	2011.01.29	1.1
3	2010.07.09	1.4	33	2011.01.29	1.1
4	2010.07.09	1.27	34	2012.02.02	1.1
5	2010.07.09	1.18	35	2012.02.02	1.1
6	2010.07.09	1.14	36	2010.07.09	1.09
7	2011.01.29	1.14	37	2012.06.10	1.09
8	2012.02.02	1.14	38	2010.07.09	1.09
9	2011.01.29	1.13	39	2010.07.09	1.09
10	2010.07.09	1.13	40	2012.02.02	1.09
11	2012.02.02	1.13	41	2012.02.02	1.09
12	2012.02.02	1.13	42	2012.02.02	1.09
13	2010.07.09	1.12	43	2012.02.02	1.09
14	2011.01.29	1.12	44	2011.01.29	1.09
15	2012.02.02	1.12	45	2012.02.02	1.09
16	2012.02.02	1.12	46	2012.02.02	1.09
17	2012.02.02	1.12	47	2012.02.02	1.09
18	2012.02.02	1.12	48	2012.06.10	1.08
19	2011.01.29	1.11	49	2010.07.09	1.08
20	2012.02.02	1.11	50	2011.01.29	1.08
21	2010.07.09	1.1	51	2012.02.02	1.08
22	2010.07.09	1.1	52	2012.02.02	1.08
23	2010.07.09	1.1	53	2012.02.02	1.08
24	2011.01.29	1.1	54	2012.02.02	1.08
25	2011.01.29	1.1	55	2011.01.29	1.08
26	2011.01.29	1.1	56	2011.01.29	1.08
27	2011.01.29	1.1	57	2012.02.02	1.08
28	2012.02.02	1.1	58	2012.02.02	1.08
29	2012.02.02	1.1	59	2012.02.02	1.08
30	2012.02.02	1.1	60	2012.02.02	1.08

Table A. 2: Jurien Bay Tide Gauge: Water Levels: Sample Data Set

No	Date	Water Level (AHD)m	No	Date	Water Level (AHD)m
1	2003.05.16	1.04	31	2003.05.16	0.92
2	2003.05.16	1.04	32	2003.05.16	0.92
3	2003.05.16	1.03	33	2003.05.16	0.92
4	2003.05.16	1.01	34	2003.05.16	0.92
5	2003.05.16	1.00	35	2003.05.16	0.91
6	2003.05.16	0.99	36	2003.05.16	0.9
7	2003.05.16	0.99	37	2003.05.16	0.9
8	2003.05.16	0.98	38	2003.05.16	0.9
9	2003.05.16	0.98	39	2004.05.09	0.9
10	2003.05.16	0.98	40	1995.07.12	0.89
11	2003.05.16	0.97	41	1995.07.12	0.89
12	2003.05.16	0.97	42	2003.05.16	0.89
13	2003.05.16	0.97	43	2003.05.16	0.89
14	2003.05.16	0.97	44	2005.06.07	0.89
15	2003.05.16	0.96	45	2009.06.24	0.89
16	2003.05.16	0.95	46	2012.02.02	0.89
17	2003.05.16	0.95	47	2012.02.02	0.89
18	2003.05.16	0.94	48	2012.02.02	0.89
19	2003.05.16	0.94	49	2013.05.08	0.89
20	2003.05.16	0.94	50	1995.07.12	0.88
21	2003.05.16	0.94	51	2005.06.07	0.88
22	2003.05.16	0.94	52	2005.06.07	0.88
23	2003.05.16	0.94	53	2009.06.24	0.88
24	2003.05.16	0.93	54	2009.06.24	0.88
25	2003.05.16	0.93	55	2012.02.02	0.88
26	2003.05.16	0.93	56	2012.02.02	0.88
27	2003.05.16	0.93	57	2012.02.02	0.88
28	2003.05.16	0.93	58	2012.02.02	0.88
29	2003.05.16	0.93	59	2012.02.02	0.88
30	2009.06.24	0.93	60	2013.05.08	0.88

Table A. 3: Significant Wave Height in South West (202.5 to 247.5deg): Sample Data set

No	Significant Wave Height(Hs) m	No	Significant Wave Height(Hs) m
1	9.29	31	8.2
2	9.26	32	8.2
3	9.21	33	8.17
4	9.06	34	8.17
5	9	35	8.16
6	8.93	36	8.16
7	8.77	37	8.15
8	8.76	38	8.13
9	8.75	39	8.12
10	8.74	40	8.11
11	8.7	41	8.1
12	8.64	42	8.07
13	8.62	43	8.07
14	8.56	44	8.05
15	8.48	45	8.05
16	8.4	46	8.05
17	8.4	47	8.04
18	8.39	48	8.04
19	8.38	49	7.99
20	8.38	50	7.98
21	8.37	51	7.96
22	8.34	52	7.95
23	8.32	53	7.95
24	8.31	54	7.94
25	8.3	55	7.94
26	8.29	56	7.94
27	8.29	57	7.91
28	8.29	58	7.9
29	8.29	59	7.88
30	8.2	60	7.86

Table A. 4: Wind Speed South to South West (157.5 to 292.5 deg): Sample Data Set

No	Wind Speed(m/s)	No	Wind Speed(m/s)
1	20.00	31	18.89
2	20.00	32	18.89
3	20.00	33	18.89
4	20.00	34	18.89
5	19.44	35	18.89
6	19.44	36	18.89
7	19.44	37	18.89
8	19.44	38	18.89
9	19.44	39	18.89
10	19.44	40	18.89
11	19.44	41	18.89
12	19.44	42	18.89
13	19.44	43	18.89
14	19.44	44	18.89
15	19.44	45	18.89
16	18.89	46	18.89
17	18.89	47	18.61
18	18.89	48	18.61
19	18.89	49	18.61
20	18.89	50	18.61
21	18.89	51	18.61
22	18.89	52	18.61
23	18.89	53	18.61
24	18.89	54	18.61
25	18.89	55	18.61
26	18.89	56	18.61
27	18.89	57	18.61
28	18.89	58	18.61
29	18.89	59	18.61
30	18.89	60	18.61

Appendix B

Inundation Maps

South Beach (North)

Figure B. 1: Inundation map of South Beach (North) – 1, 100, 500 year ARI event at present (0.0 m SLR)

Figure B. 2: Integrated inundation map of South Beach (North) at present (0.0 m SLR)

Figure B. 3: Inundation map of South Beach (North) - 1, 100 and 500 year ARI event in 2070 (0.5 m SLR)

Figure B. 4: Integrated inundation map of South Beach (North) in 2070 (0.5 m SLR)

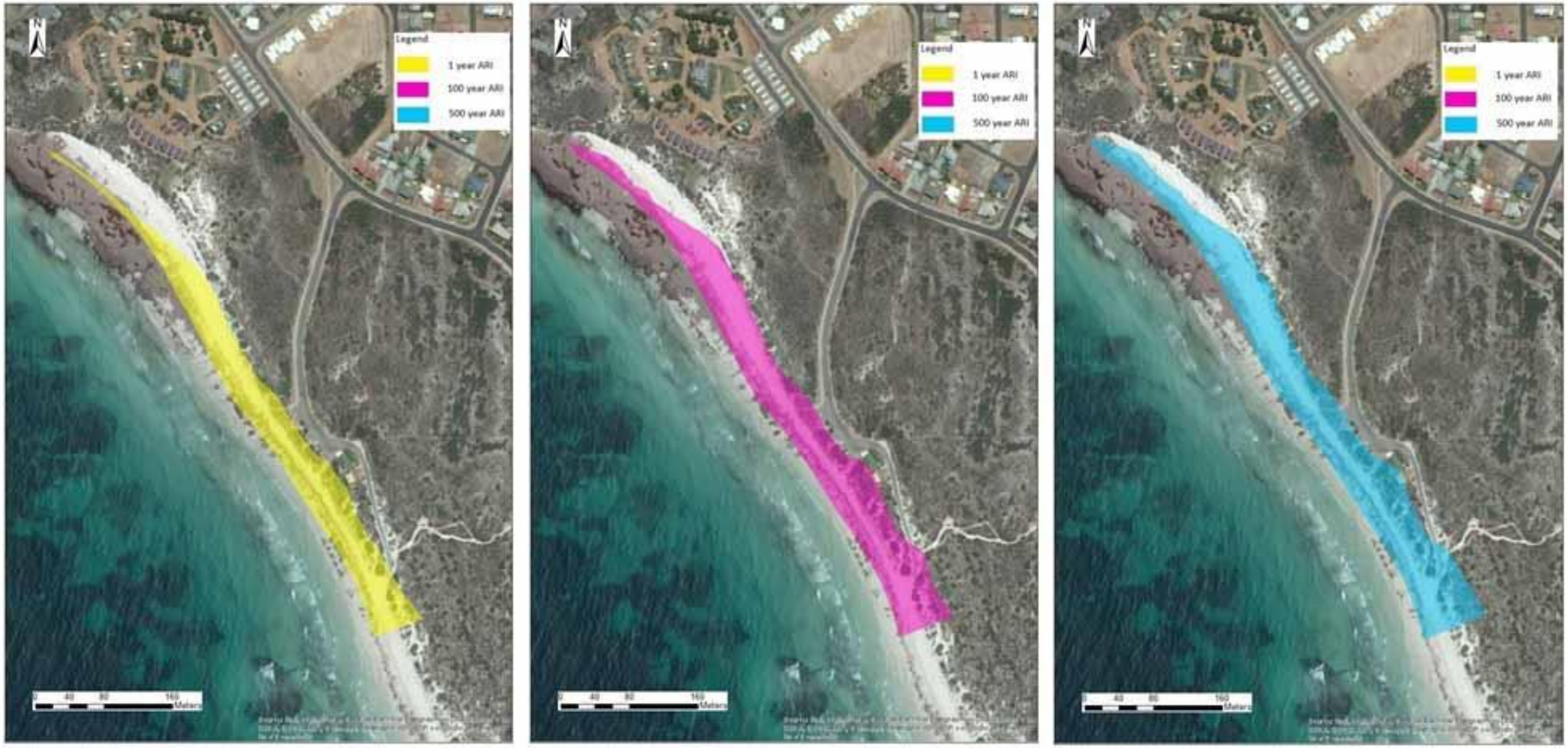

Figure B. 5: Inundation map of South Beach (North) - 1,100 and 500 year ARI event in 2110 (0.9 m SLR)

Figure B. 6: Integrated inundation map of South Beach (North) in 2110 (0.9 m SLR)

Figure B. 7: Inundation map of South Beach (North) - 1, 100 and 500 year ARI event in 2110 (1.5m SLR)

Figure B. 8: Inundated map of South Beach (North) in 2110 (1.5m SLR)

South Beach (South)

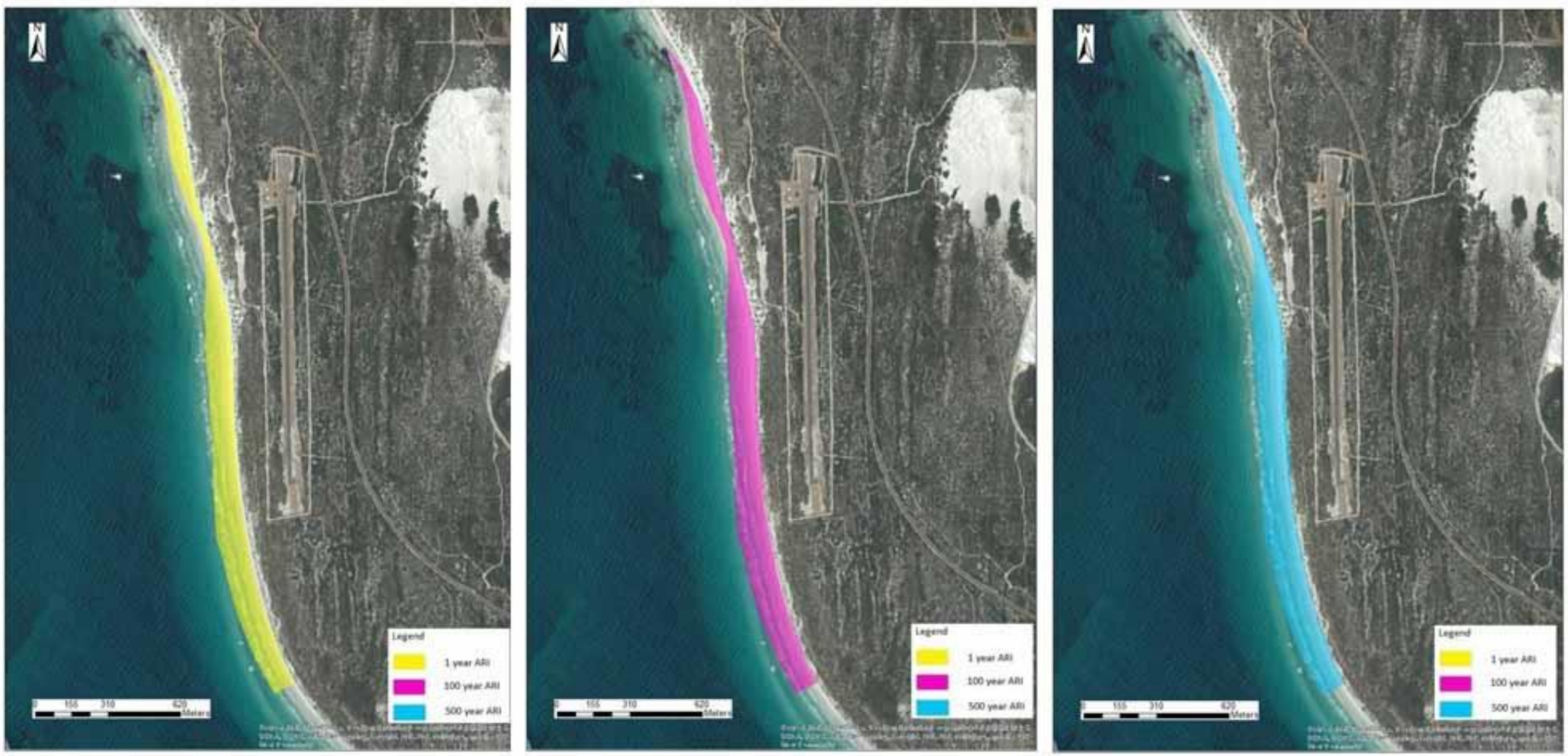

Figure B. 9: Inundation map of South Beach (South) – 1, 100, 500 year ARI event at present (0.0 m SLR)

Figure B. 10: Integrated inundation map of South Beach (South) at present (0.0 m SLR)

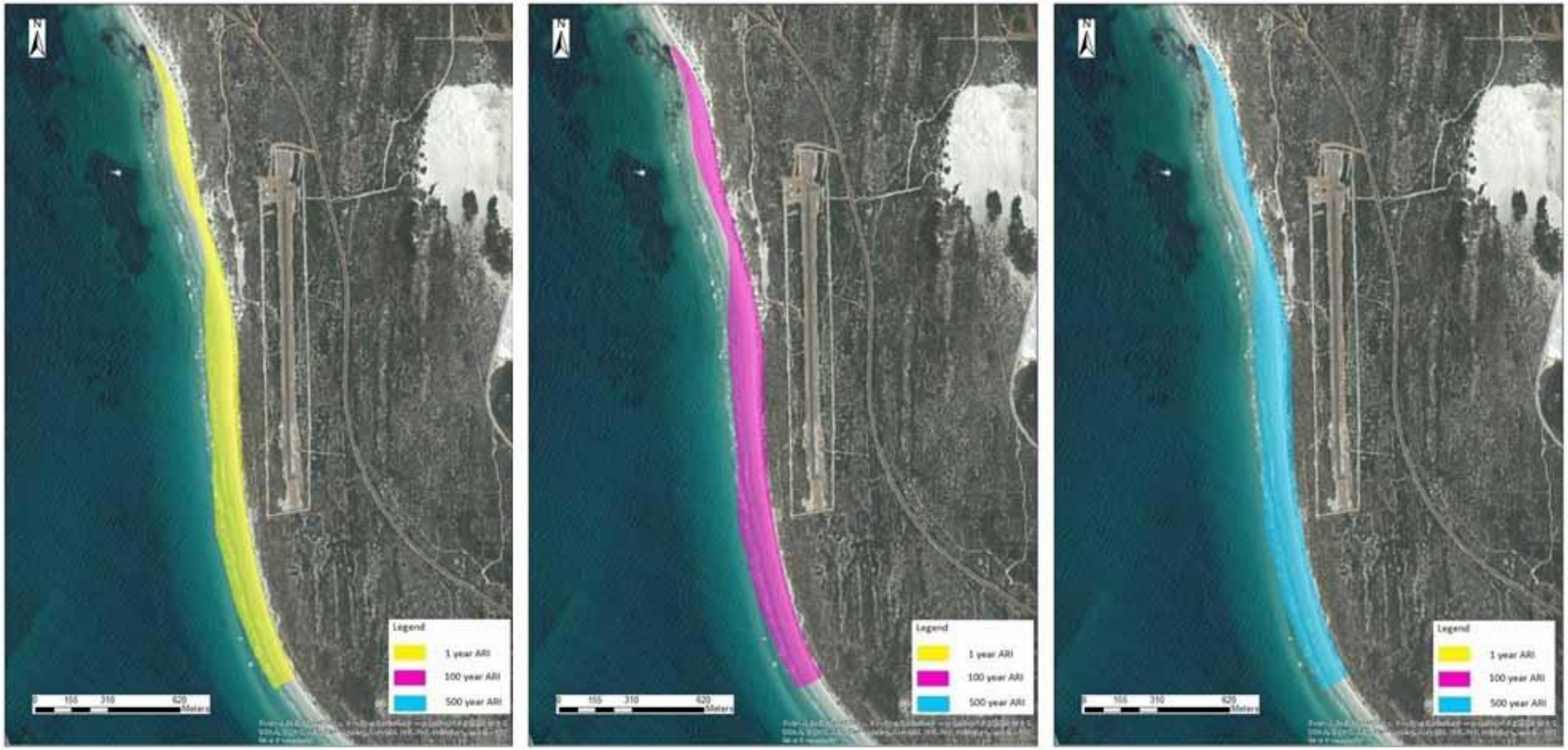

Figure B. 11: Inundation map of South Beach (South) - 1, 100 and 500 year ARI event in 2070 (0.5 m SLR)

Figure B. 12: Integrated inundation map of South Beach (South) in 2070 (0.5 m SLR)

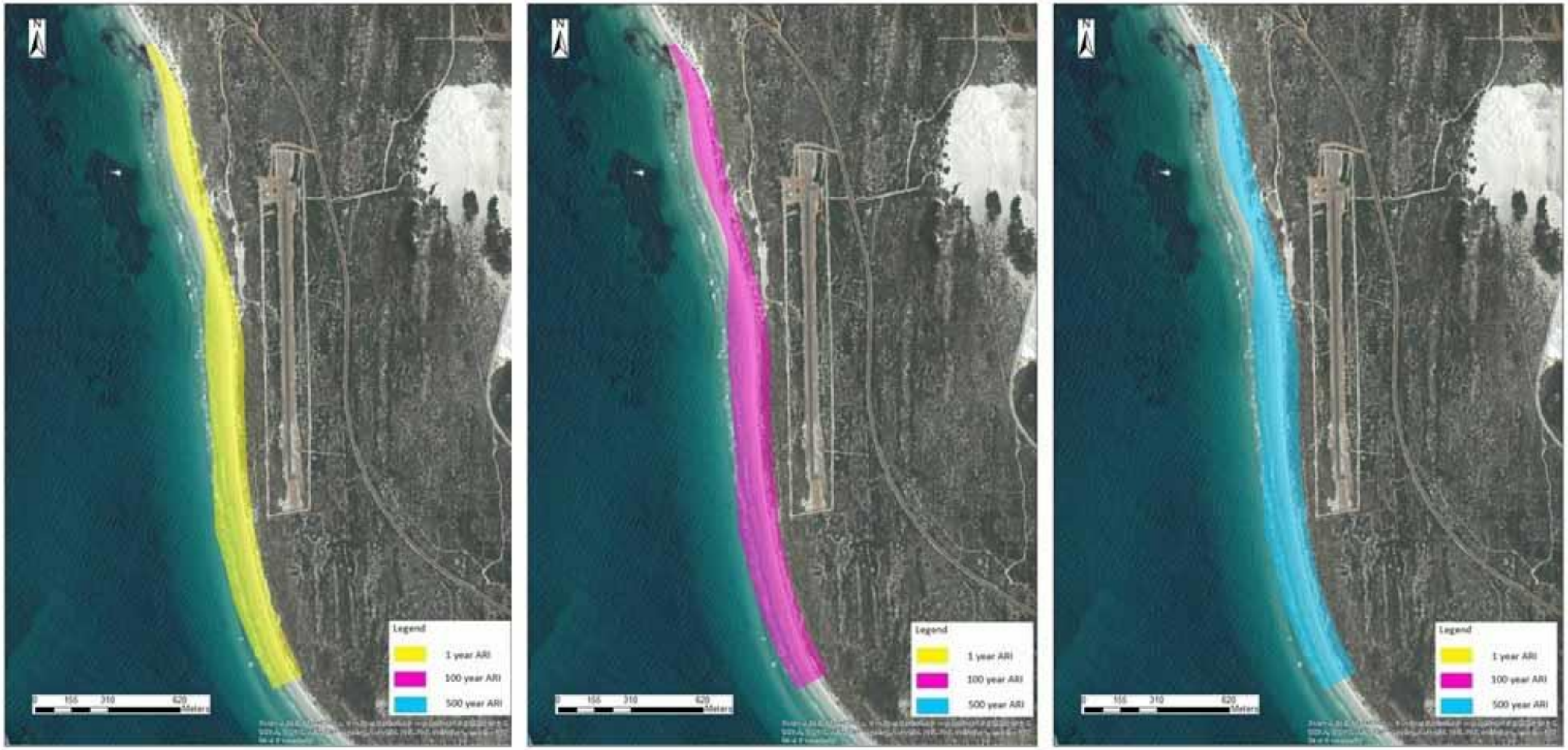

Figure B. 13: Inundation map of South Beach (South) - 1,100 and 500 year ARI event in 2110 (0.9 m SLR)

Figure B. 14: Integrated Inundation map of South Beach (South) in 2110 (0.9 m SLR)

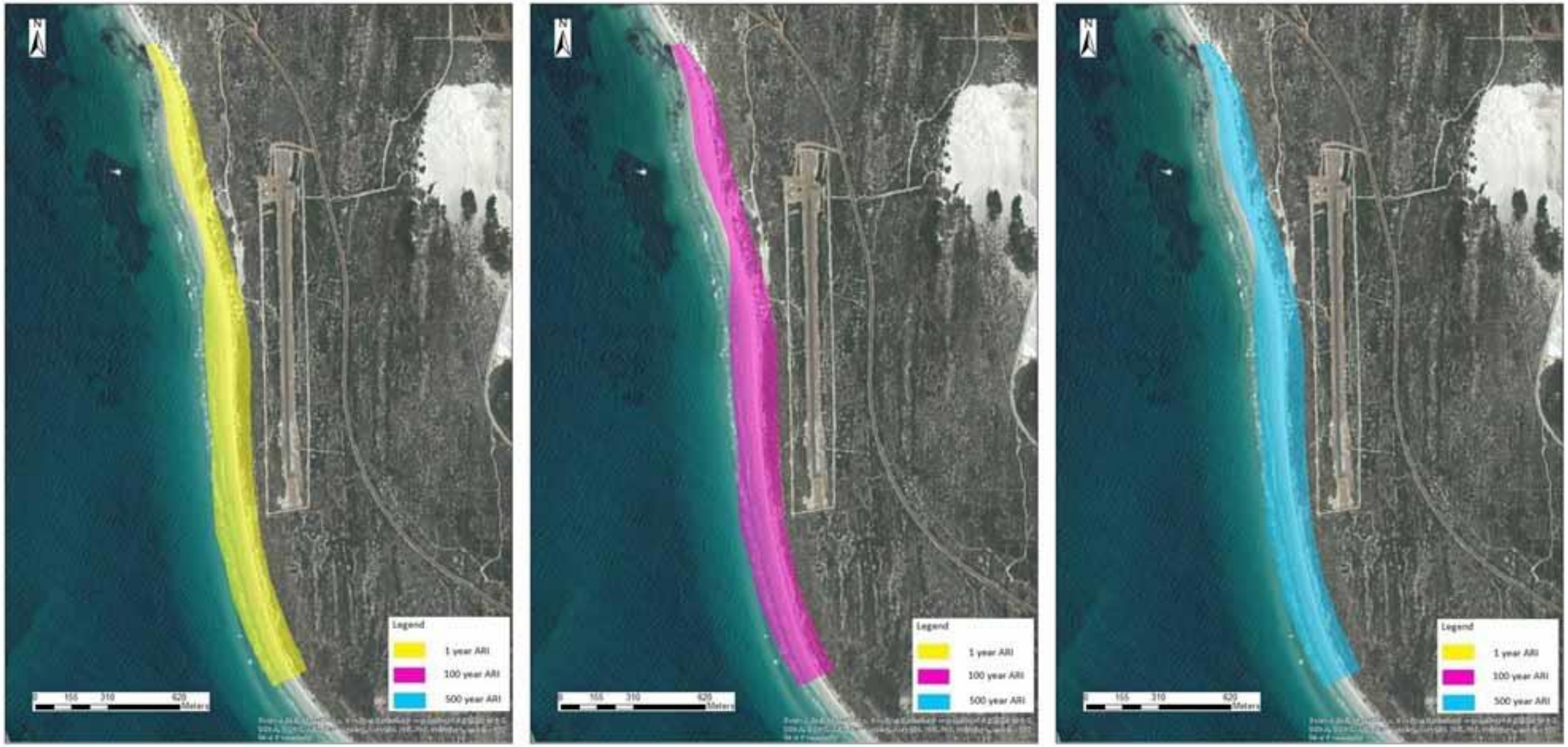

Figure B. 15: Inundation map of South Beach (South) - 1, 100 and 500 year ARI event in 2110 (1.5m SLR)

Figure B. 16: Integrated inundation map of South Beach (South) in 2110 (1.5m SLR)

Seaspray Beach/Irwin River

Figure B. 17: Inundation map of Seaspray Beach- 1 year ARI event at Present (0 m SLR)

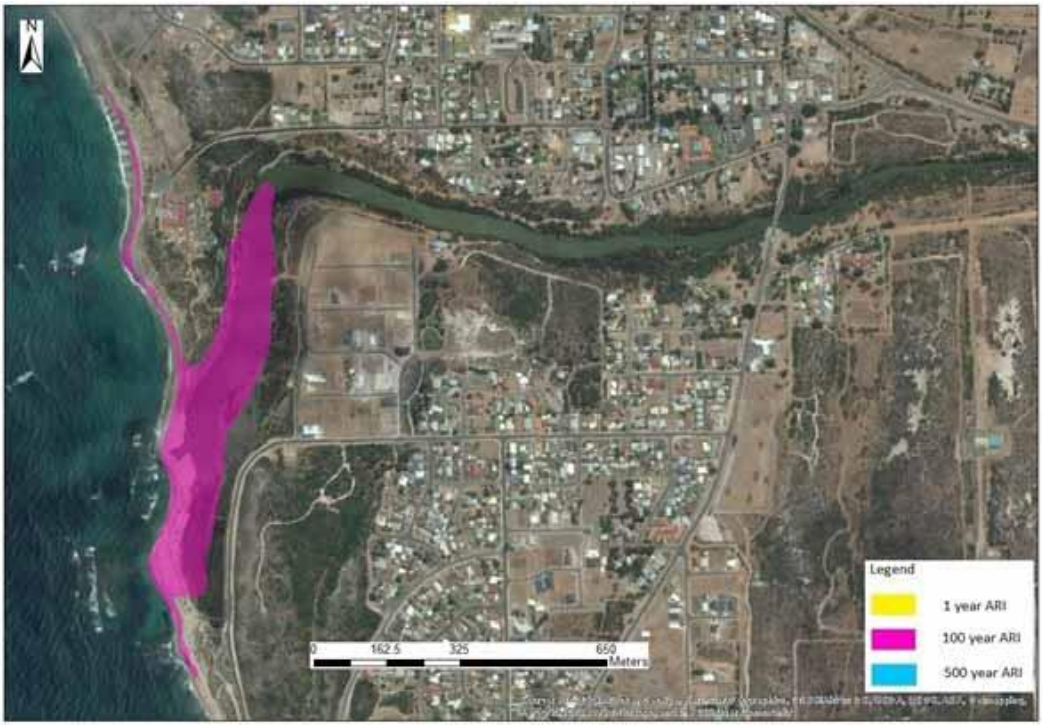

Figure B. 18: Inundation map of Seaspray Beach -100 year ARI event at present (0.0 m SLR)

Figure B. 19: Inundation map of Seaspray Beach- 500 year ARI event at Present (0 m SLR)

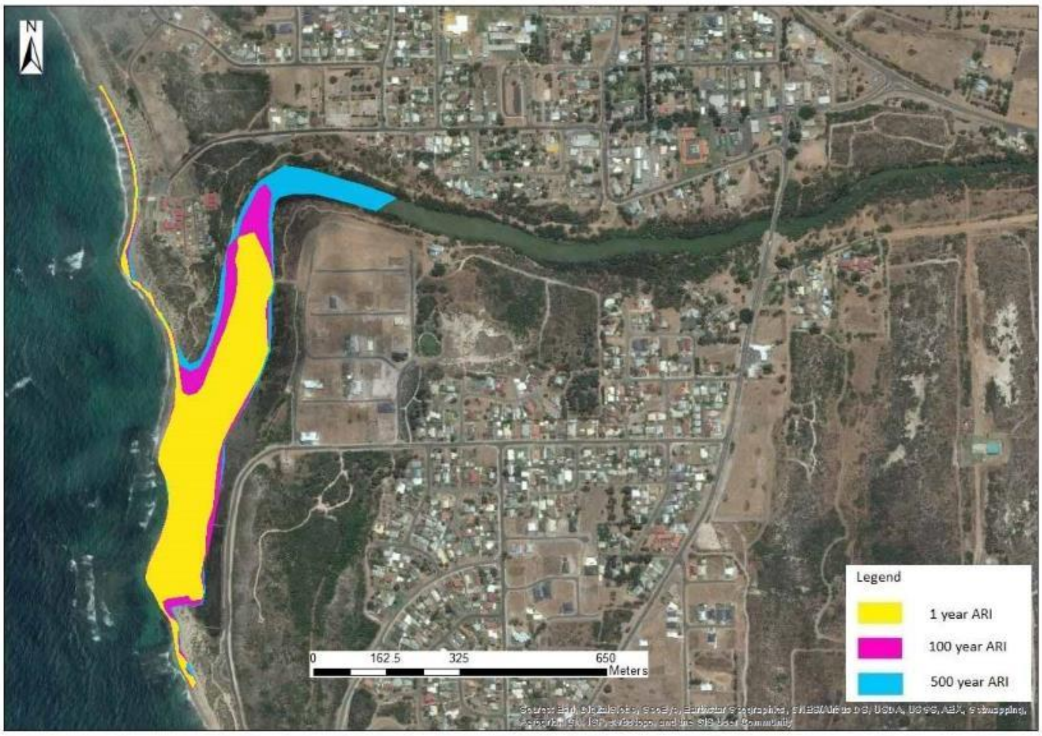

Figure B. 20: Integrated inundation map of Seaspray Beach at Present (0 m SLR)

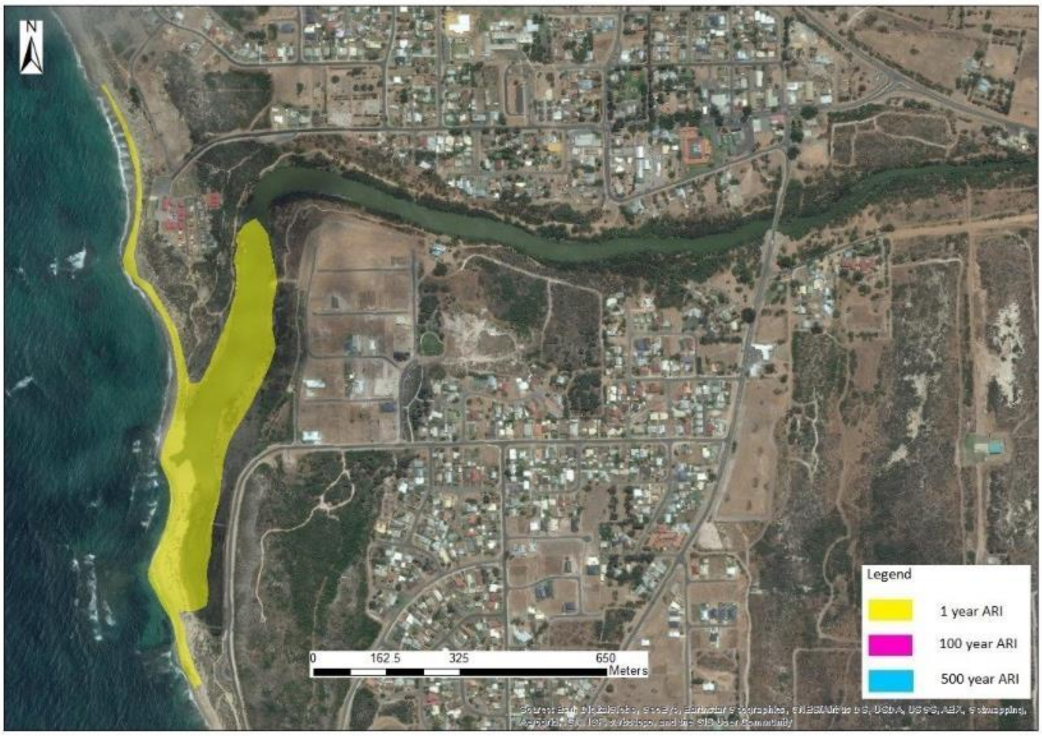

Figure B. 21: Inundation map of Seaspray Beach- 1 year ARI event in 2070 (0.5 m SLR)

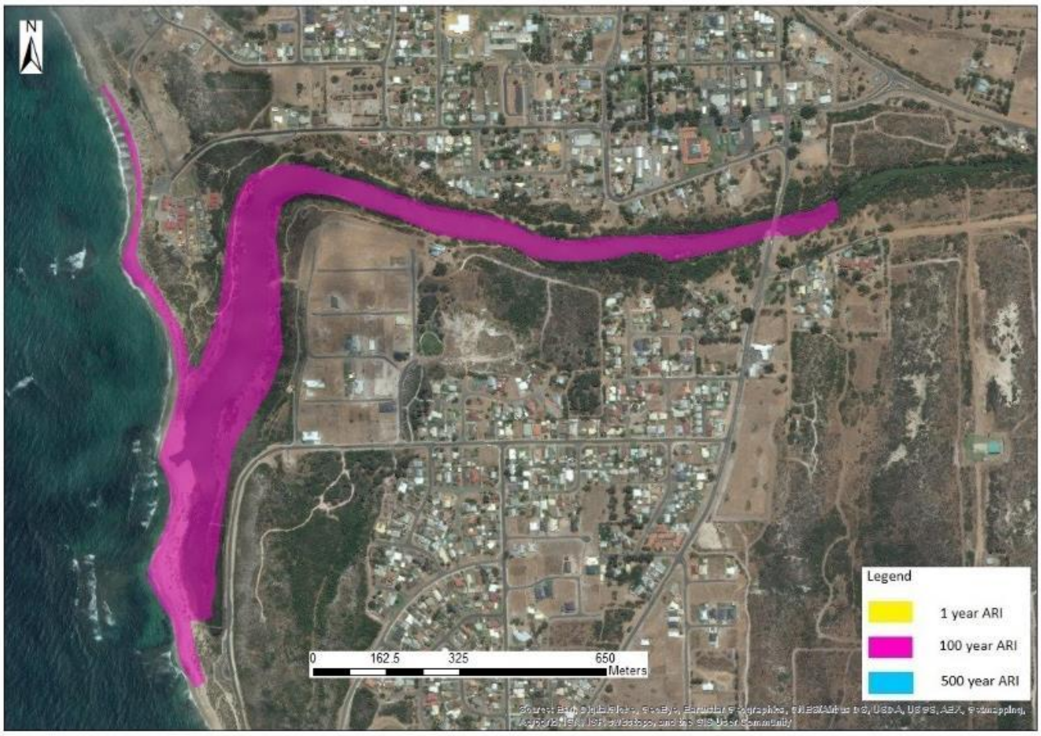

Figure B. 22: Inundation map of Seaspray Beach- 100 year ARI event in 2070 (0.5 m SLR)

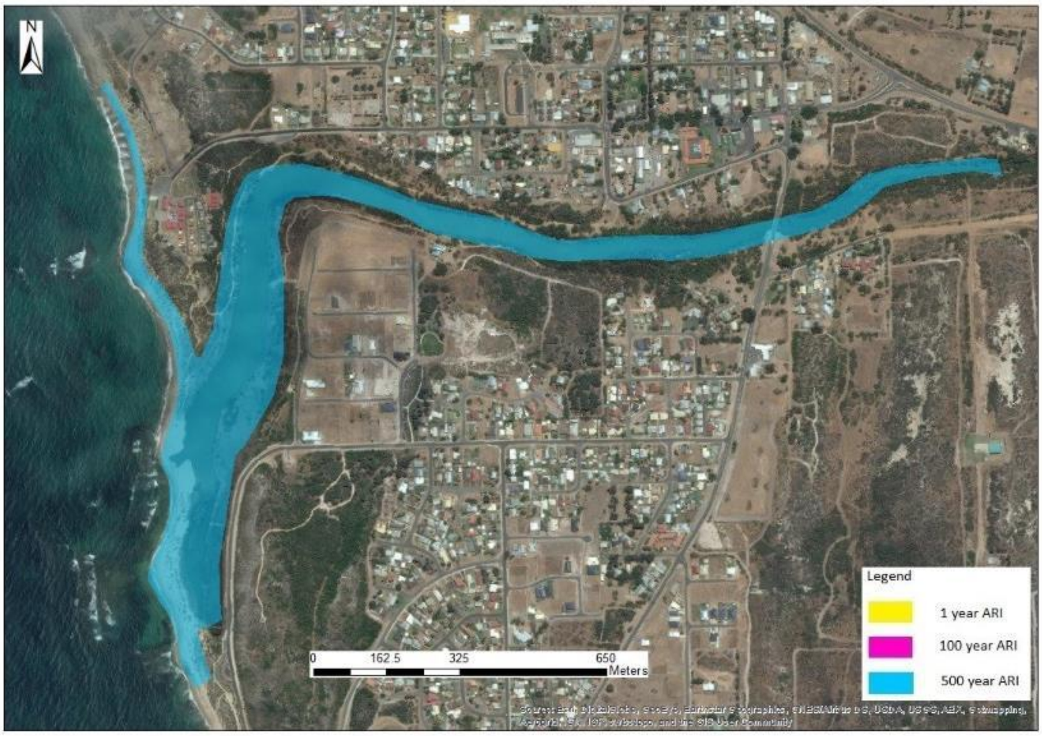

Figure B. 23: Inundation map of Seaspray Beach- 500 year ARI event in 2070 (0.5 m SLR)

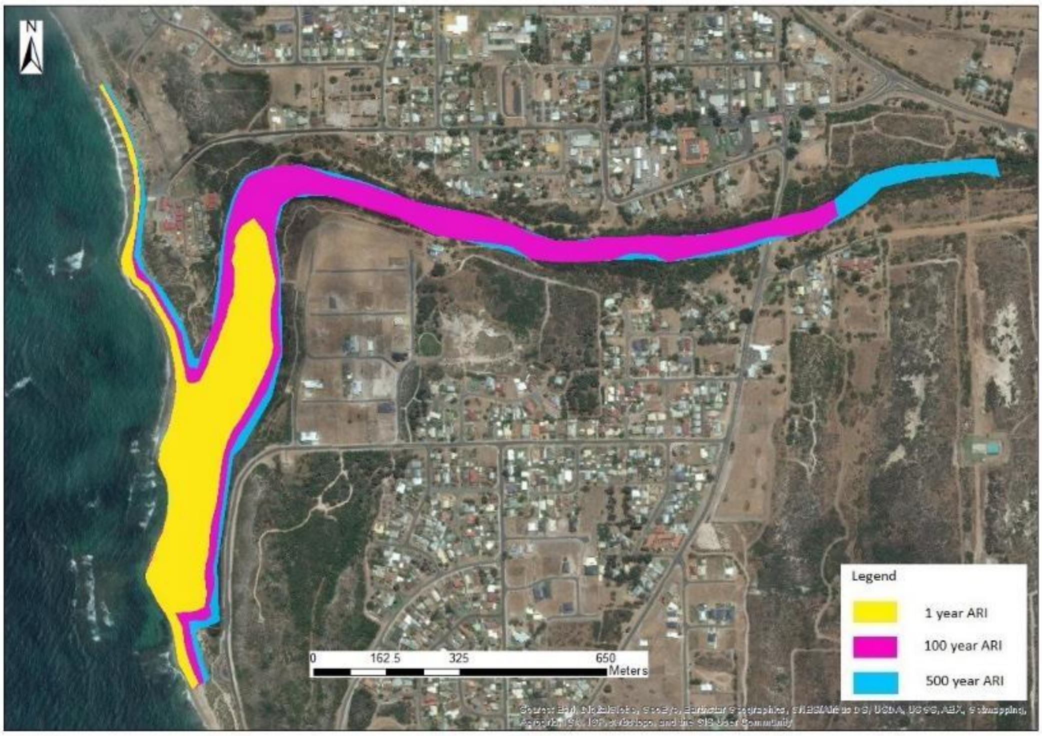

Figure B. 24: Integrated inundation map of Seaspray Beach in 2070 (0.5m SLR)

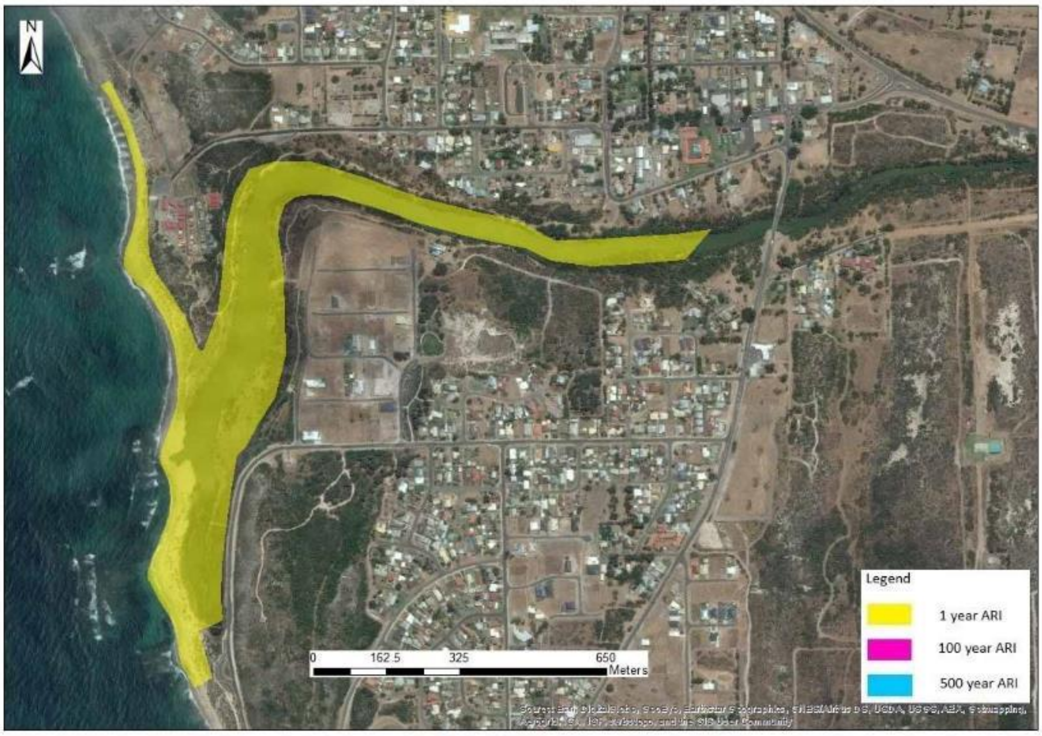

Figure B. 25: Inundation map of Seaspray Beach- 1 year ARI event in 2110 (0.9 m SLR)

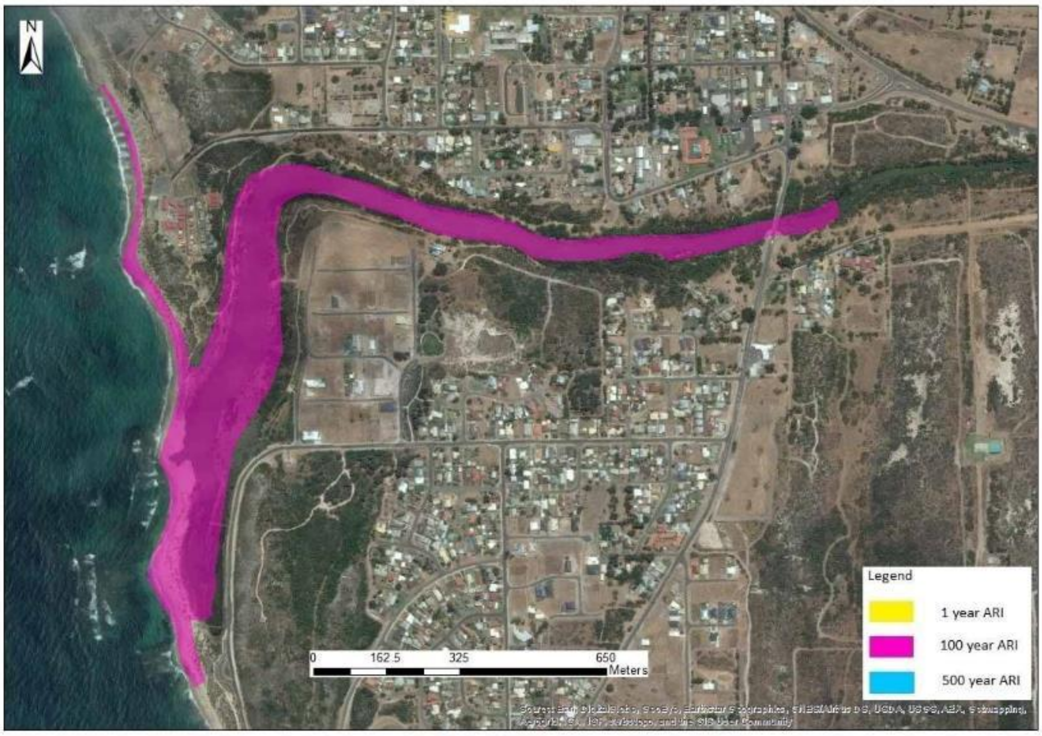

Figure B. 26 : Inundation map of Seaspray Beach- 100 year ARI event in 2110 (0.9m SLR)

Figure B. 27: Inundation map of Seaspray Beach- 500 year ARI event in 2110 (0.9 m SLR)

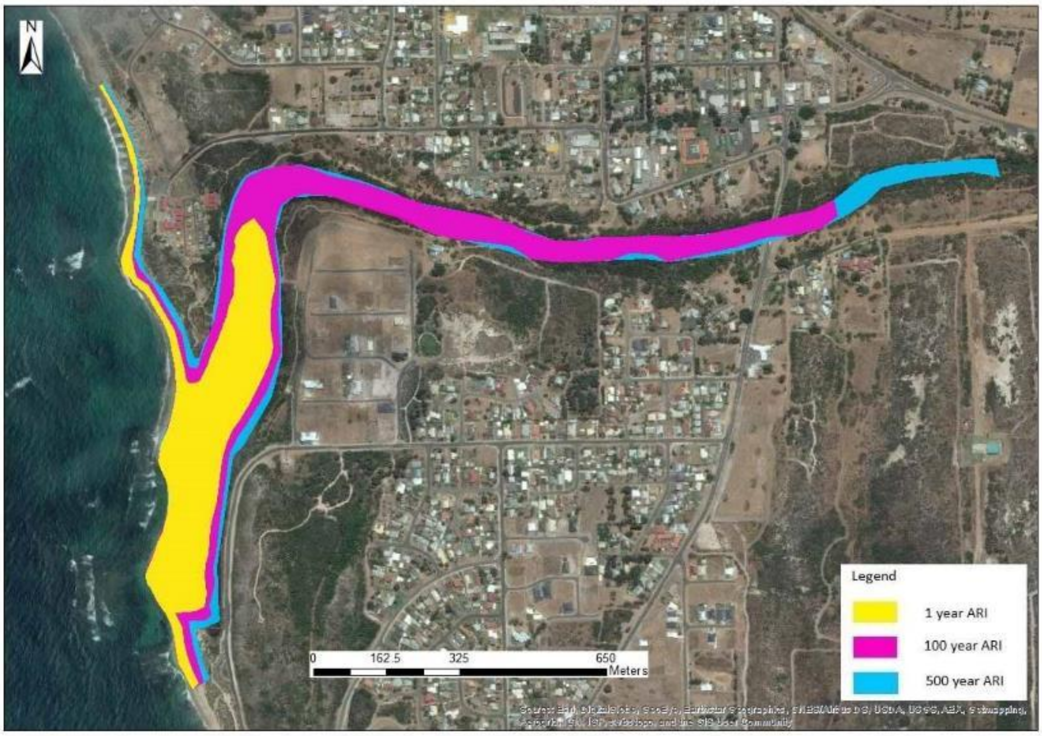

Figure B. 28: Integrated inundation map of Seaspray Beach in 2110 (0.9 m SLR)

Figure B. 29: Inundation map of Seaspray Beach- 1 year ARI event in 2110 (1.5 m SLR)

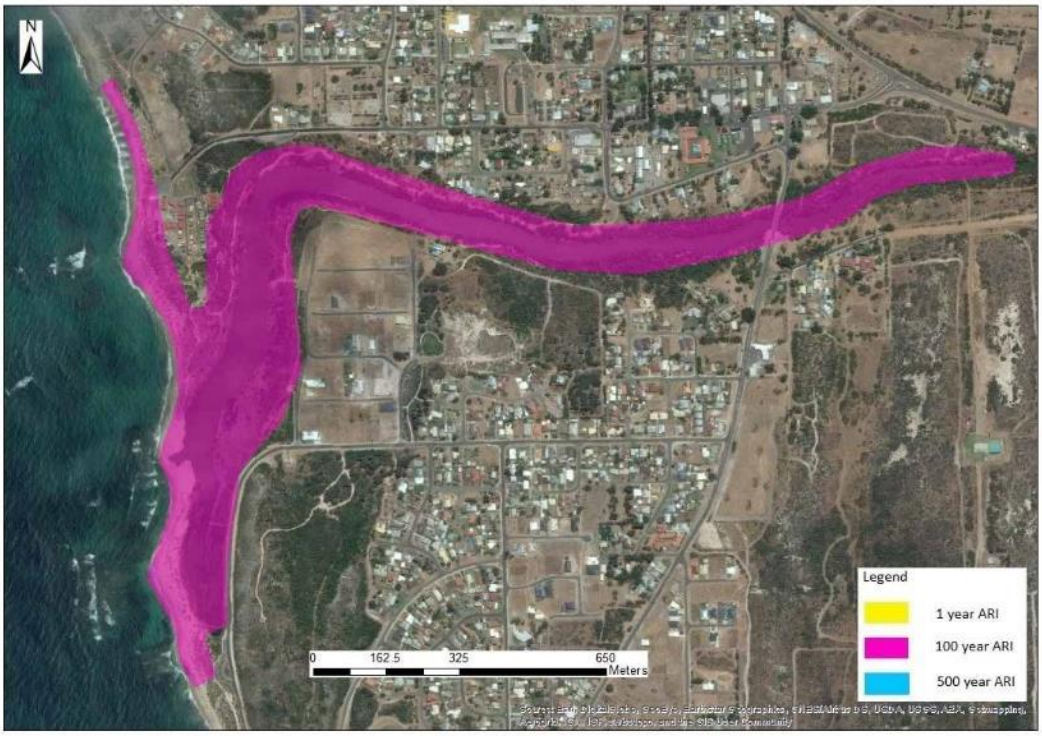

Figure B. 30: Inundation map of Seaspray Beach- 100 year ARI event in 2110 (1.5 m SLR)

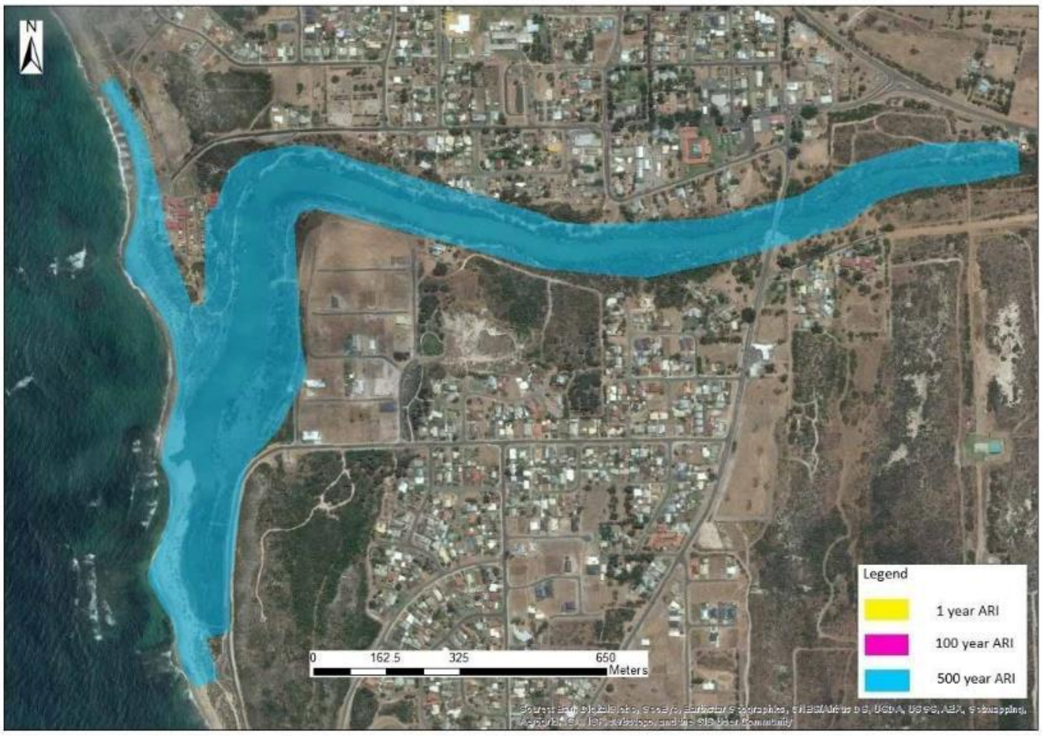

Figure B. 31: Inundation map of Seaspray Beach- 500 year ARI event in 2110 (1.5 m SLR)

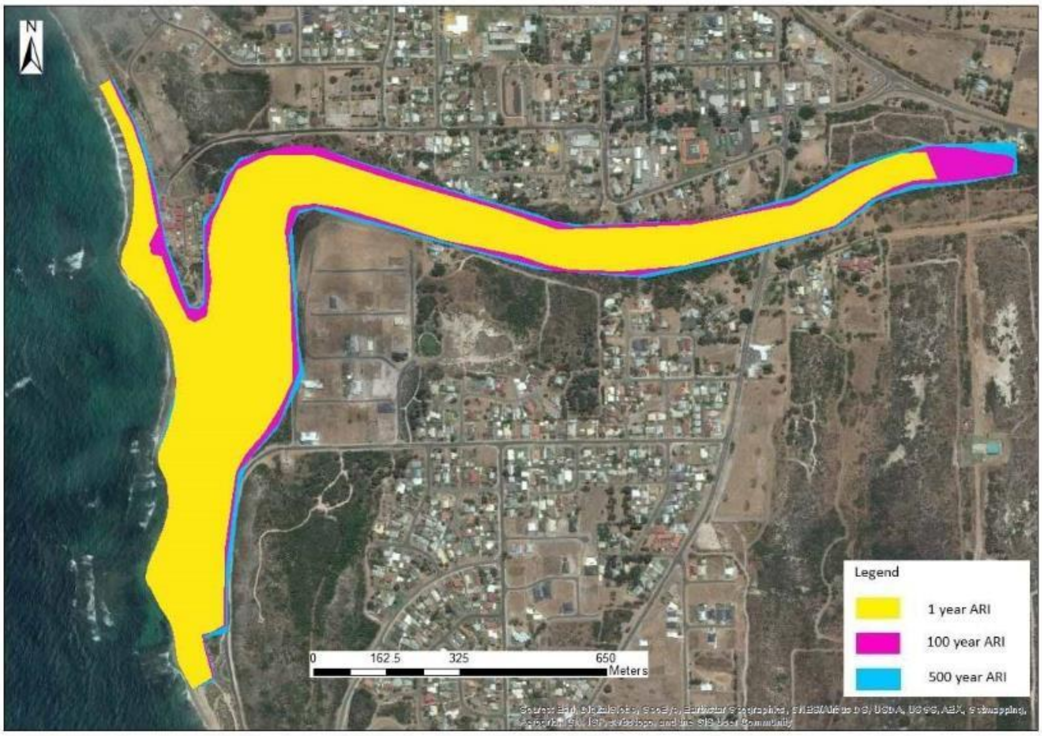

Figure B. 32: Integrated inundation map of Seaspray Beach in 2110 (1.5 m SLR)

Seven Mile Beach

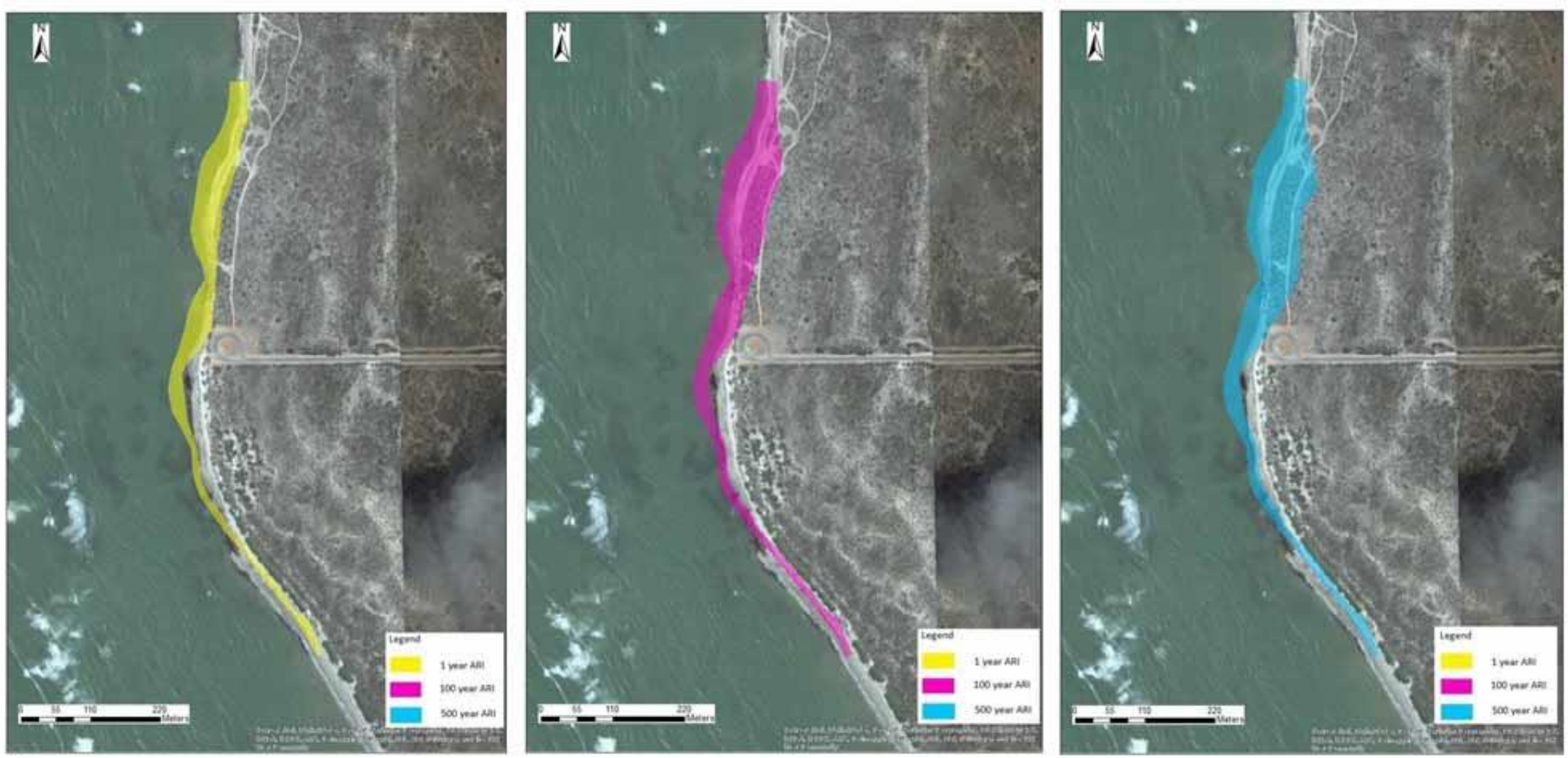

Figure B. 33: Inundation map of Seven Mile Beach-1,100 and 500 year ARI event at Present (0.0 m SLR)

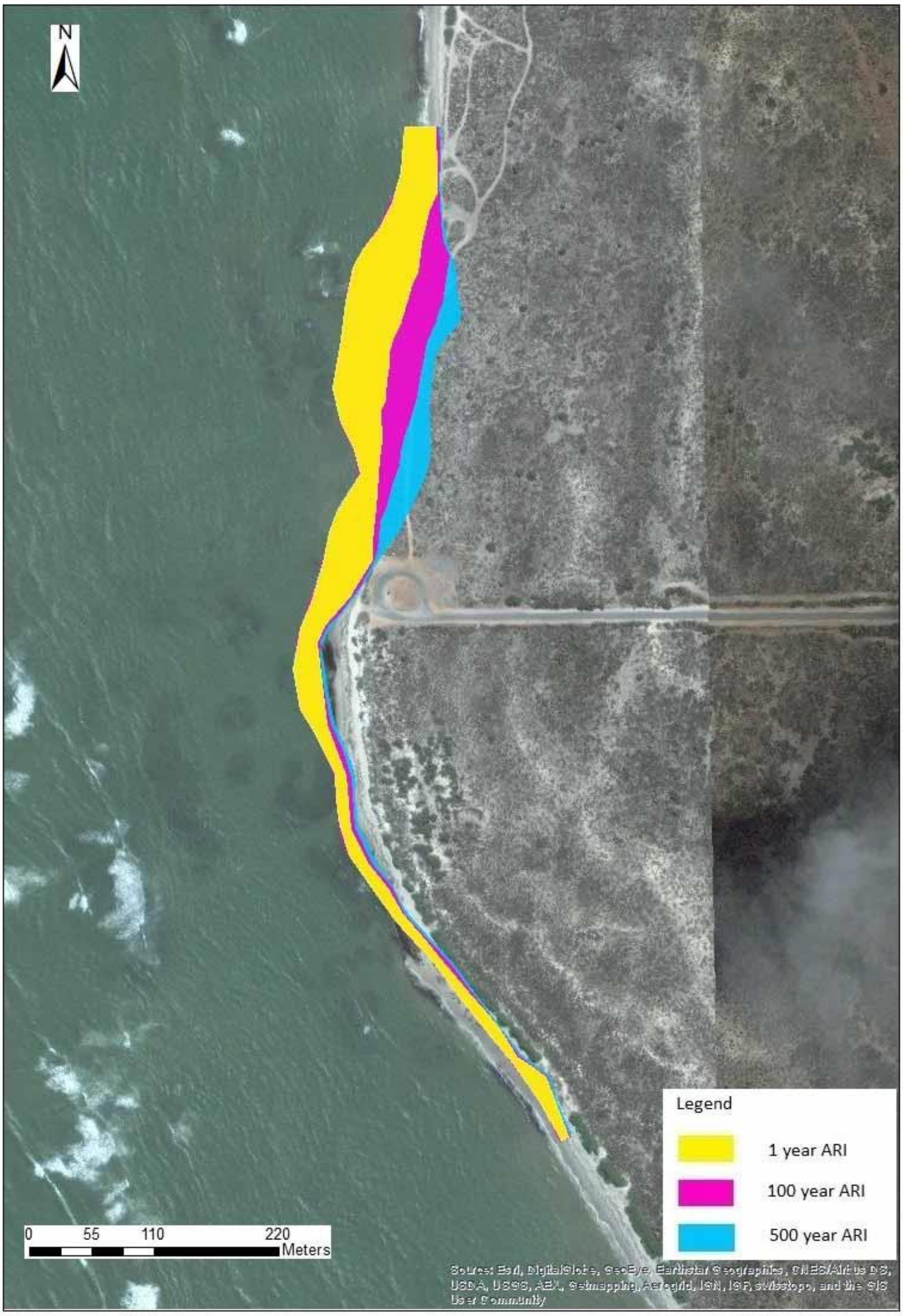

Figure B. 34: Integrated inundation map of Seven Mile Beach at Present (0.0 m SLR)

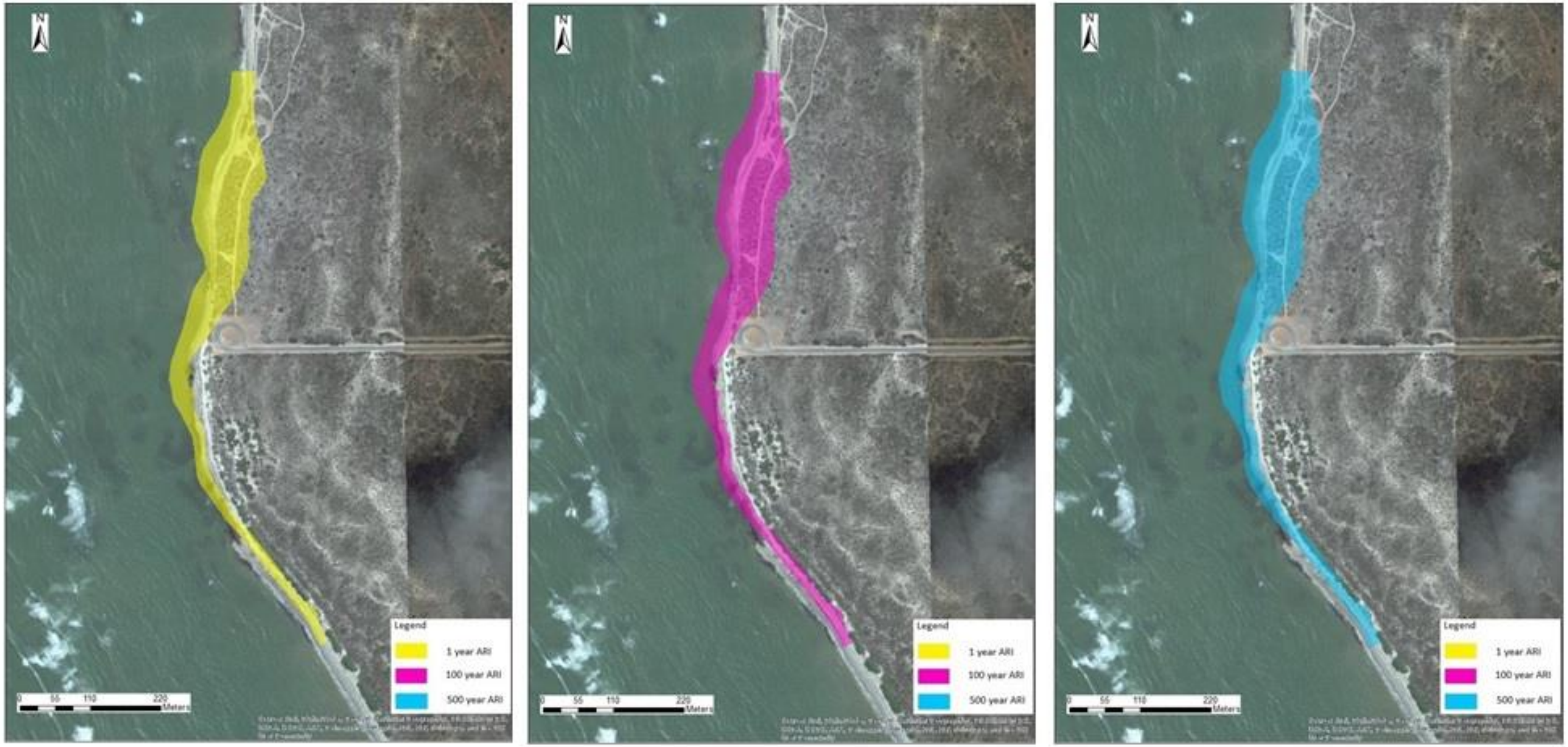

Figure B. 35: Inundation map of Seven Mile Beach-1, 100 and 500 year ARI event in 2070 (0.5 m SLR)

Figure B. 36: Integrated inundation map of Seven Mile Beach in 2070 (0.5 m SLR)

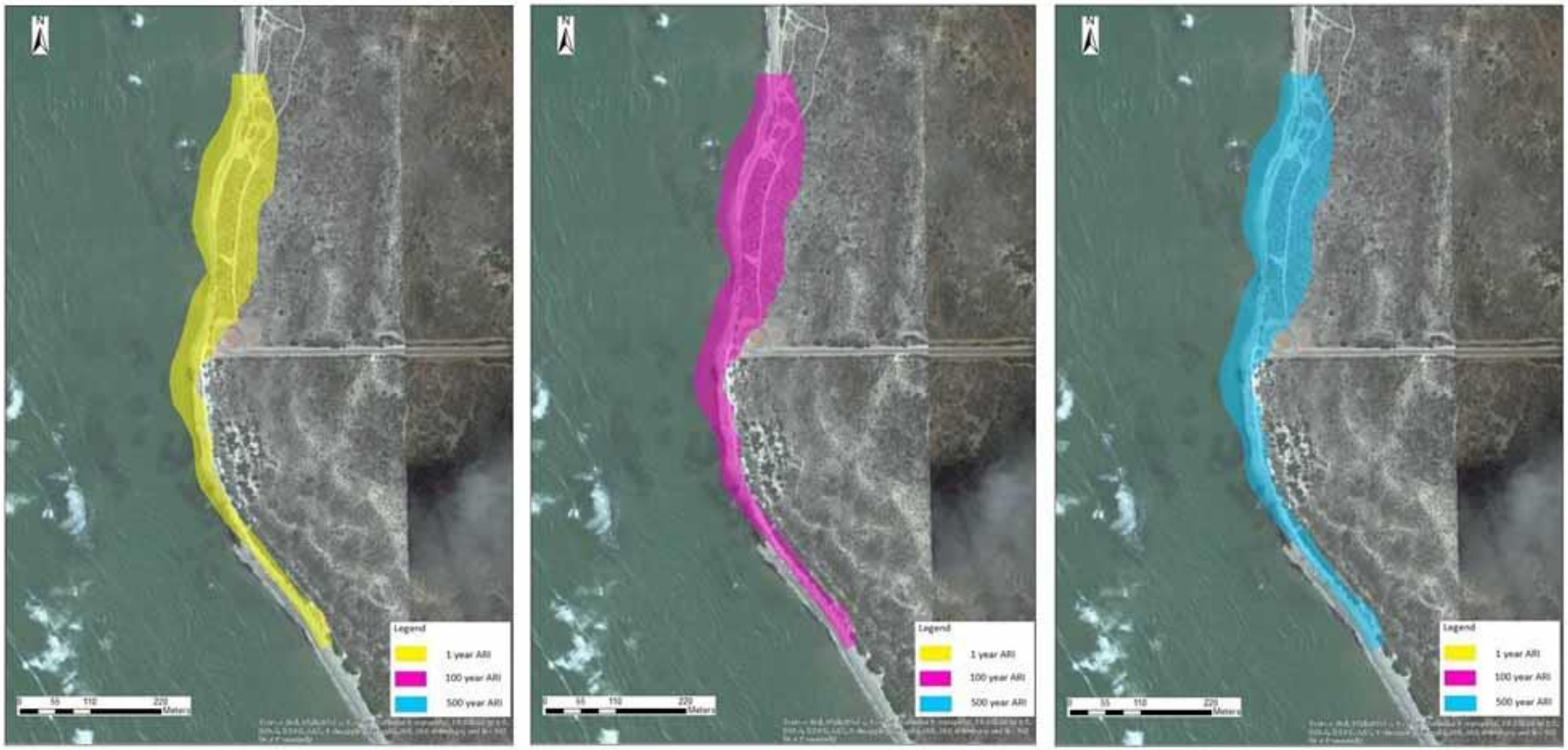

Figure B. 37: Inundation map of Seven Mile Beach-1 year ARI event in 2110 (0.9 m SLR)

Figure B. 38: Integrated inundation map of Seven Mile Beach in 2110 (0.9 m SLR)

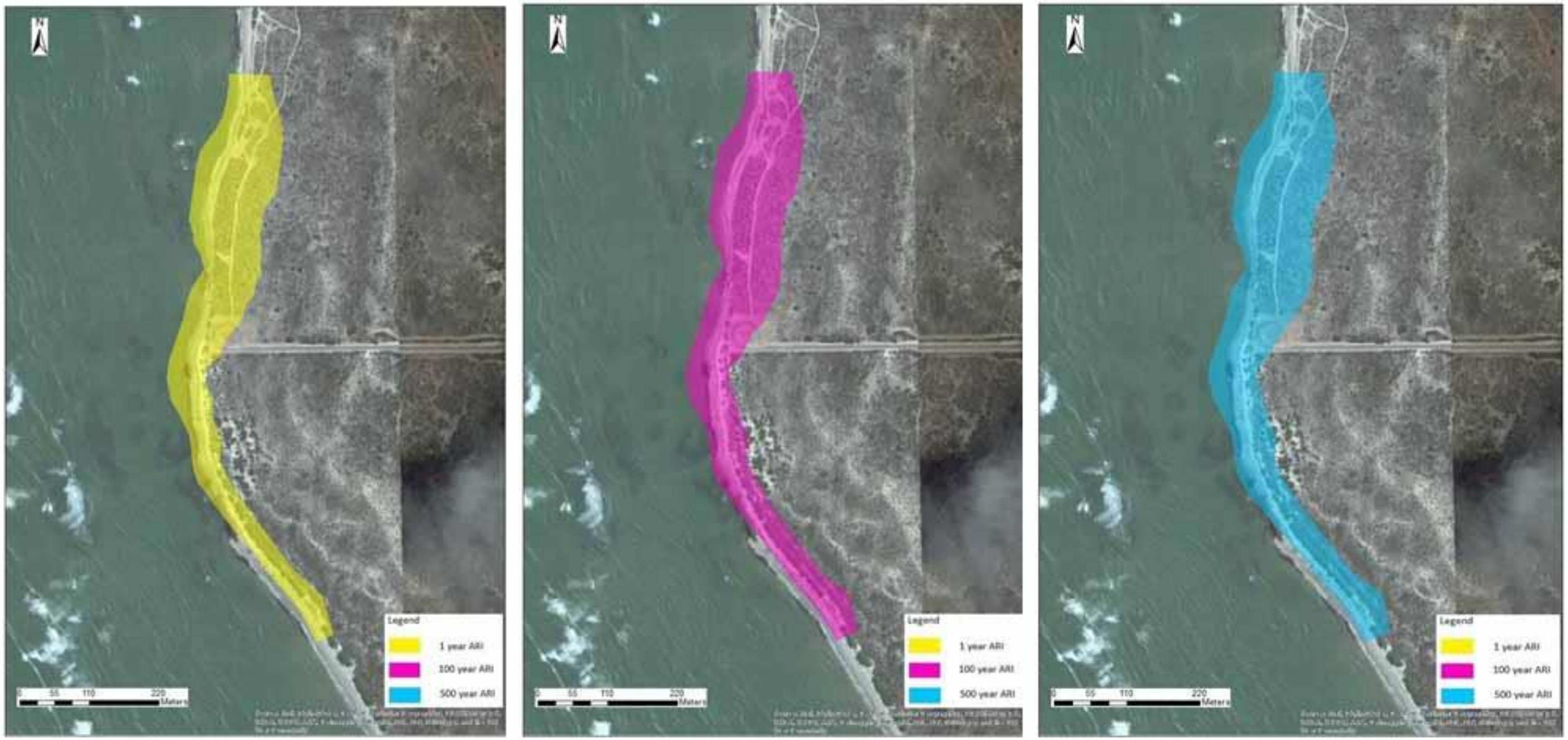

Figure B. 39: Inundation map of Seven Mile Beach-1, 100 and 500 year ARI event in 2110 (1.5 m SLR)

Figure B. 40: Integrated inundation map of Seven Mile Beach in 2110 (1.5 m SLR)

Freshwater Point

Figure B. 41: Inundation map of Freshwater Point- 1,100 and 500 year ARI event at Present (0 m SLR)

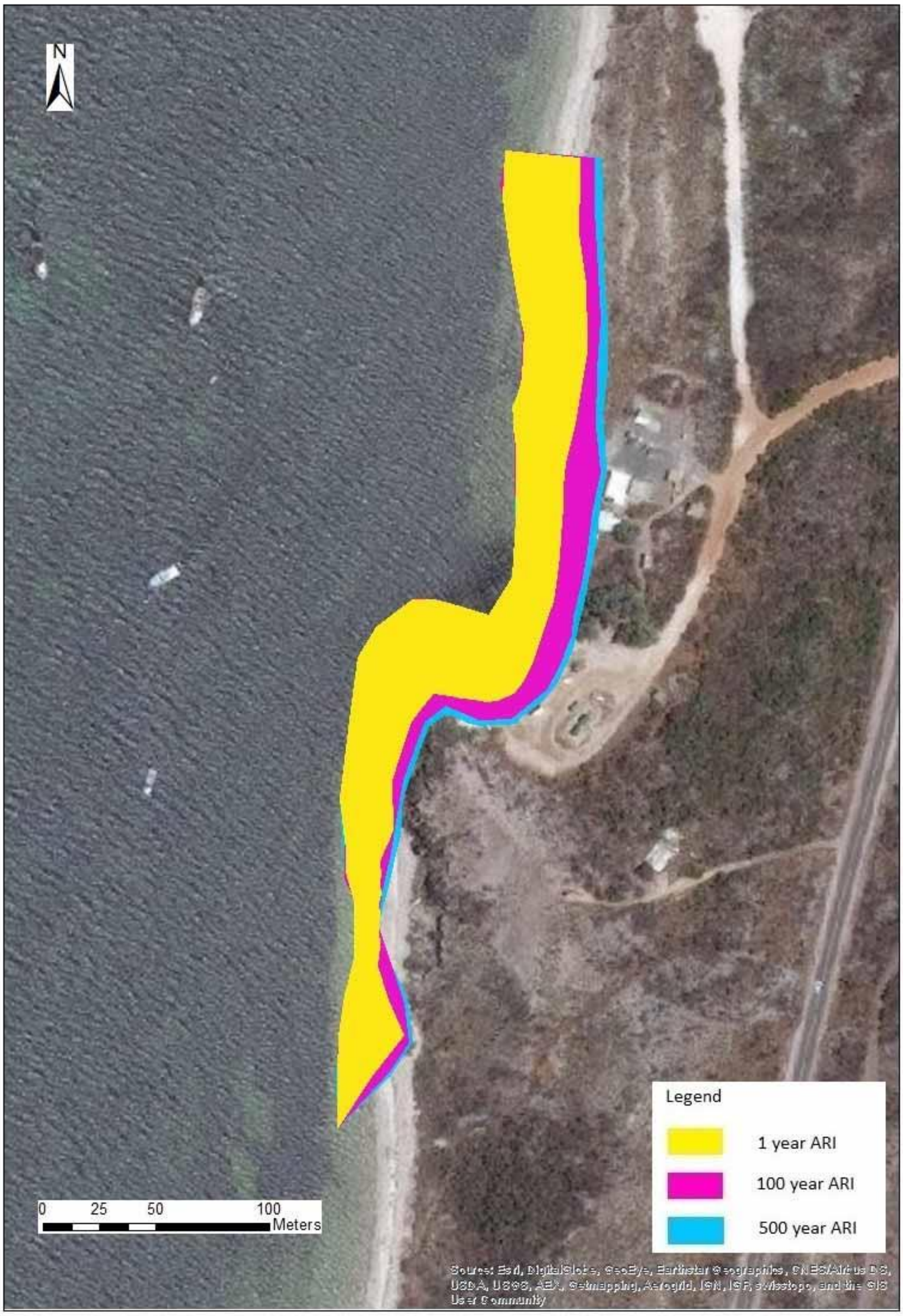

Figure B. 42: Integrated inundation map of Freshwater Point at present (0.0 m SLR)

Figure B. 43: Inundation map of Freshwater Point- 1, 100 and 500 year ARI event in 2070 (0.5 m SLR)

Figure B. 44: Integrated inundation map of Freshwater Point in 2070(0.5 m SLR)

Figure B. 45: Inundation map of Freshwater Point- 1, 100 and 500 year ARI event in 2110 (0.9 m SLR)

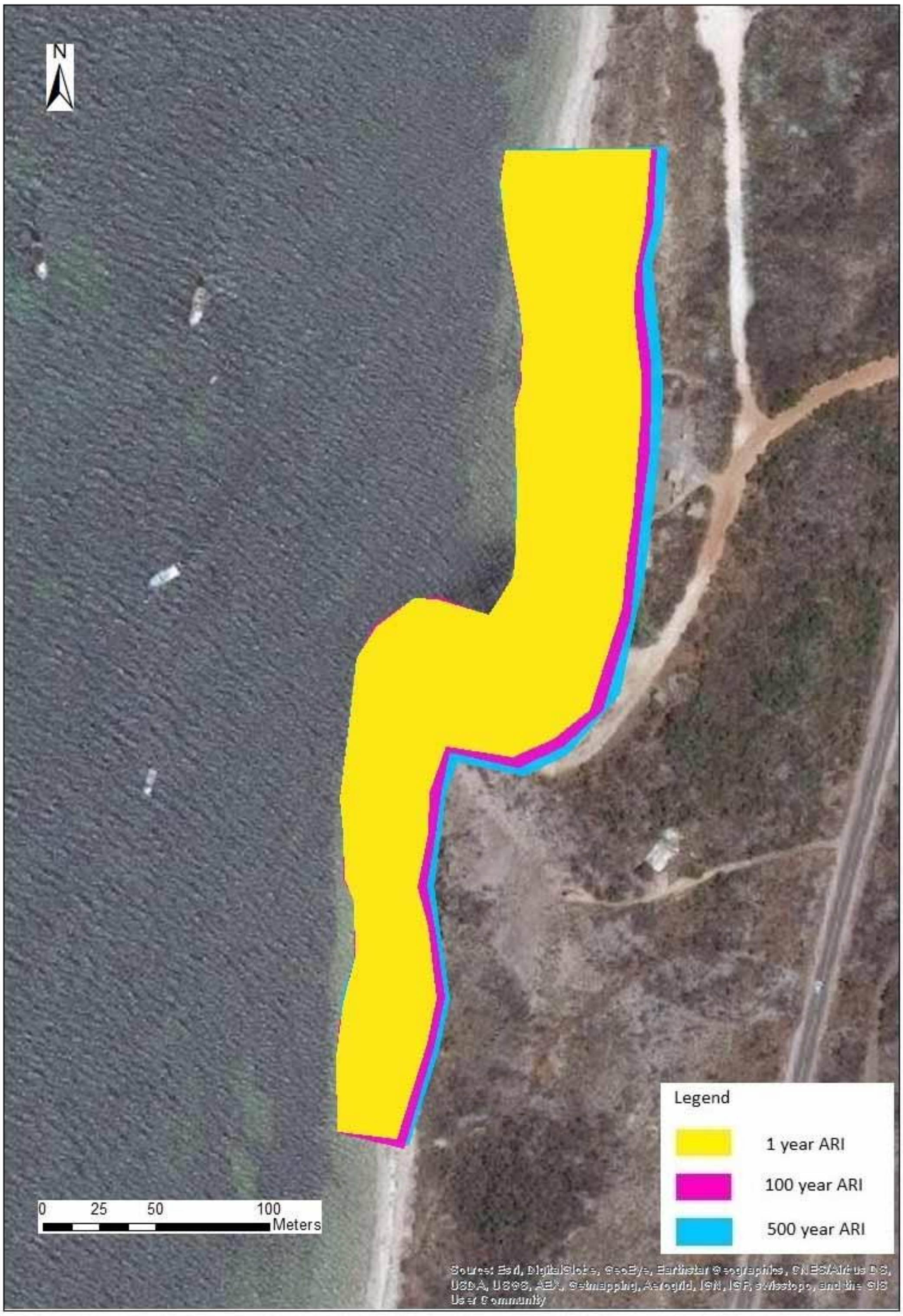

Figure B. 46: Integrated inundation map of Freshwater Point in 2110 (0.9 m SLR)

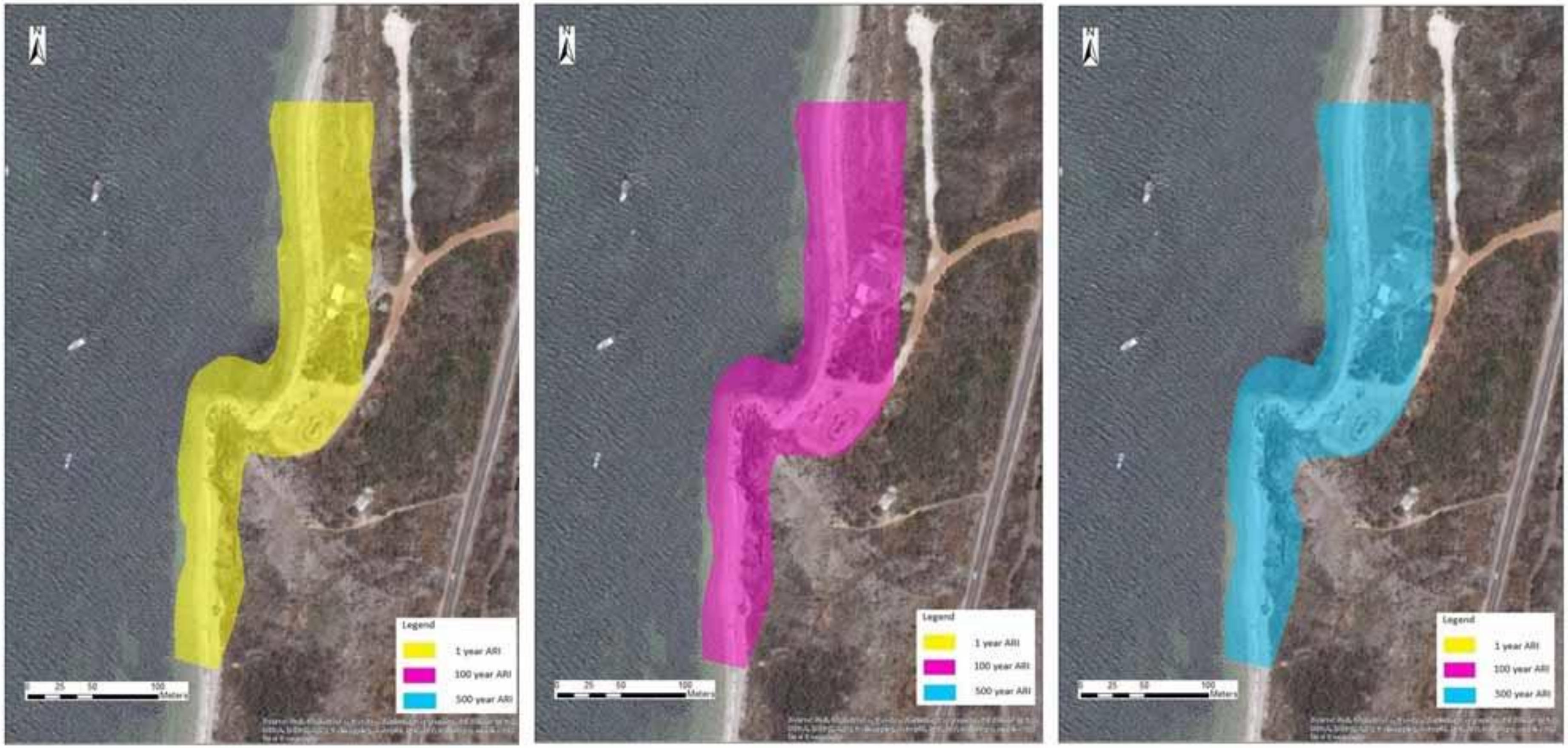

Figure B. 47: Inundation map of Freshwater Point- 1, 100 and 500 year ARI event in 2110 (1.5 m SLR)

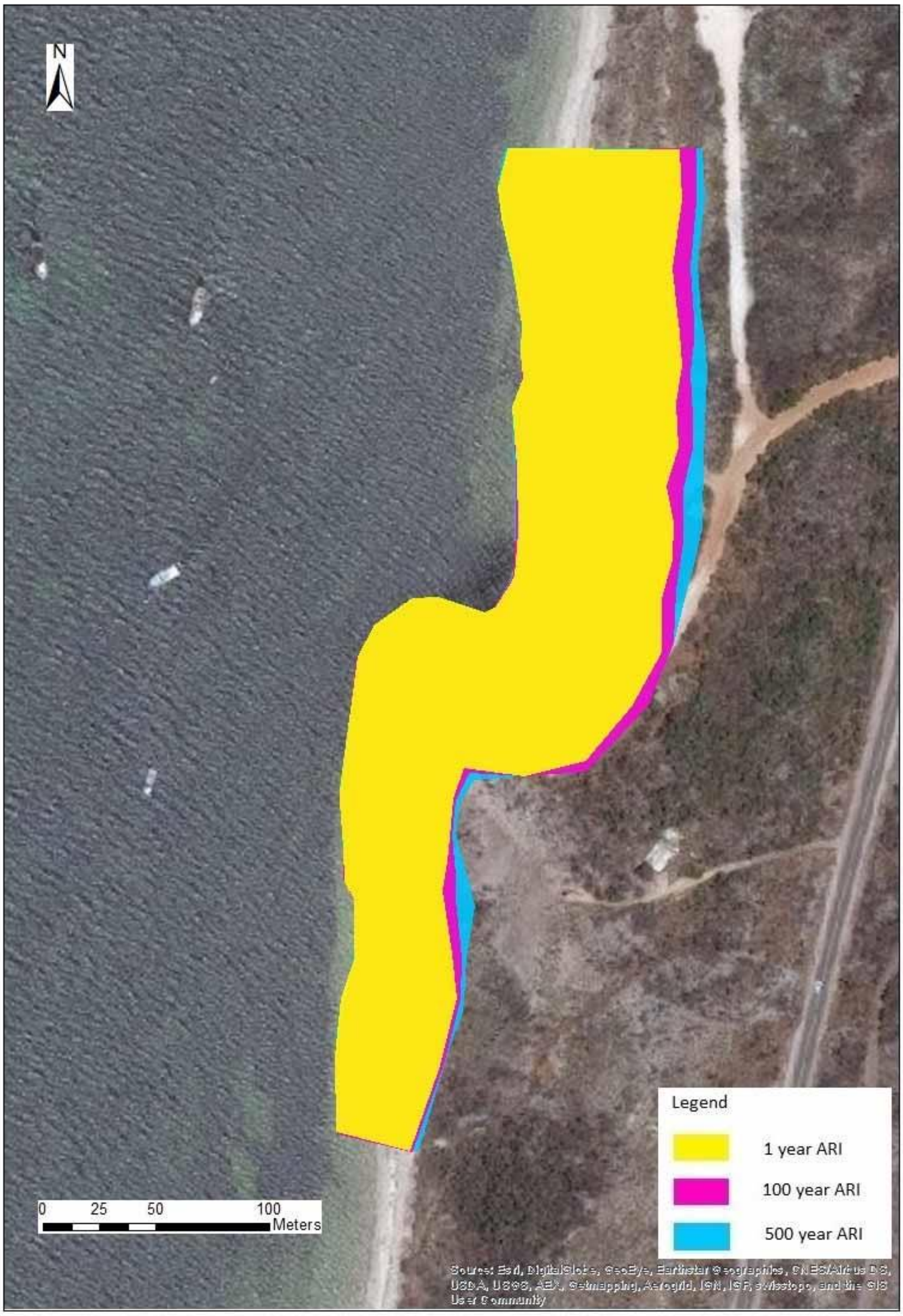

Figure B. 48: Integrated inundation map of Freshwater Point in 2110(1.5 m SLR)

Cliff Head (North)

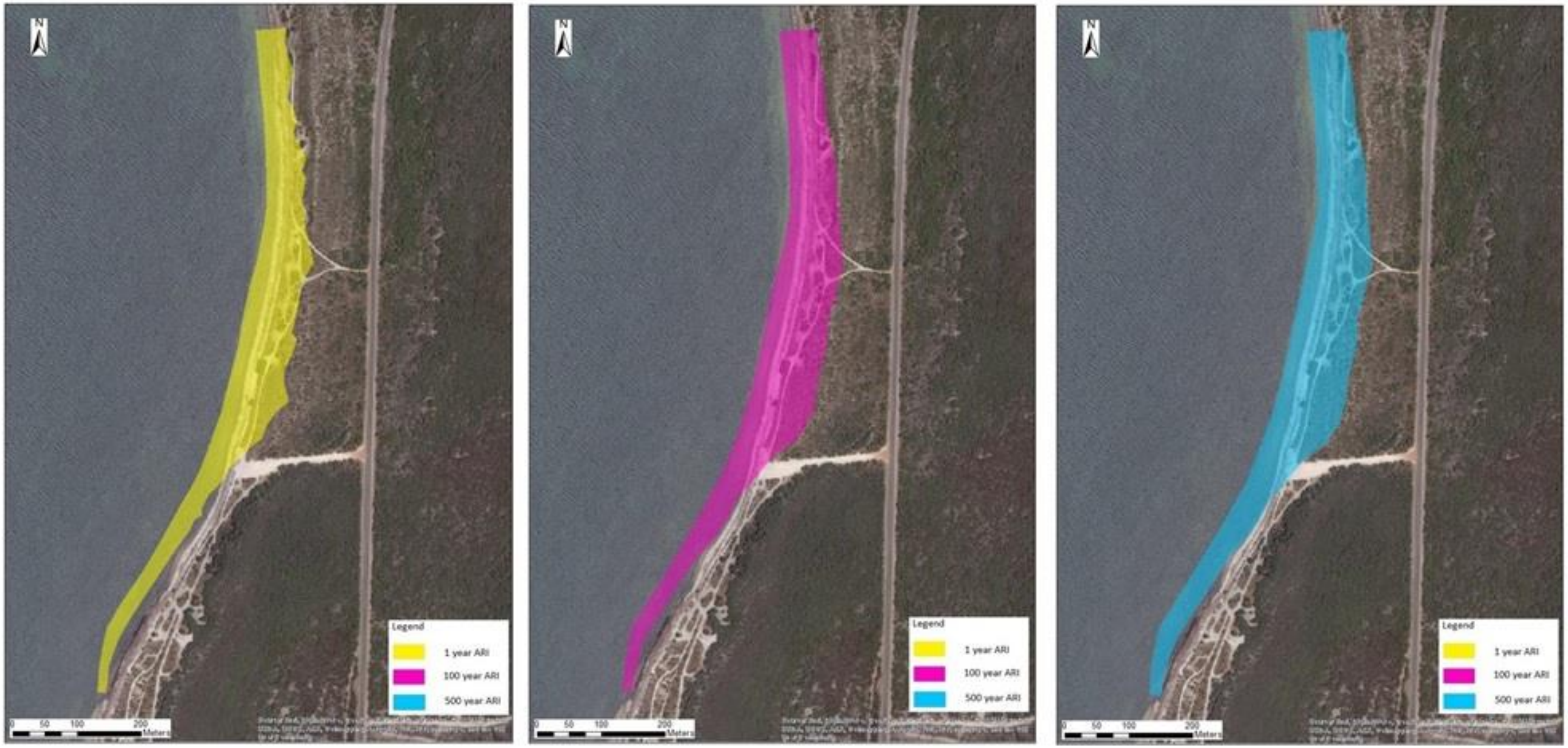

Figure B. 49: Inundation map of Cliff Head (North) - 1, 100 and 500 year ARI at present (0.0m SLR)

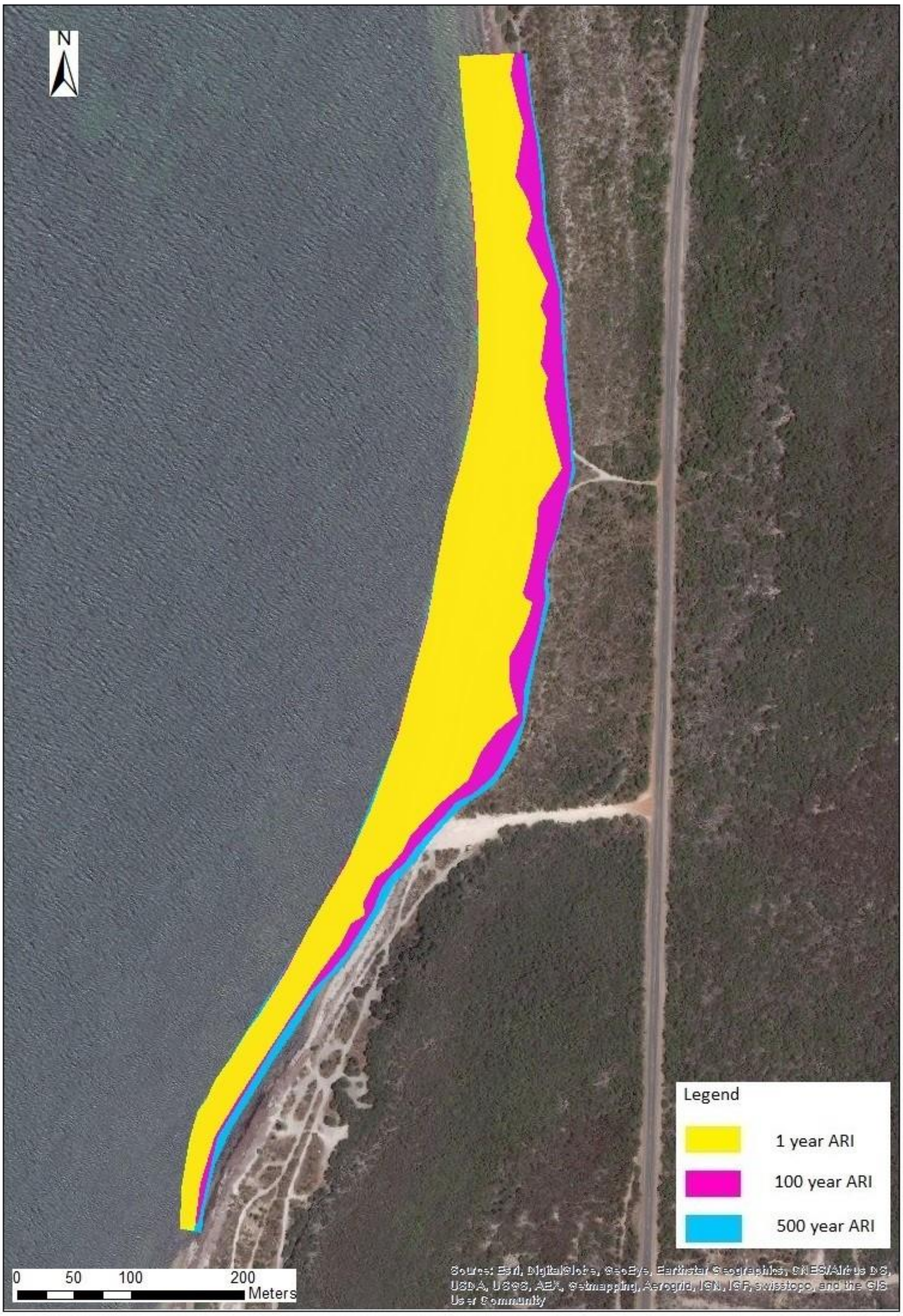

Figure B. 50: Integrated inundation map of Cliff Head (North) at present (0.0m SLR)

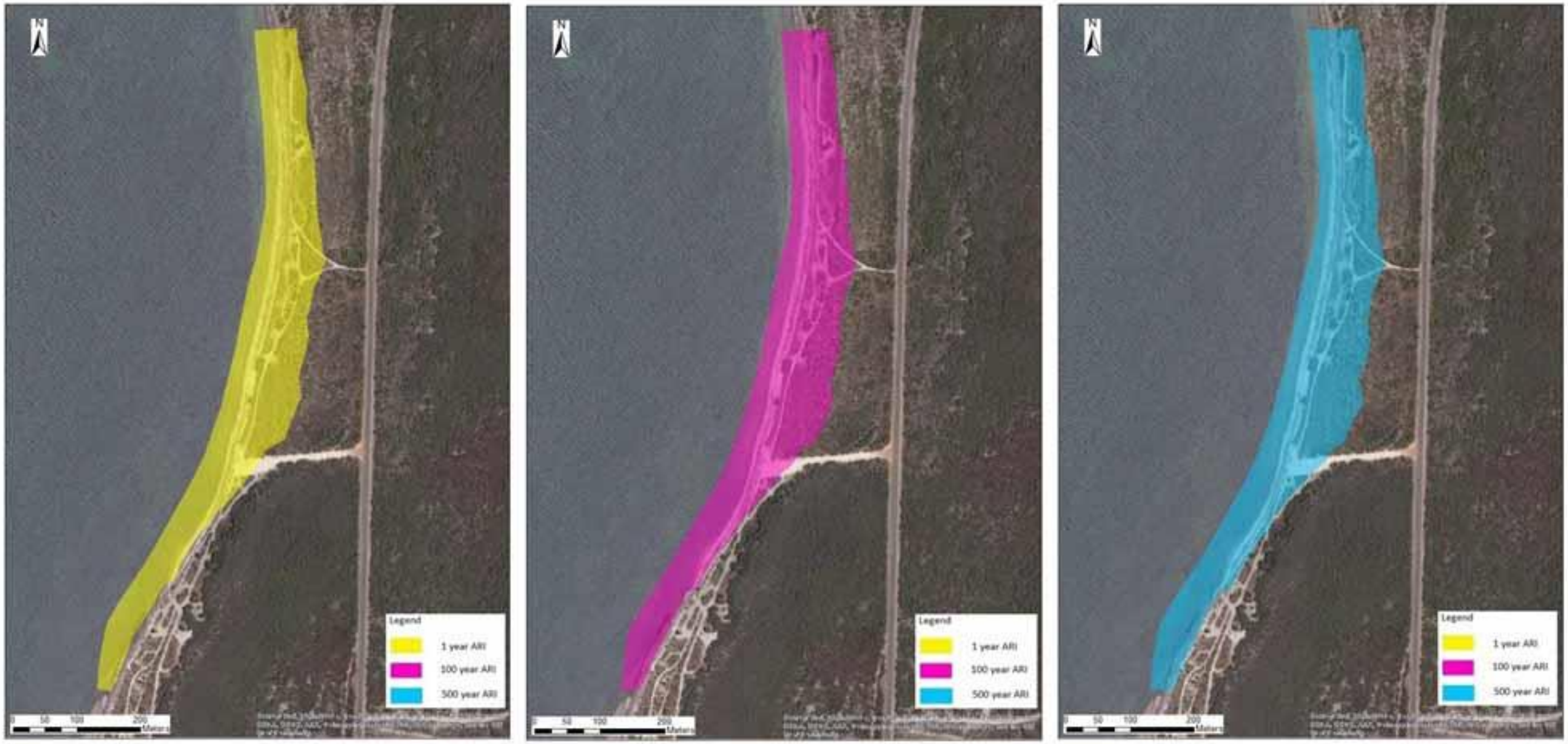

Figure B. 51: Inundation map of Cliff Head (North) - 1,100 and 500 year ARI in 2070 (0.5m SLR)

Figure B. 52: Integrated inundation map of Cliff Head (North) in 2070 (0.5m SLR)

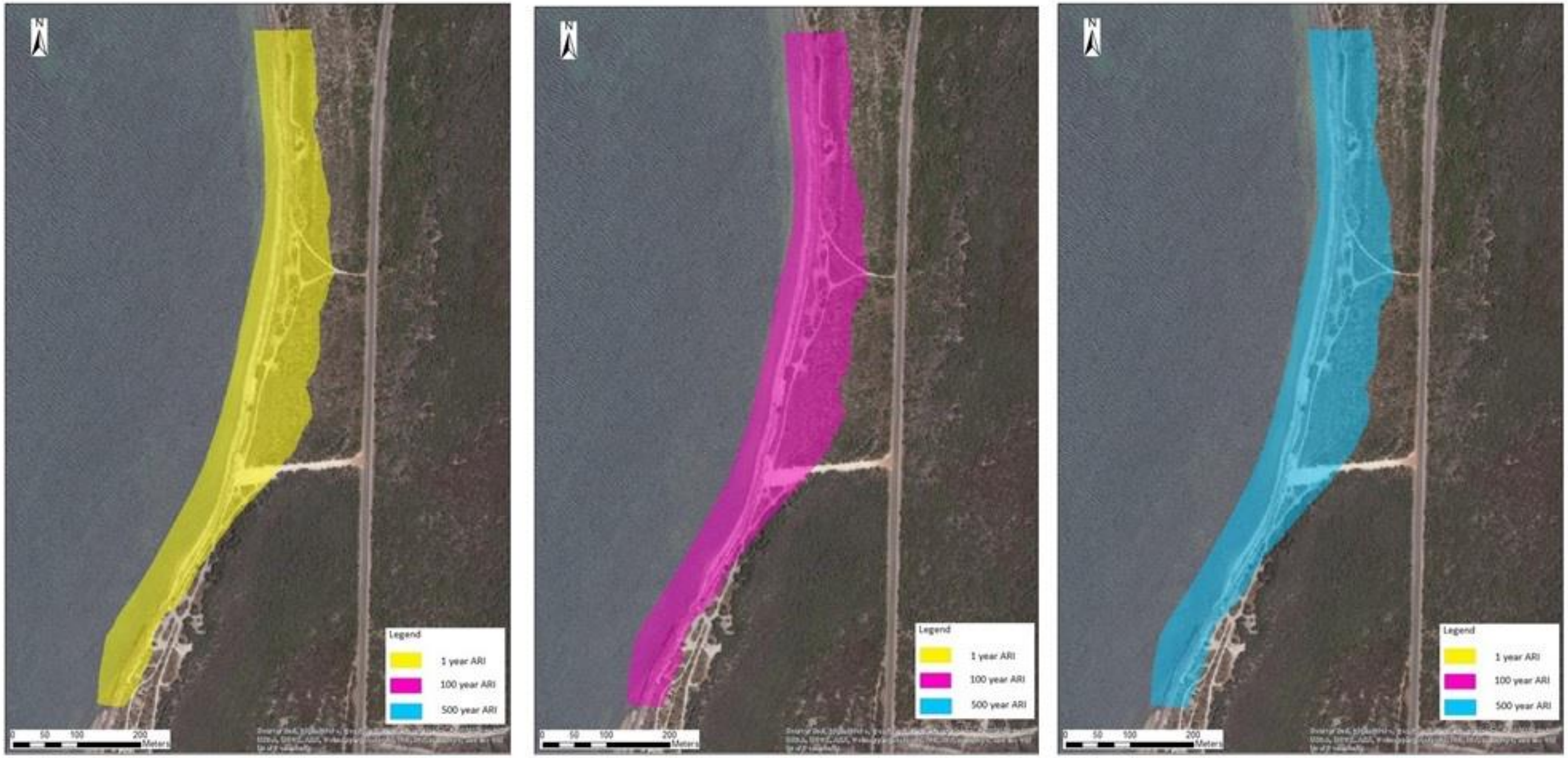

Figure B. 53: Inundation map of Cliff Head (North) - 1,100 and 500 year ARI in 2110(0.9m SLR)

Figure B. 54: Integrated inundation map of Cliff Head (North) in 2110 (0.9m SLR)

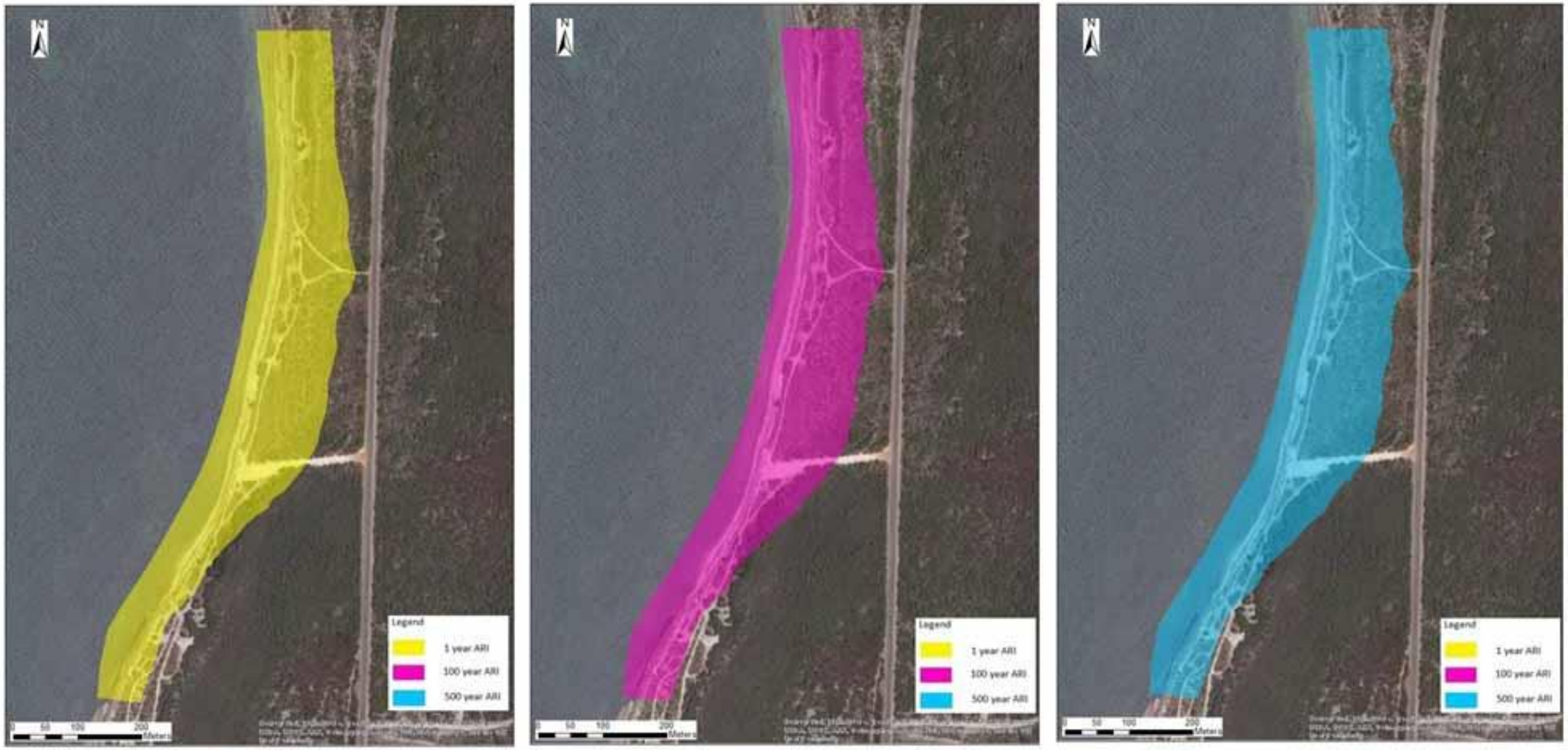

Figure B. 55: Inundation map of Cliff Head (North) - 1, 100 and 500 year ARI in 2110 (1.5m SLR)

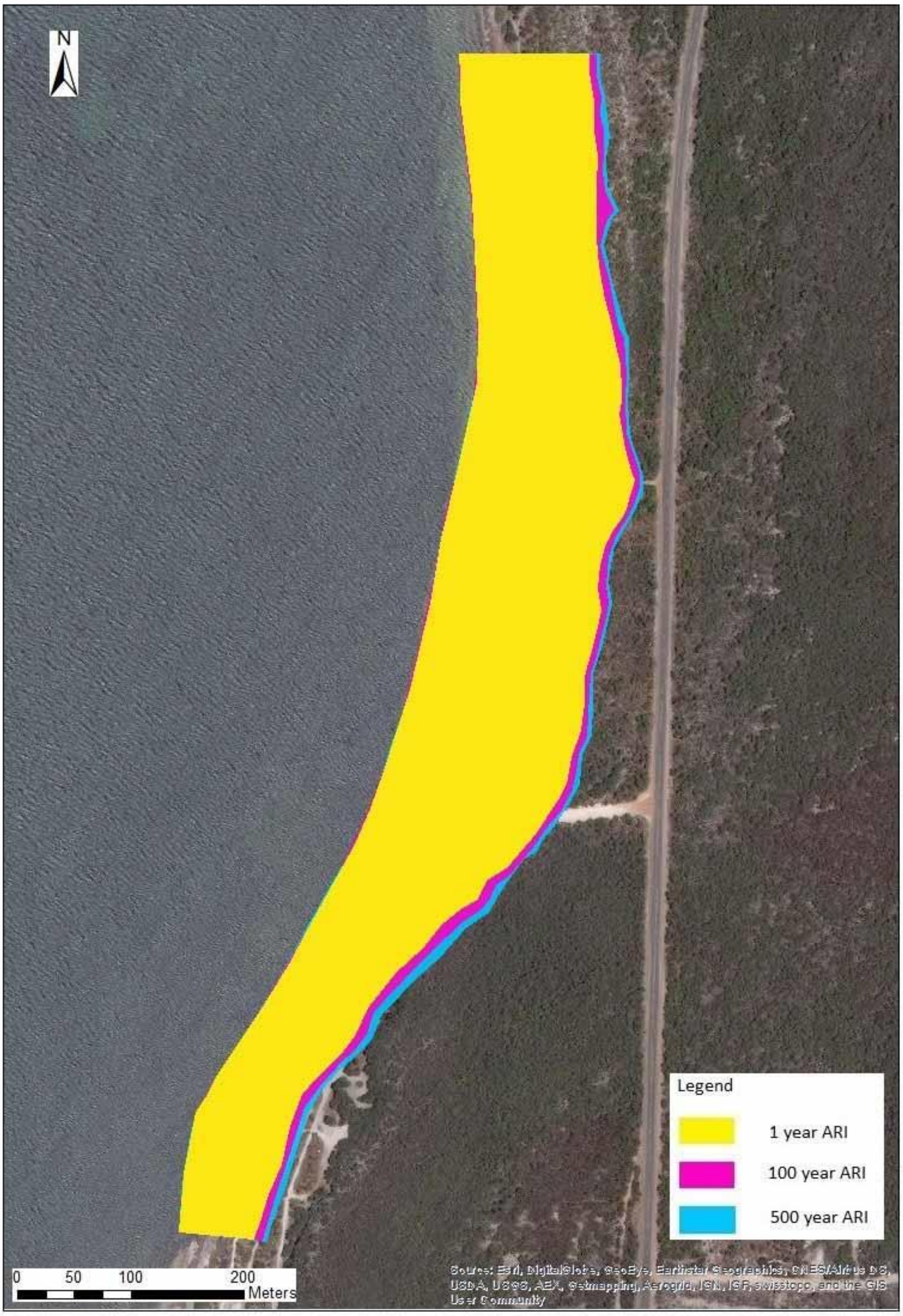

Figure B. 56: Integrated inundation map of Cliff Head (North) in 2110 (1.5m SLR)

Cliff Head (South)

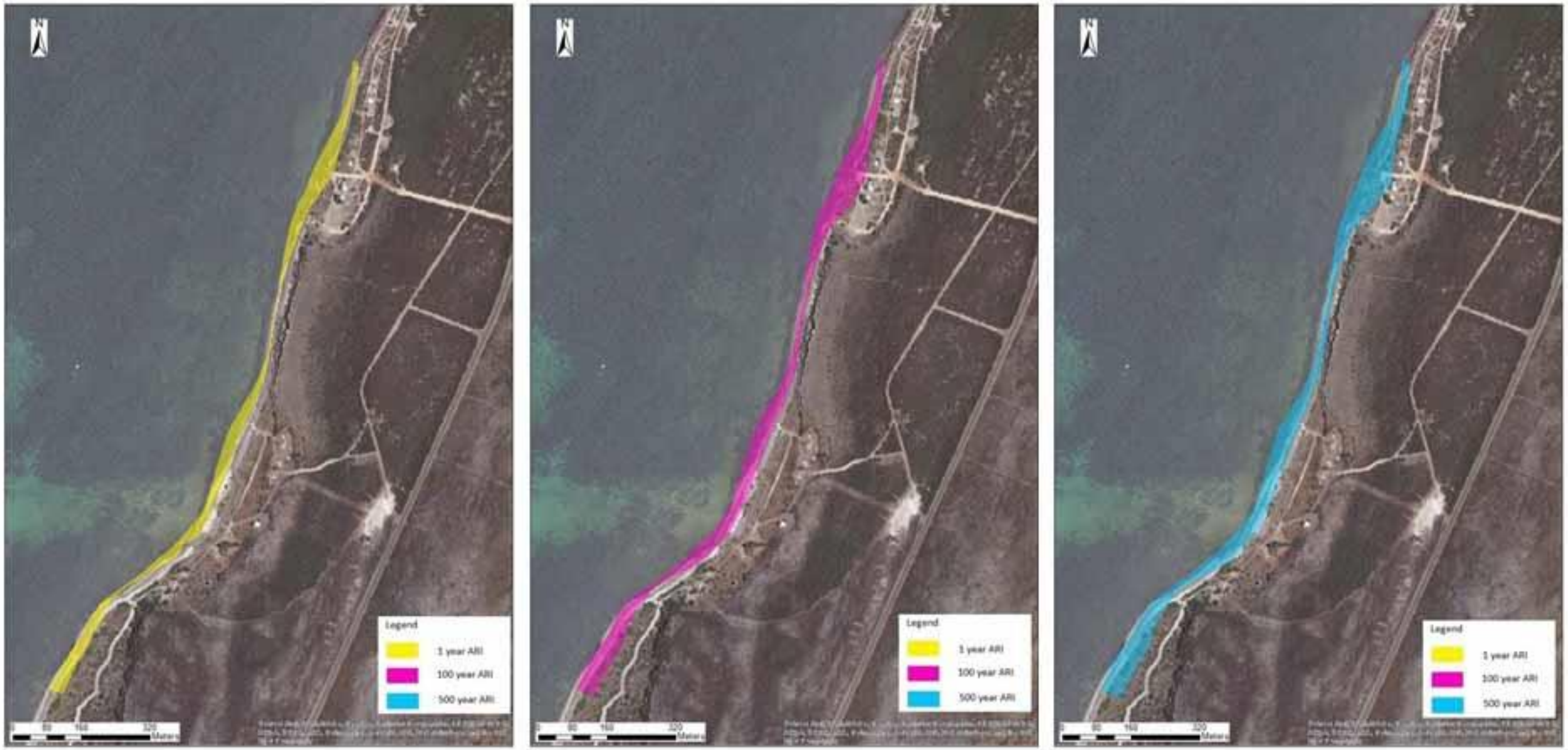

Figure B. 57: Inundation map of Cliff Head (South) 1,100 and 500 year ARI event at present (0.0m SLR)

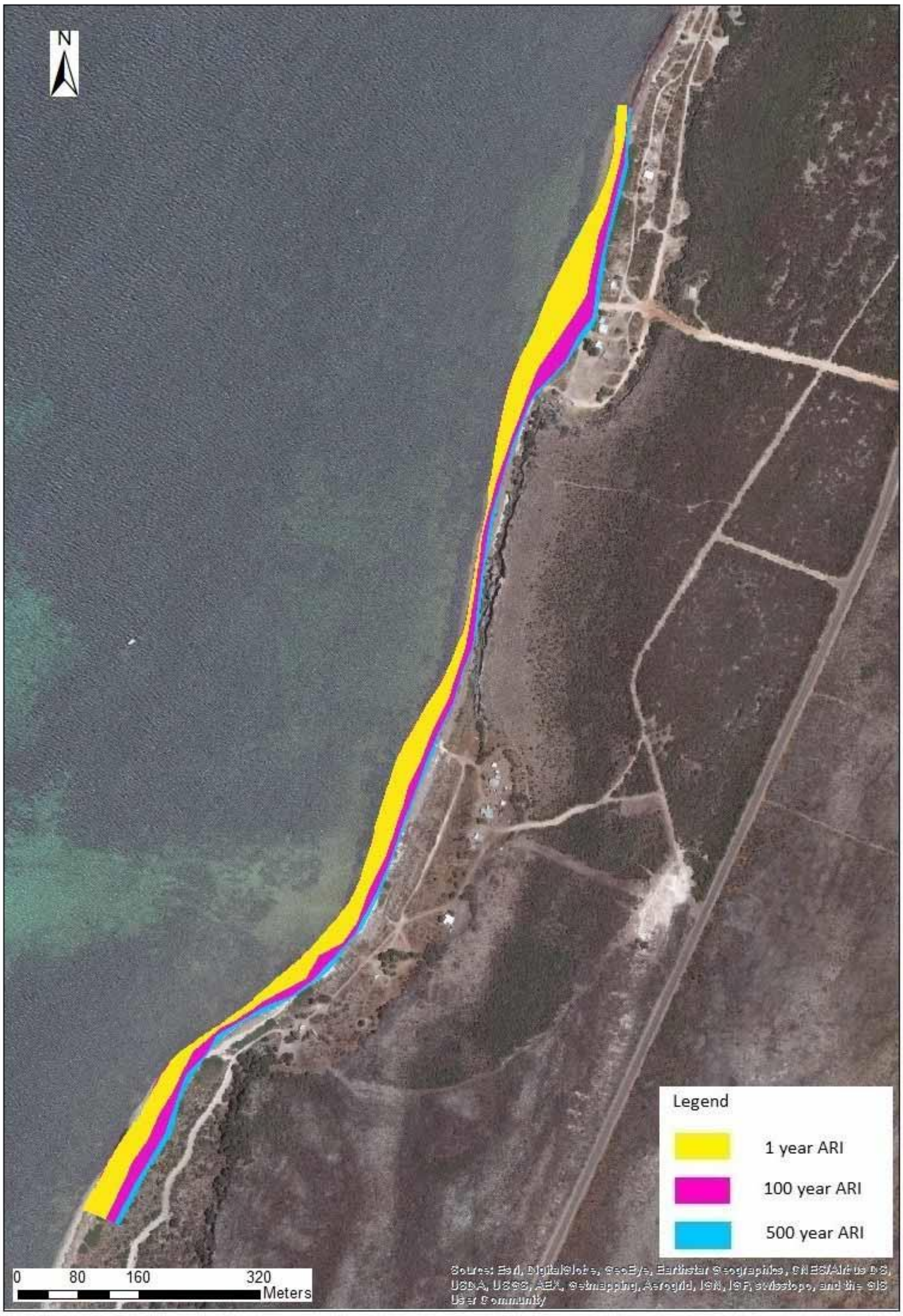

Figure B. 58: Integrated inundation map of Cliff Head (South) at present (0.0m SLR)

Figure B. 59: Inundation map of Cliff Head (South) -1,100 and 500 year ARI in 2070 (0.5m SLR)

Figure B. 60: Integrated inundation map of Cliff Head (South) in 2070 (0.5m SLR)

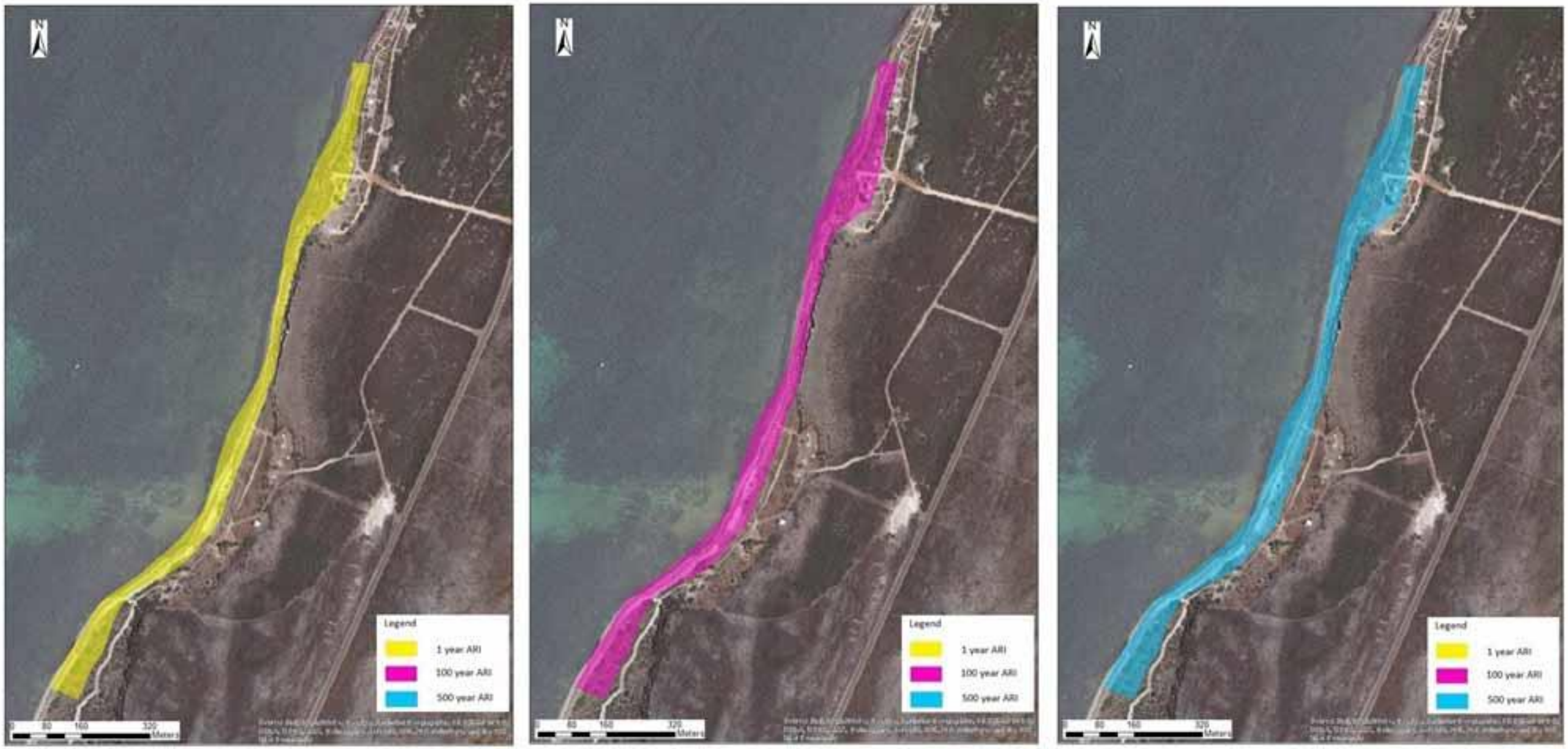

Figure B. 61: Inundation map of Cliff Head (South) -1,100 and 500 year ARI in 2110 (0.9m SLR)

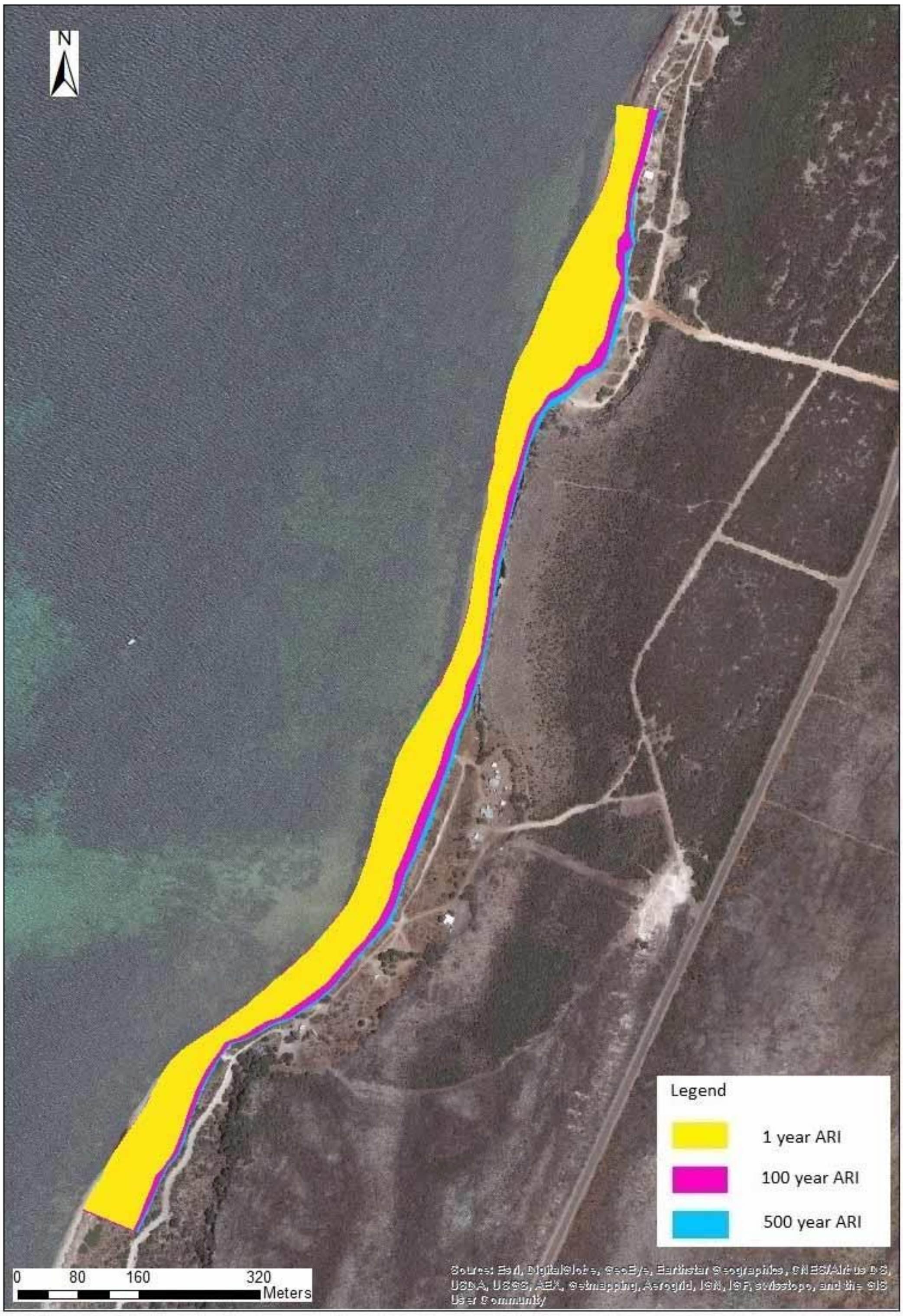

Figure B. 62: Integrated inundation map of Cliff Head (South) in 2110 (0.9m SLR)

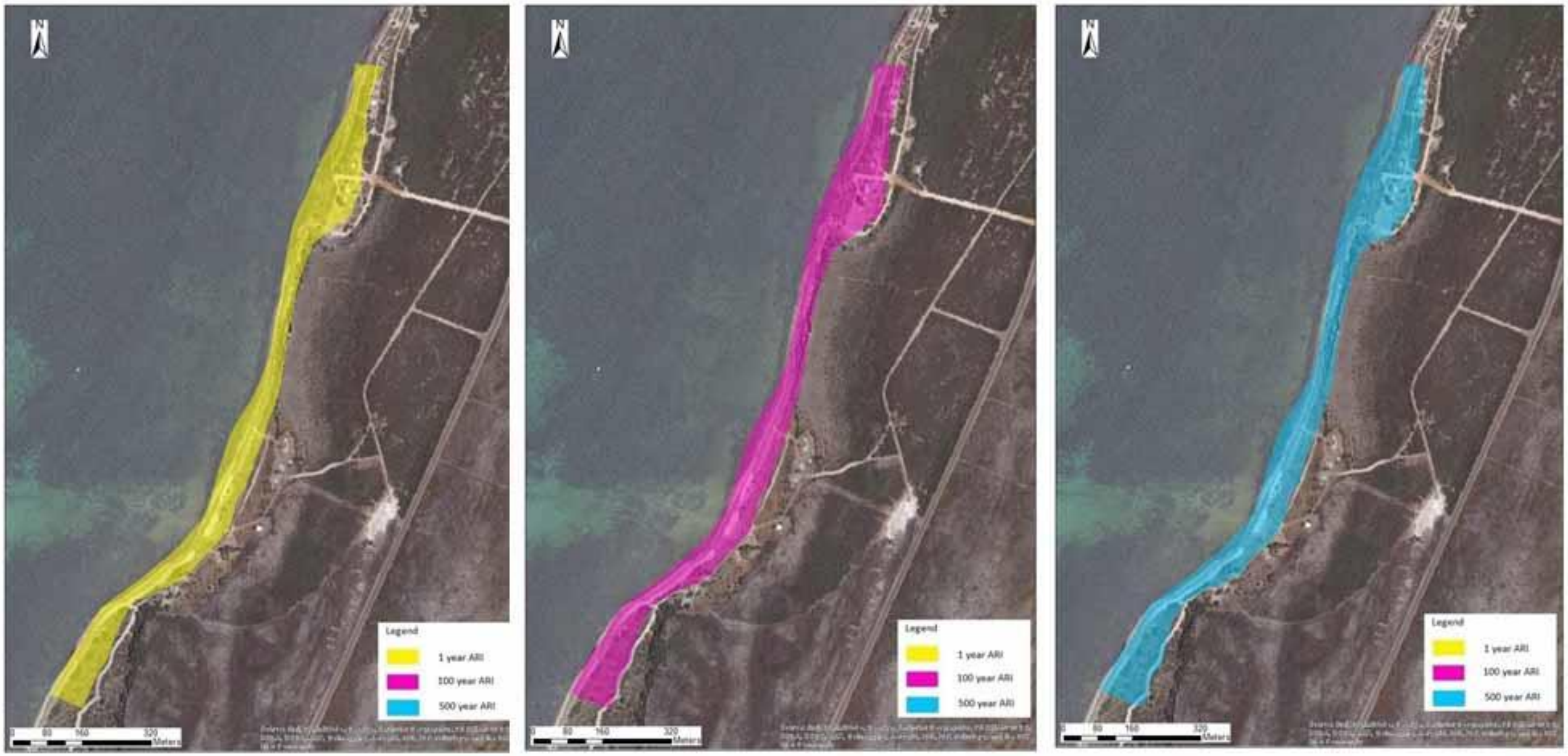

Figure B. 63: Inundation map of Cliff Head (South) -1,100 and 500 year ARI in 2110 (1.5m SLR)

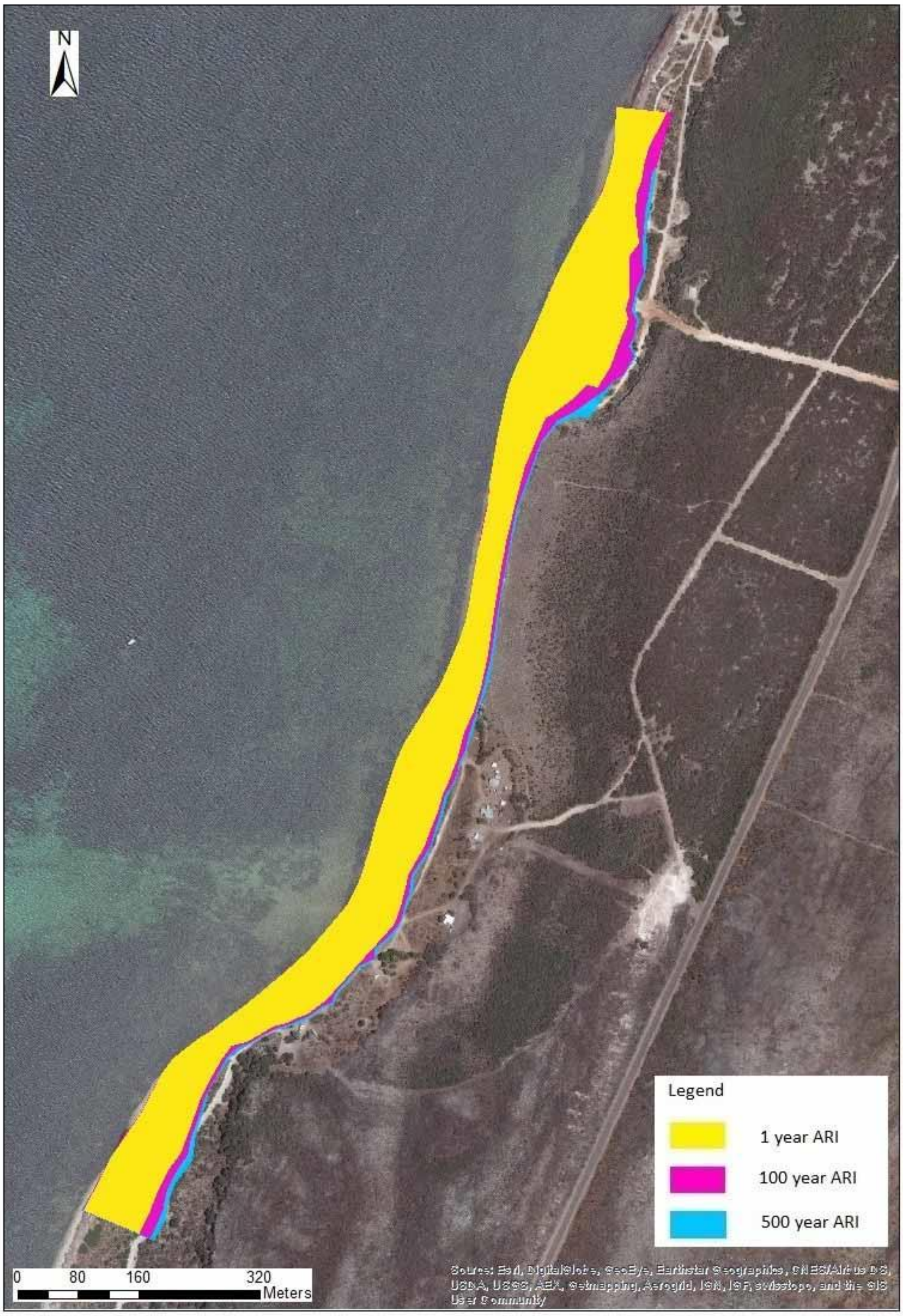

Figure B. 64: Integrated inundation map of Cliff Head (South) in 2110 (1.5m SLR)

Appendix C

Erosion Maps

South Beach (North)

Figure C. 1: Erosion map of South Beach (North) -1, 100 and 500 year ARI at present (0m SLR)

Figure C. 2: Integrated erosion map of South Beach (North) at present (0m SLR)

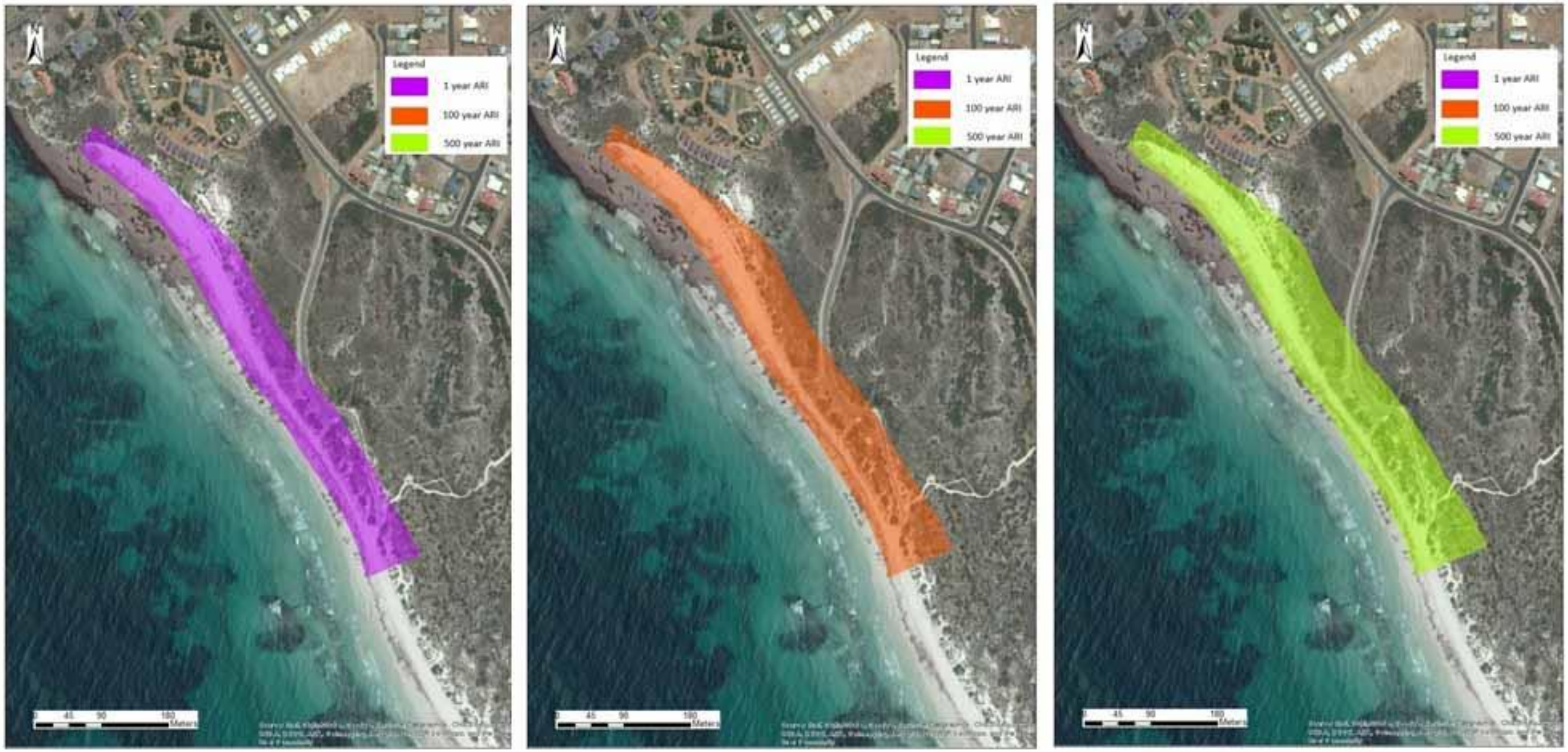

Figure C. 3: Erosion map of South Beach (North) -1, 100 and 500 year ARI in 2070 (0.5m SLR) + (Shore line movement + allowance for uncertainty)

Figure C. 4: Integrated erosion map of South Beach (North) in 2070 (0.5m SLR) + (Shore line movement + allowance for uncertainty)

Figure C. 5: Erosion map of South Beach (North) -1, 100 and 500 year ARI in 2110 (0.9m SLR) + (Shore line movement + allowance for uncertainty)

Figure C. 6: Integrated erosion map of South Beach (North) in 2110 (0.9m SLR) + (Shore line movement + allowance for uncertainty)

Figure C. 7: Erosion map of South Beach (North) -1, 100 and 500 year ARI in 2110 (1.5m SLR) + (Shore line movement + allowance for uncertainty)

Figure C. 8: Integrated erosion map of South Beach (North) -500 in 2110 (1.5m SLR) + (Shore line movement + allowance for uncertainty)

South Beach (South)

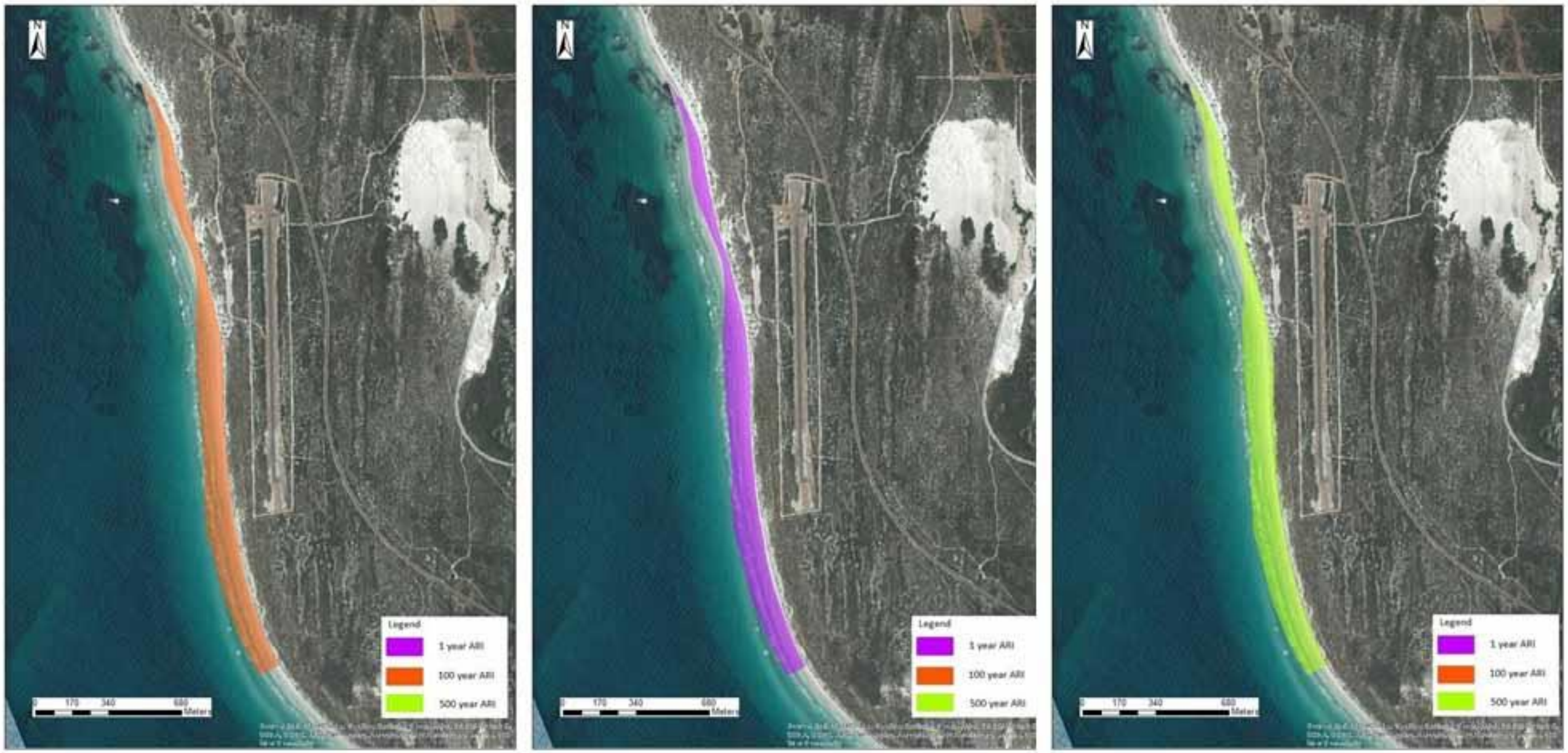

Figure C. 9: Erosion map of South Beach (South) -1, 100 and 500 year ARI at present (0m SLR)

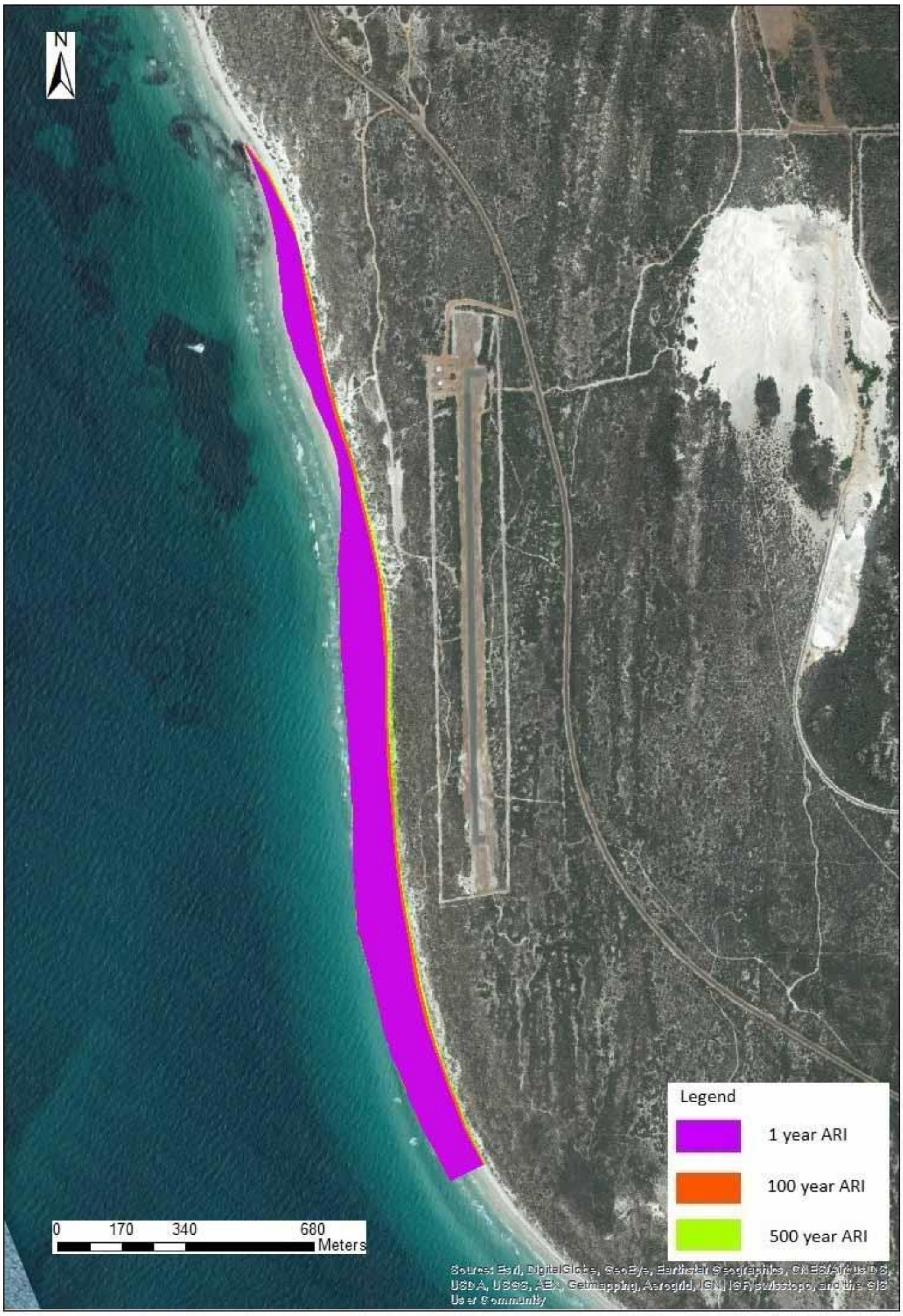

Figure C. 10: Integrated erosion map of South Beach (South) at present (0m SLR)

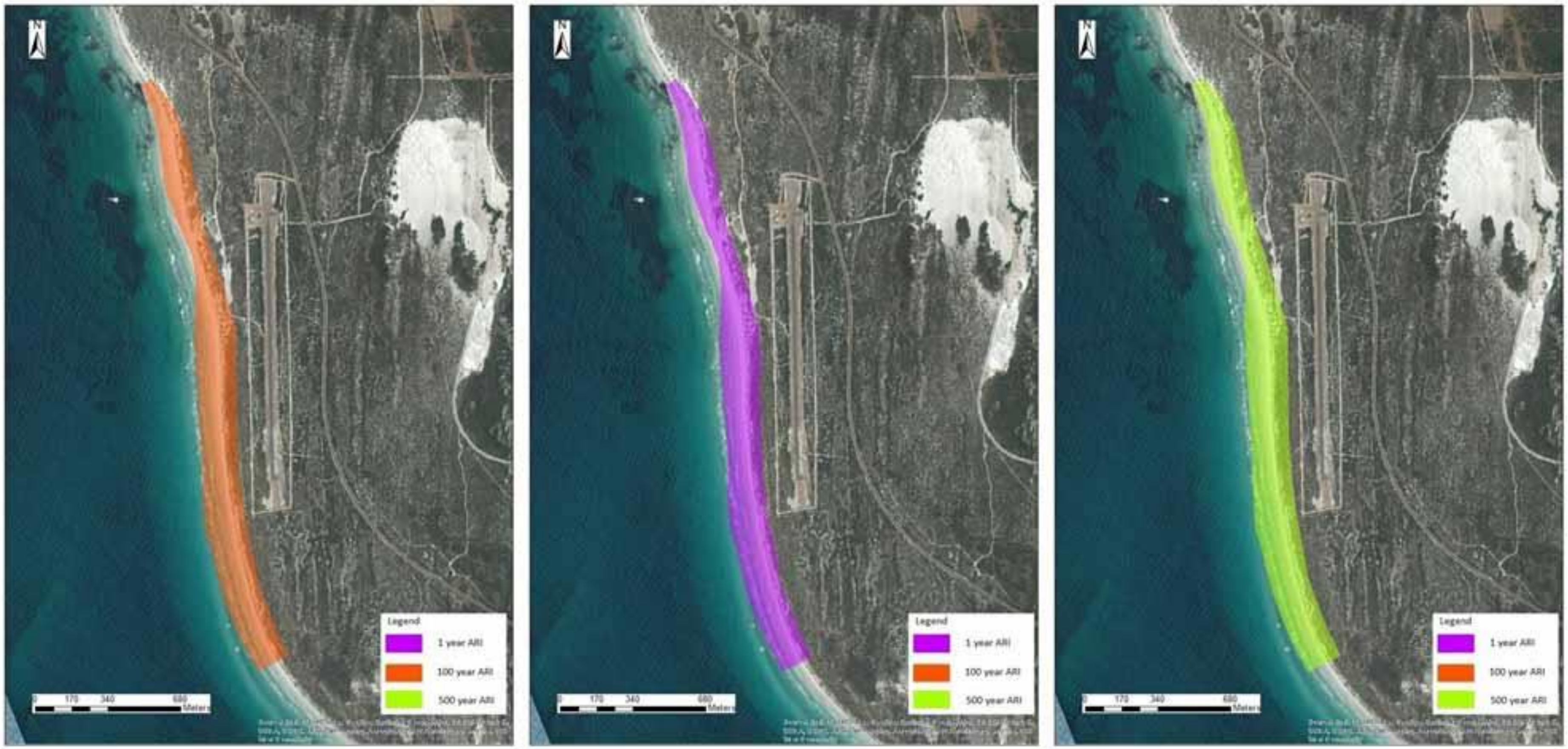

Figure C. 11: Erosion map of South Beach (South) -1, 100 and 500 year ARI in 2070 (0.5m SLR) + (Shore line movement + allowance for uncertainty)

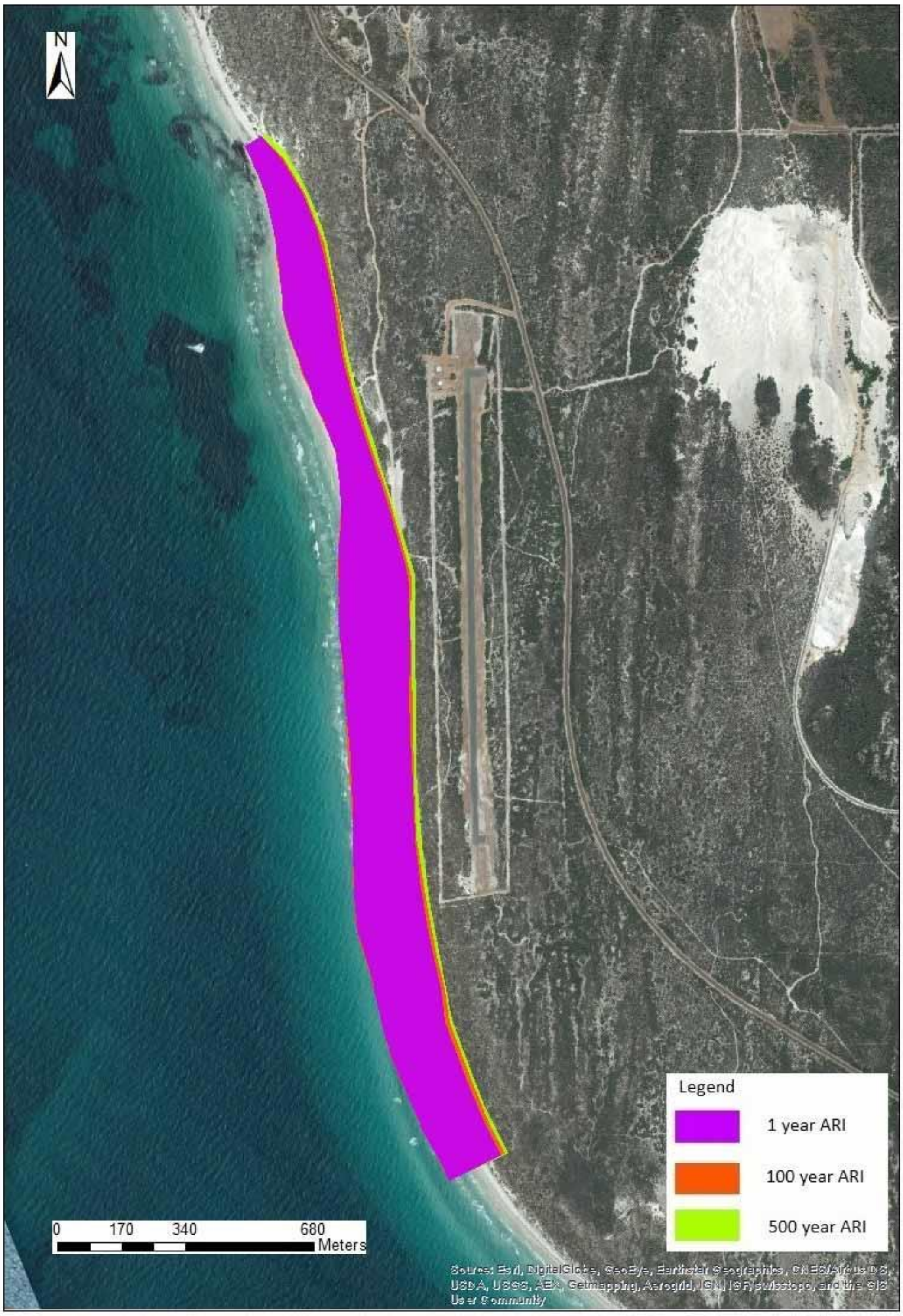

Figure C. 12: Integrated erosion map of South Beach (South) in 2070 (0.5m SLR) + (Shore line movement + allowance for uncertainty)

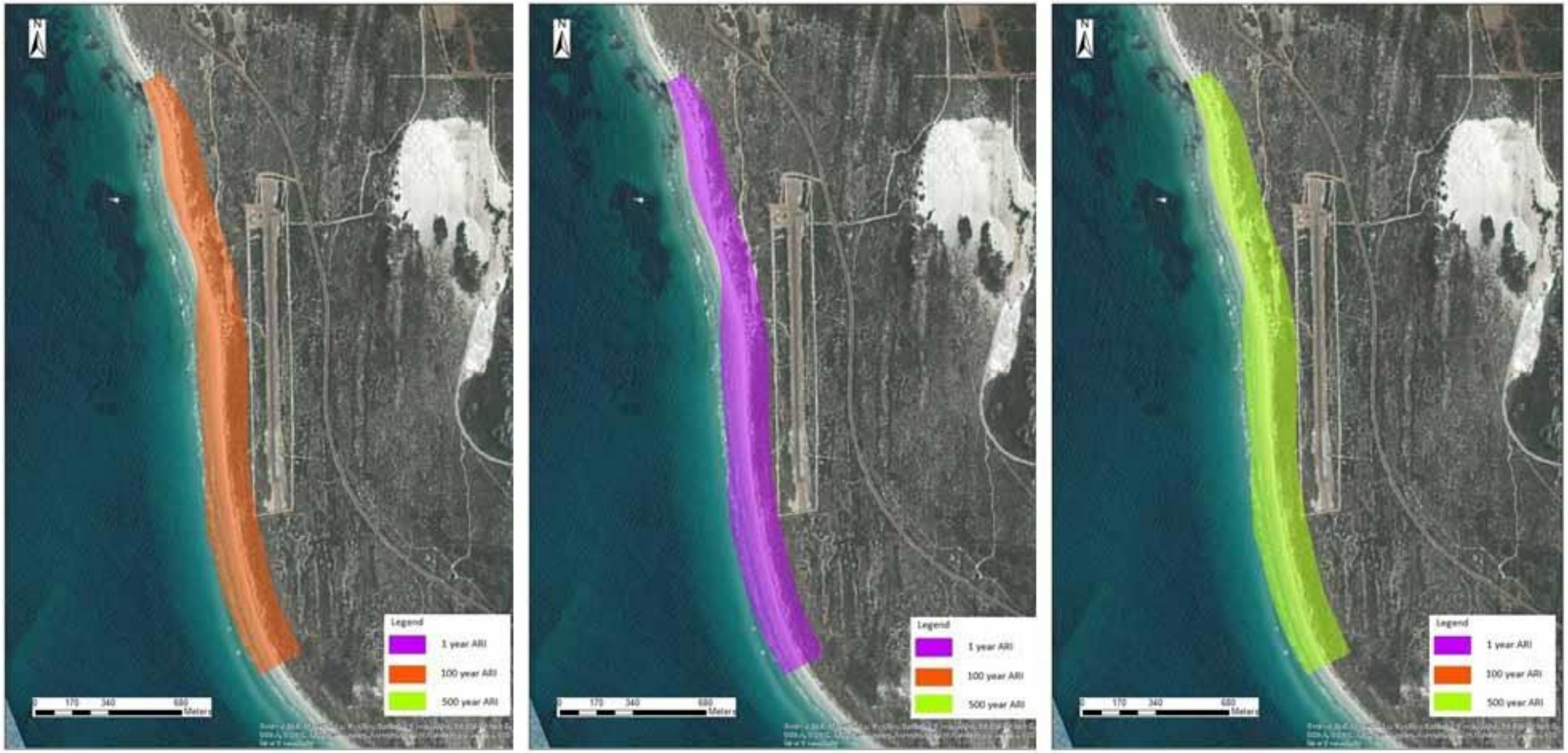

Figure C. 13: Erosion map of South Beach (South) -1, 100 and 500 year ARI in 2110 (0.9m SLR) + (Shore line movement + allowance for uncertainty)

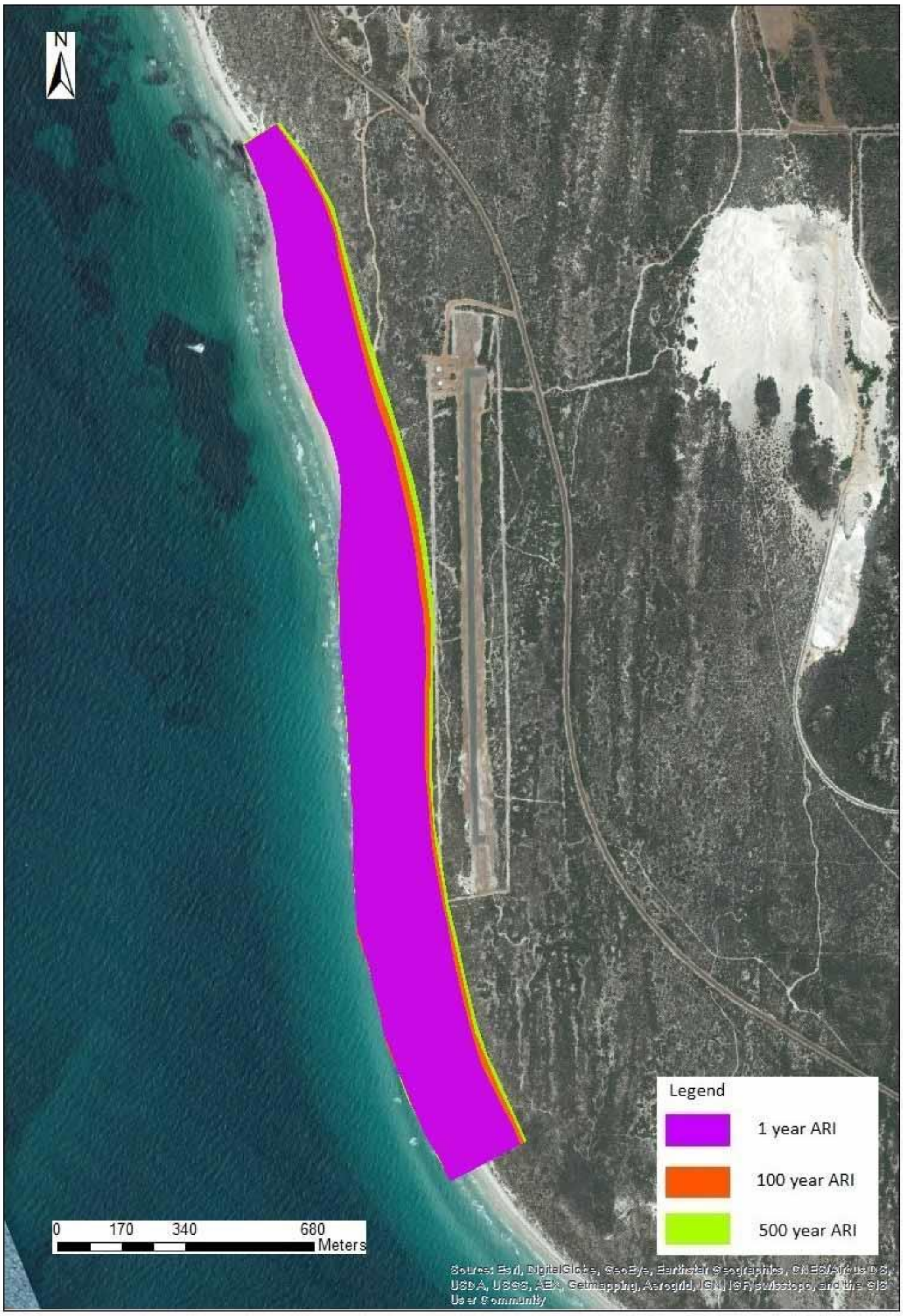

Figure C. 14: Integrated erosion map of South Beach (South) in 2110 (0.9m SLR) + (Shore line movement + allowance for uncertainty)

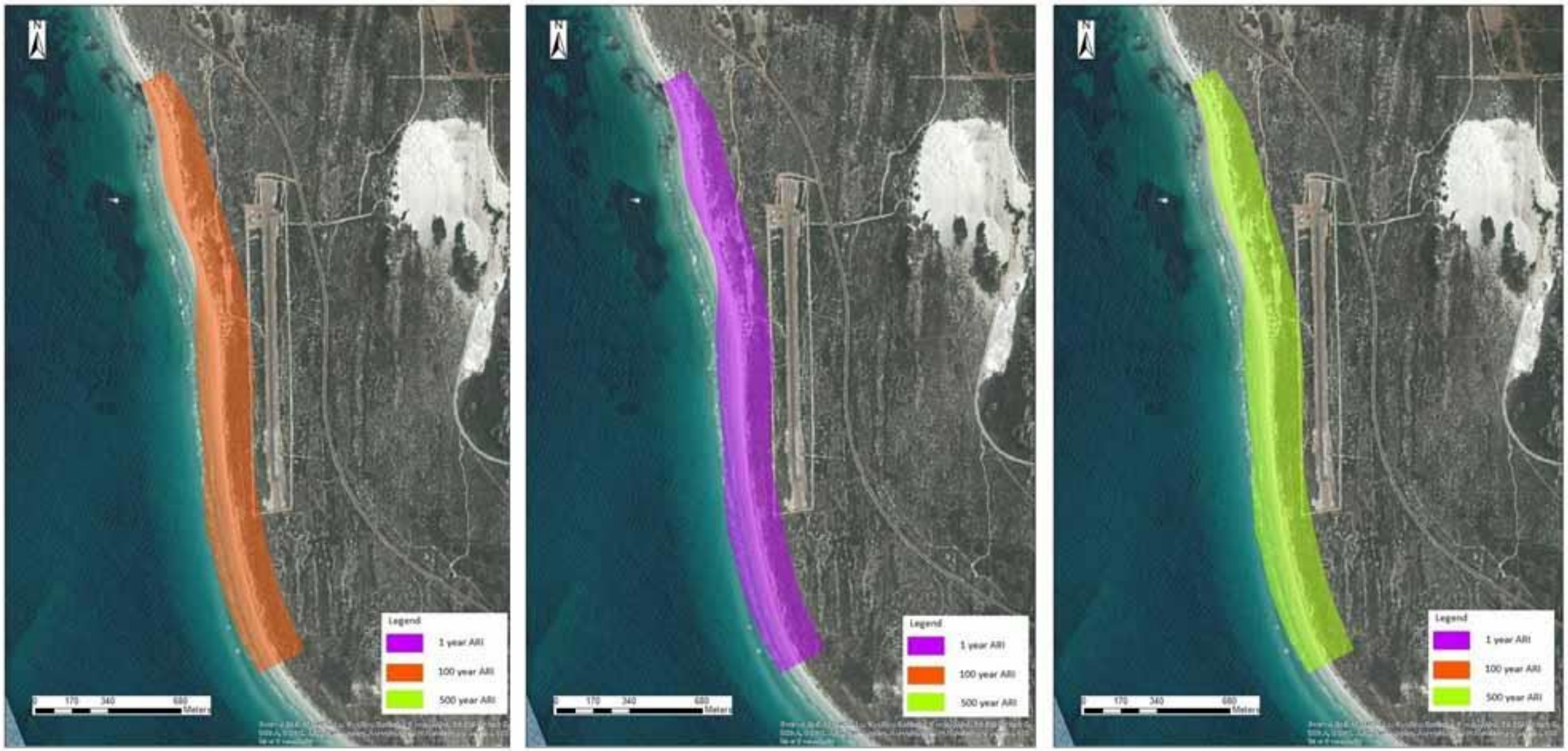

Figure C. 15: Erosion map of South Beach (South)-1, 100 and 500 year ARI in 2110 (1.5m SLR) + (Shore line movement + allowance for uncertainty)

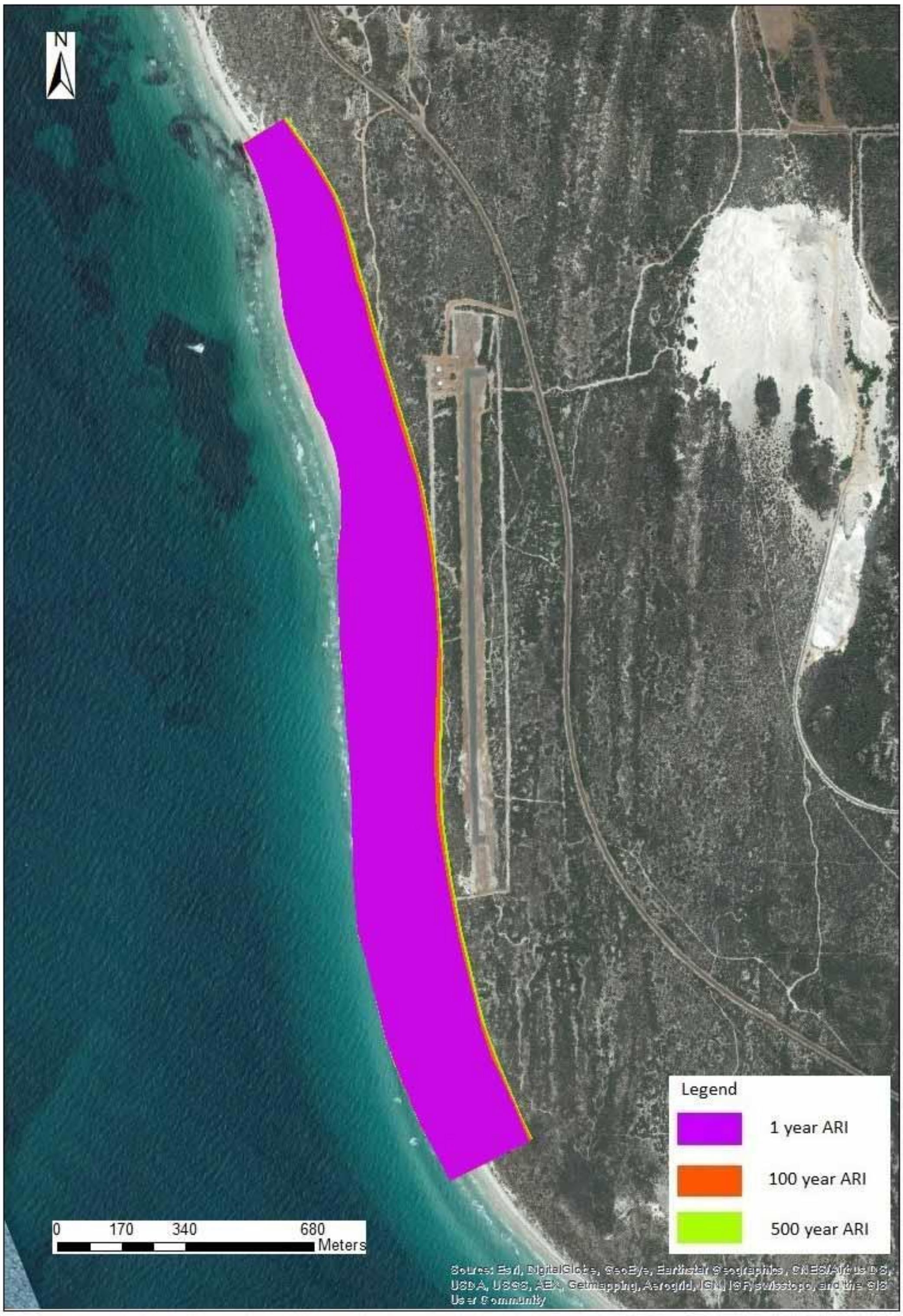

Figure C. 16: Integrated erosion map of South Beach (South) -500 in 2110 (1.5m SLR) + (Shore line movement + allowance for uncertainty)

Seaspray Beach/Irwin River

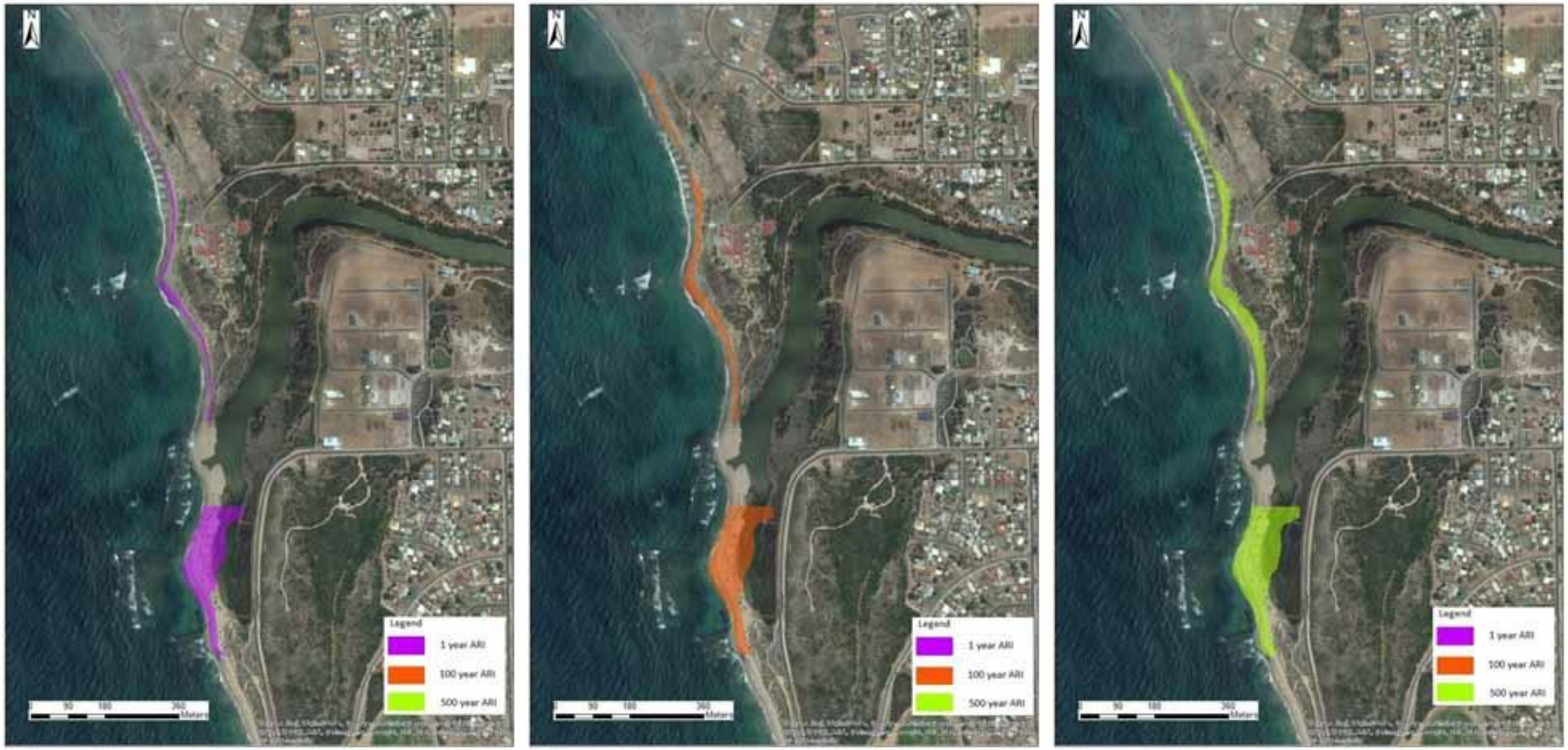

Figure C. 17: Erosion map of Seaspray Beach-1, 100 and 500 year ARI at present (0.0m SLR)

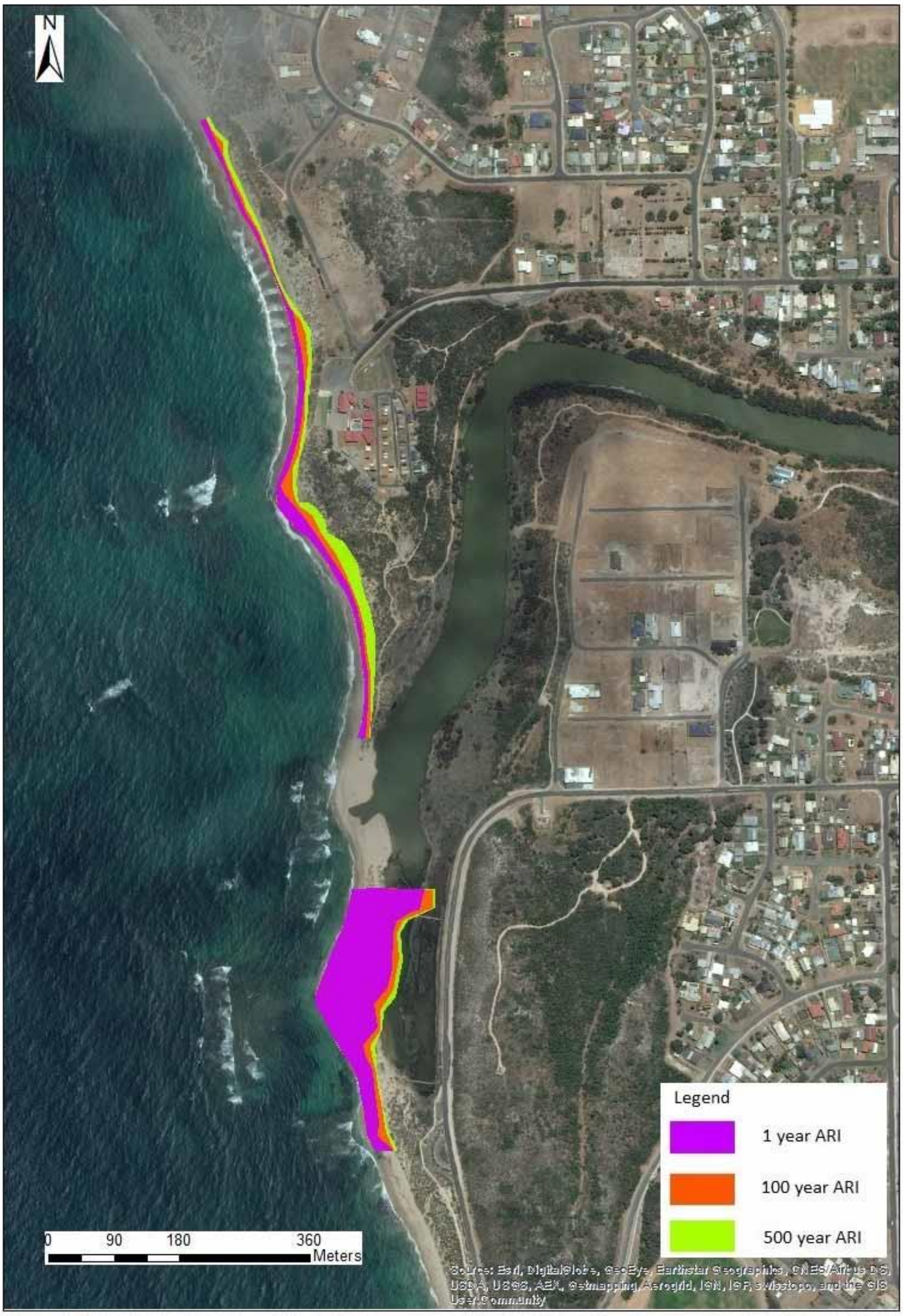

Figure C. 18: Integrated erosion map of Seaspray Beach at present (0.0m SLR)

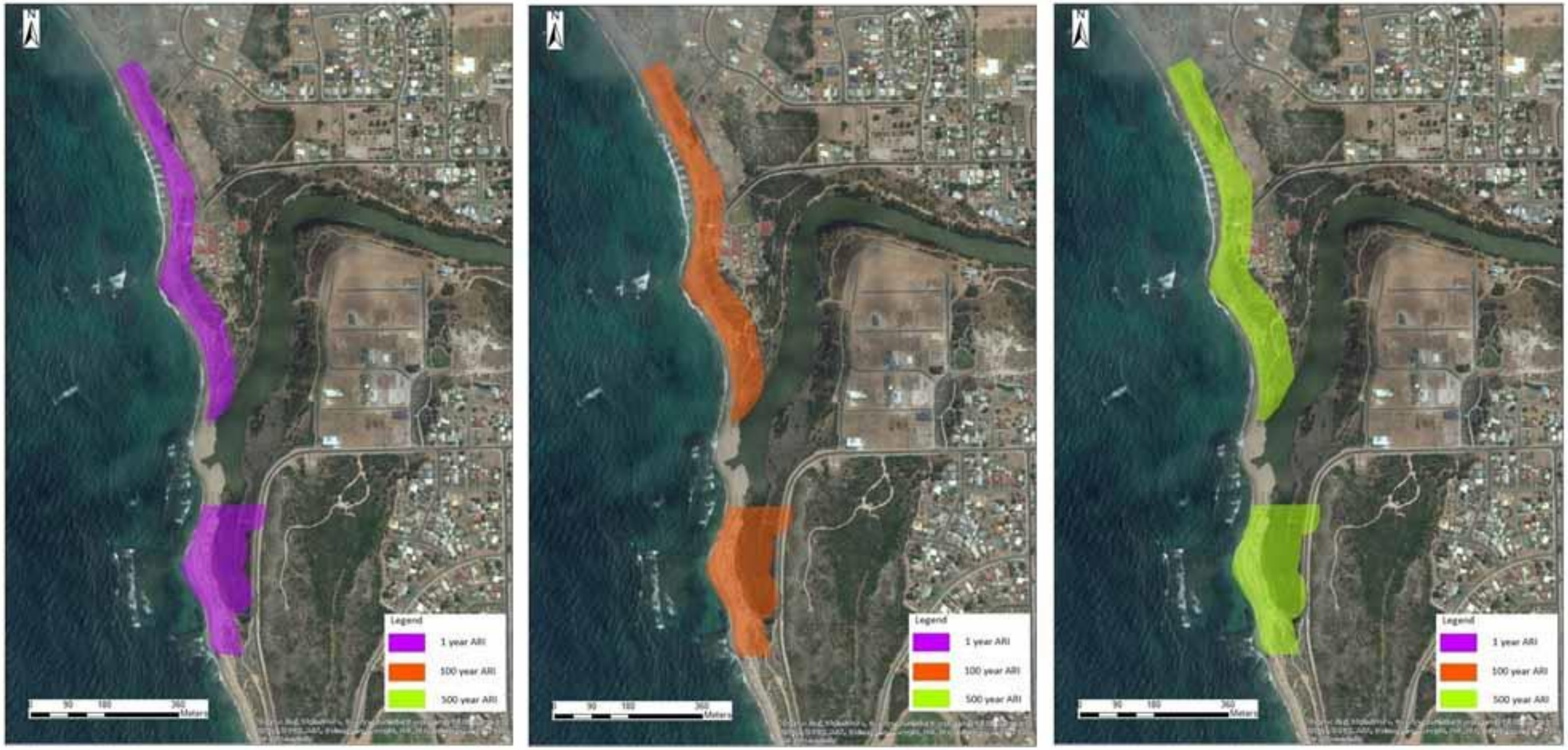

Figure C. 19: Erosion map of Seaspray Beach- 1, 100 and 500 year ARI in 2070 (0.5m SLR) + (Shore line movement + allowance for uncertainty)

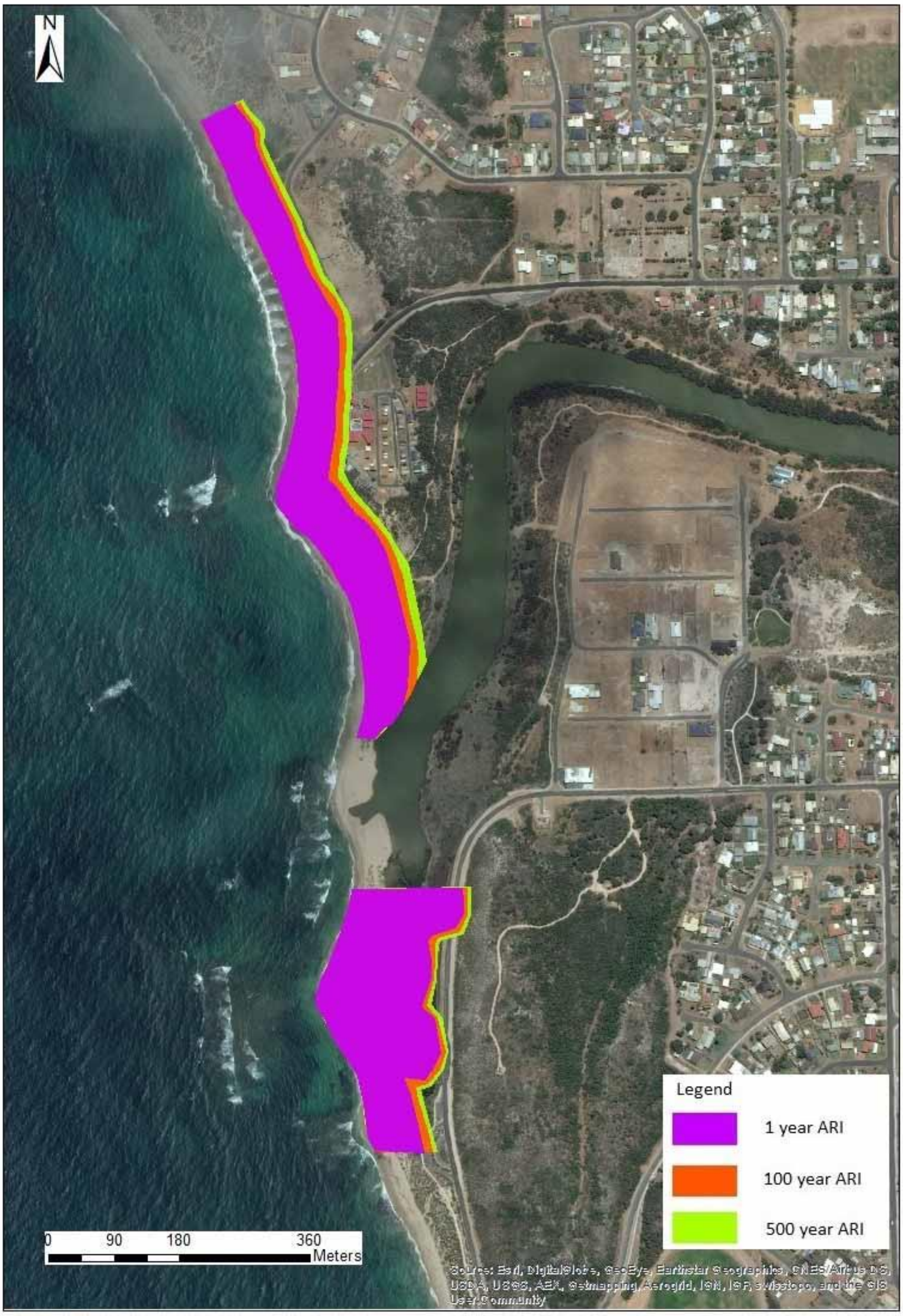

Figure C. 20: Integrated erosion map of Seaspray Beach in 2070 (0.5m SLR) + (Shore line movement + allowance for uncertainty)

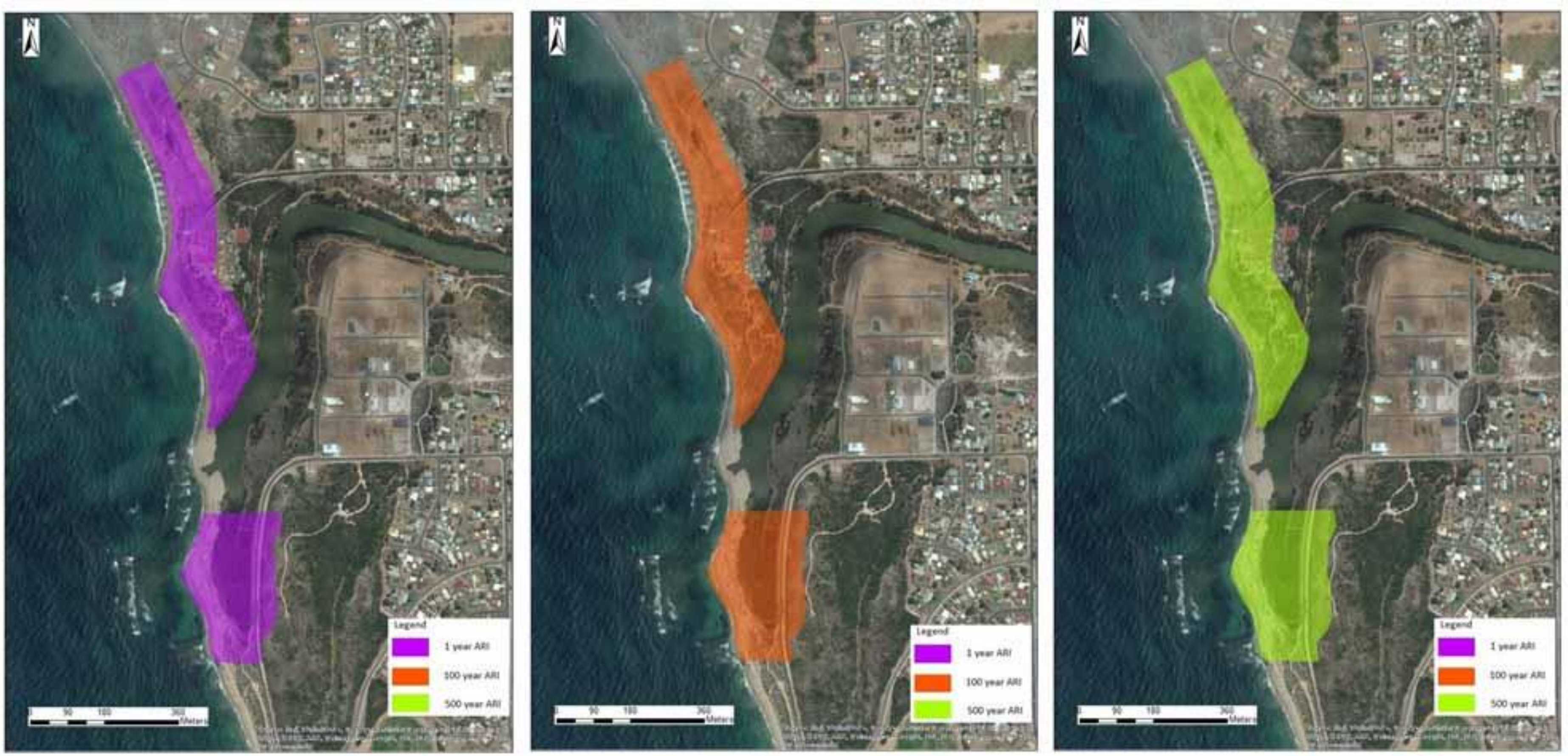

Figure C. 21: Erosion map of Seaspray Beach- 1, 100 and 500 year ARI in 2110(0.9m SLR) + (Shore line movement + allowance for uncertainty)

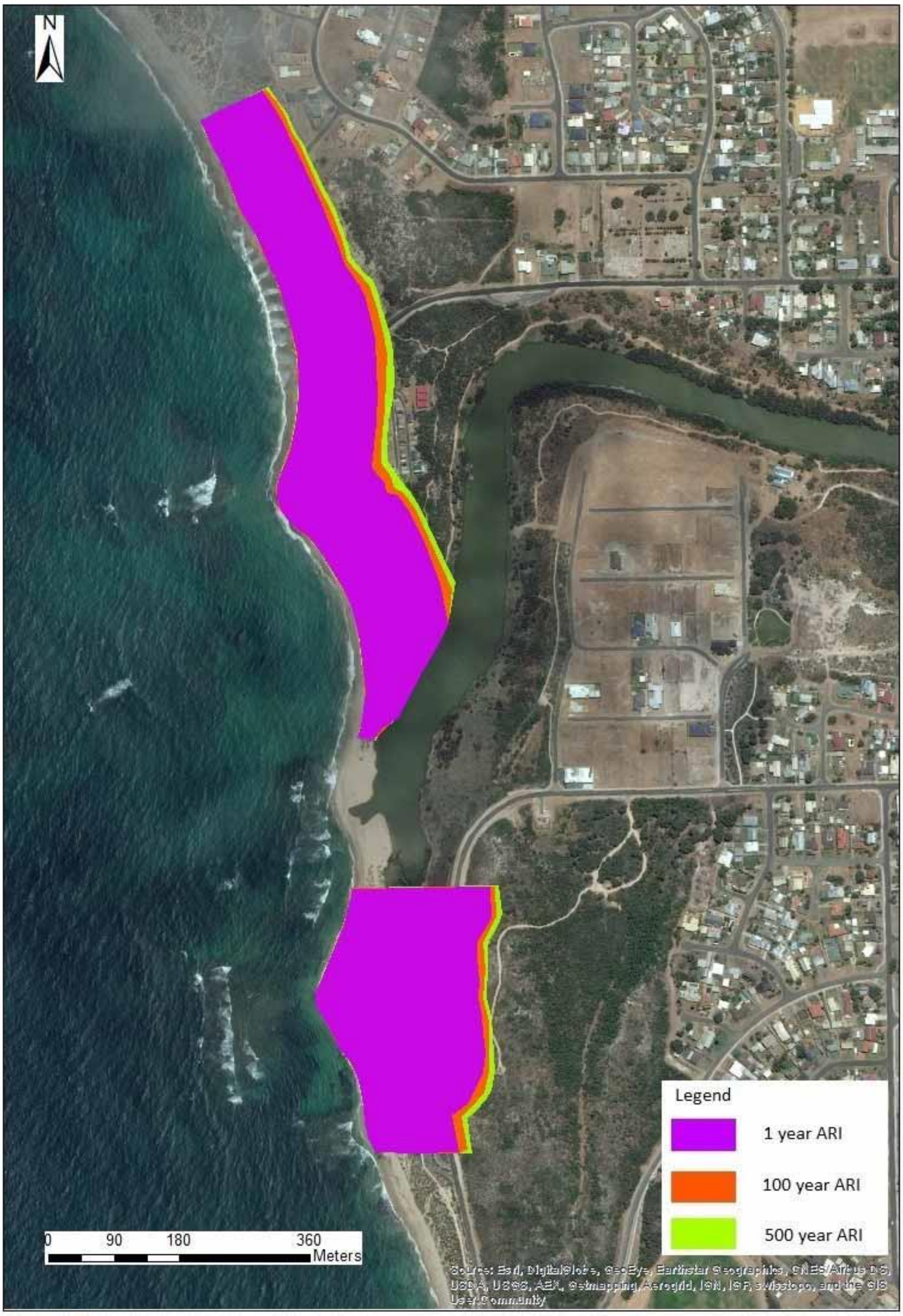

Figure C. 22: Integrated erosion map of Seaspray Beach in 2110(0.9m SLR) + (Shore line movement + allowance for uncertainty)

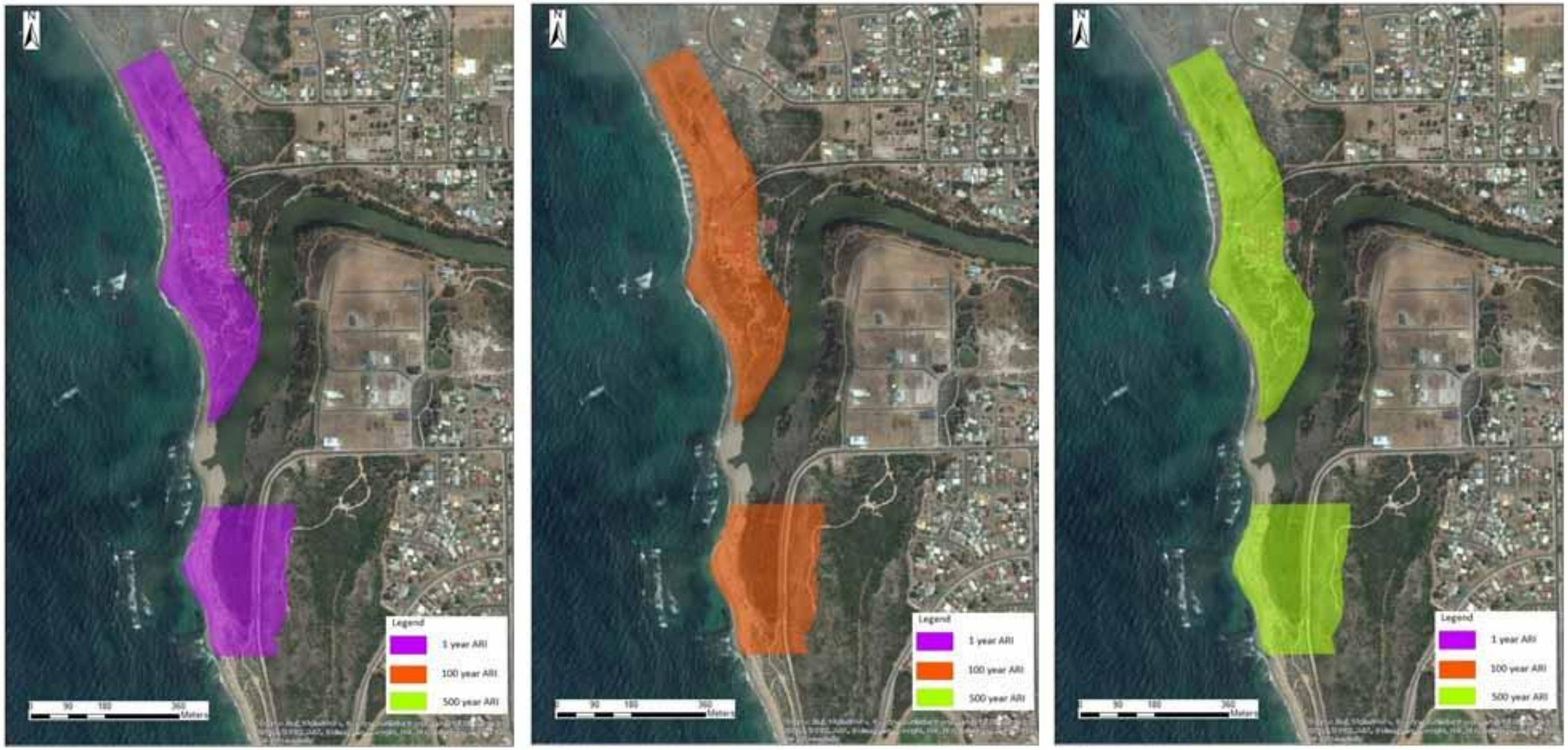

Figure C. 23: Erosion map of Seaspray Beach- 1, 100 and 500 year ARI in 2110(1.5m SLR) + (Shore line movement + allowance for uncertainty)

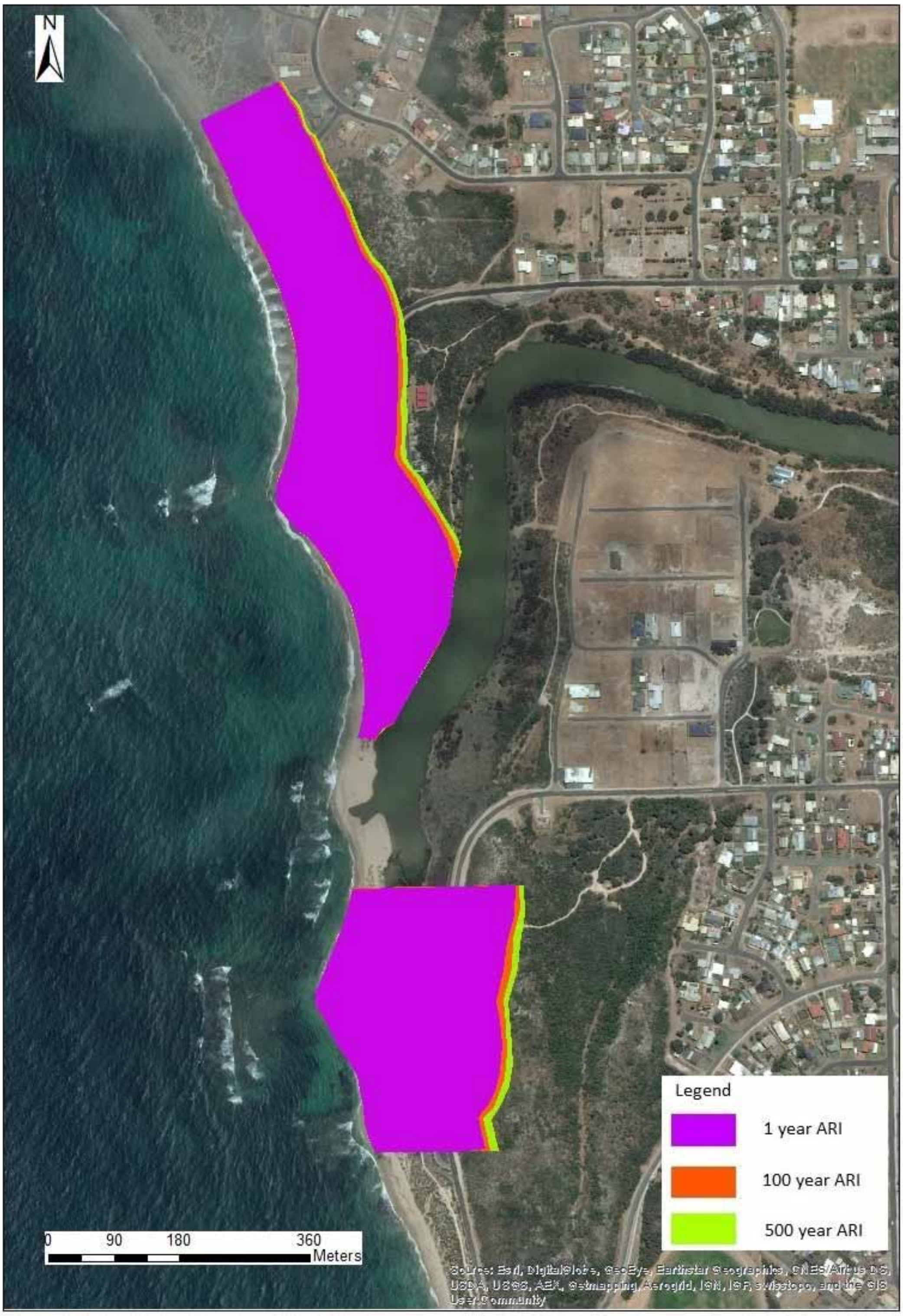

Figure C. 24: Integrated erosion map of Seaspray Beach in 2110(1.5m SLR) + (Shore line movement + allowance for uncertainty)

Seven Mile Beach

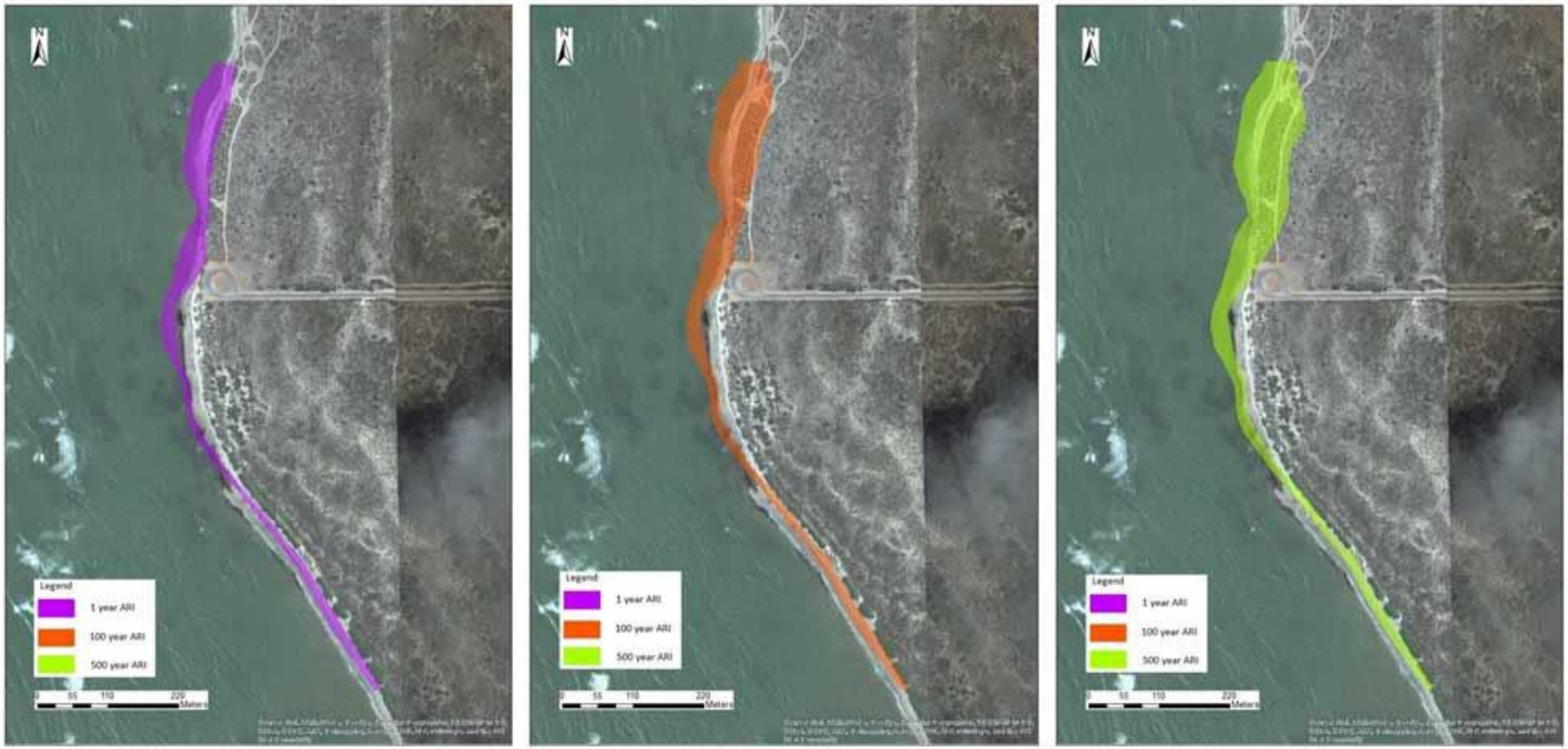

Figure C. 25: Erosion map of Seven Mile Beach- 1, 100 and 500 year ARI at present (0.0m SLR)

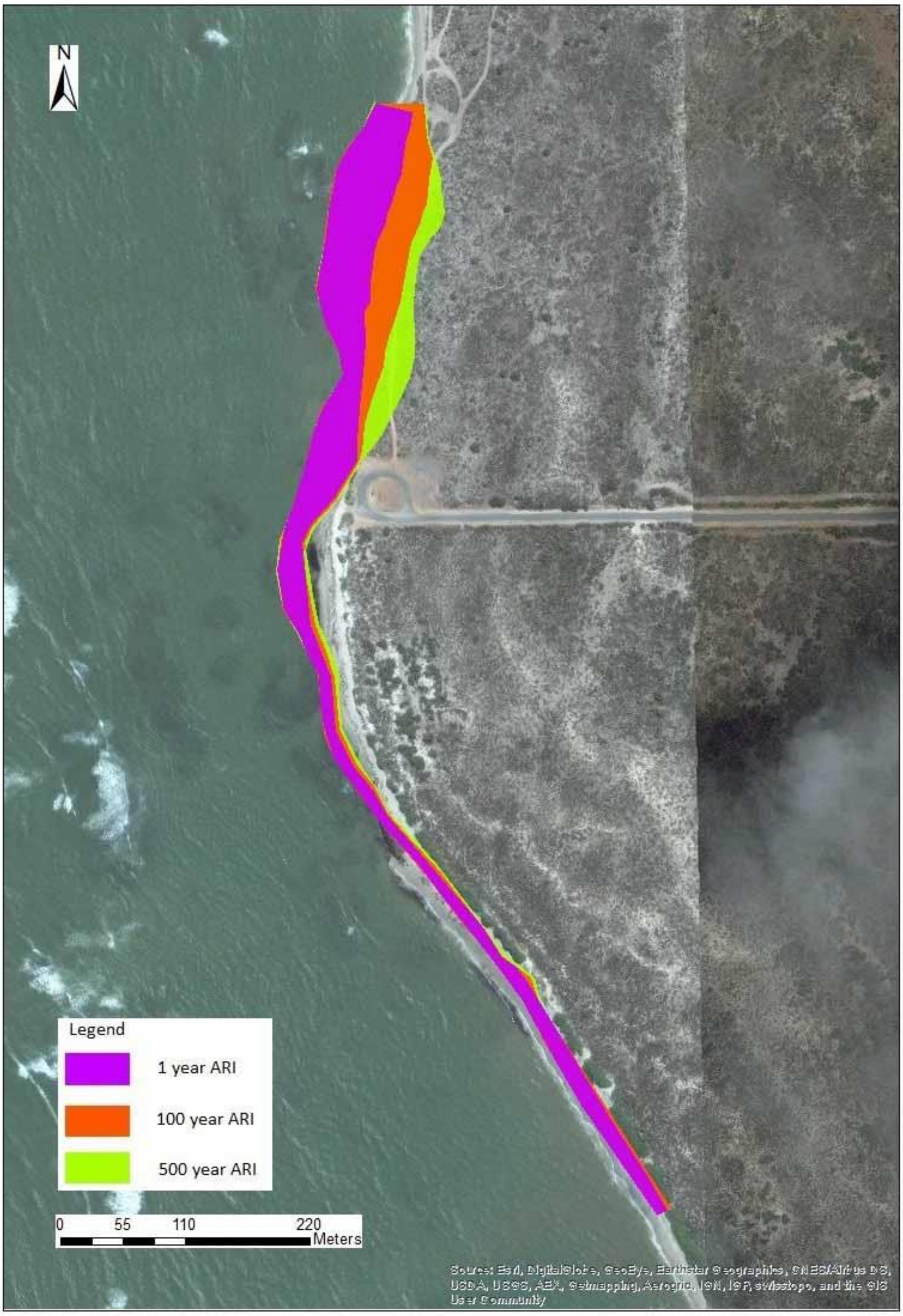

Figure C. 26: Integrated erosion map of Seven Mile Beach at present (0.0m SLR)

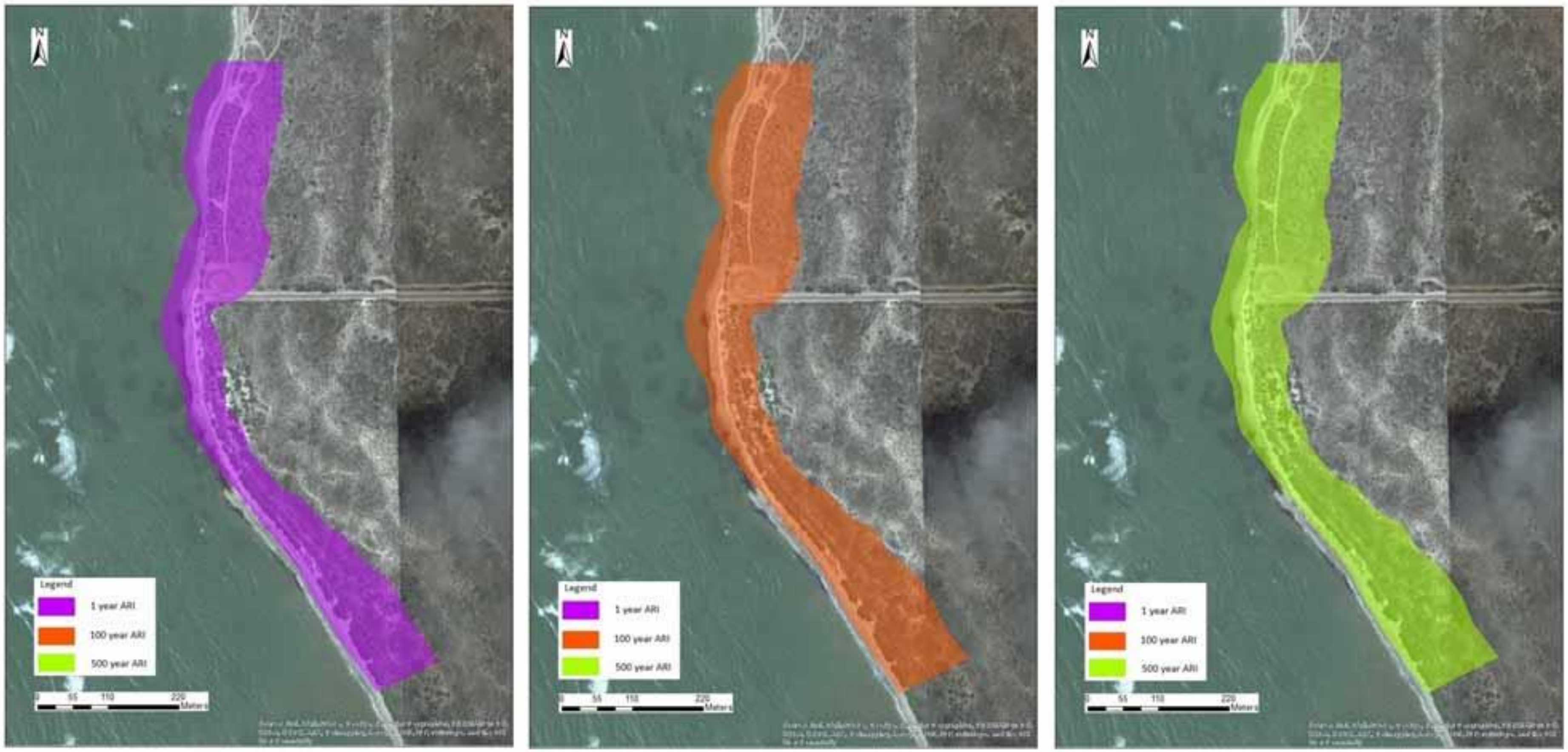

Figure C. 27: Erosion map of Seven Mile Beach- 1, 100 and 500 year ARI in 2070 (0.5m SLR) + (Shore line movement + allowance for uncertainty)

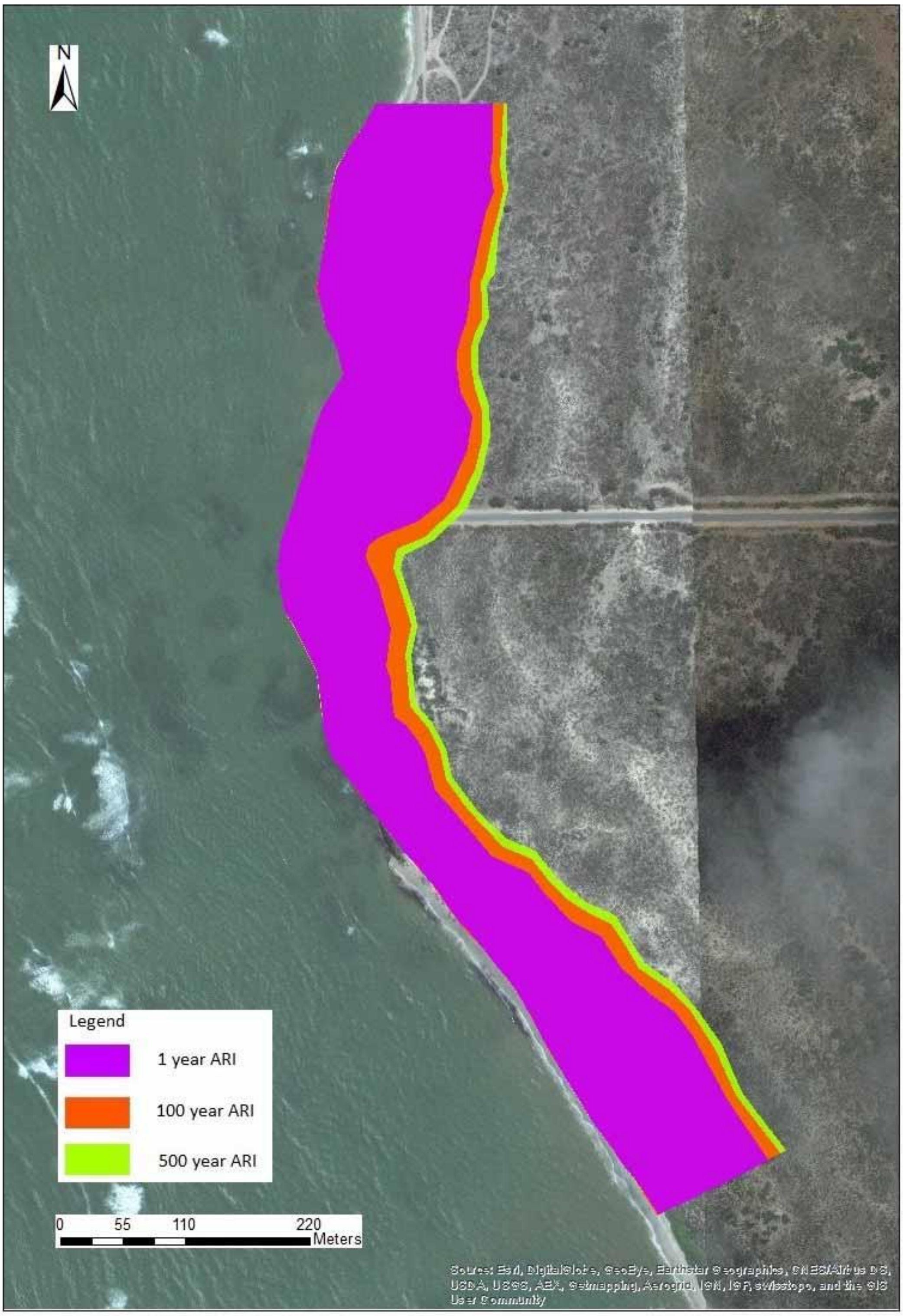

Figure C. 28: Integrated erosion map of Seven Mile Beach in 2070 (0.5m SLR) + (Shore line movement + allowance for uncertainty)

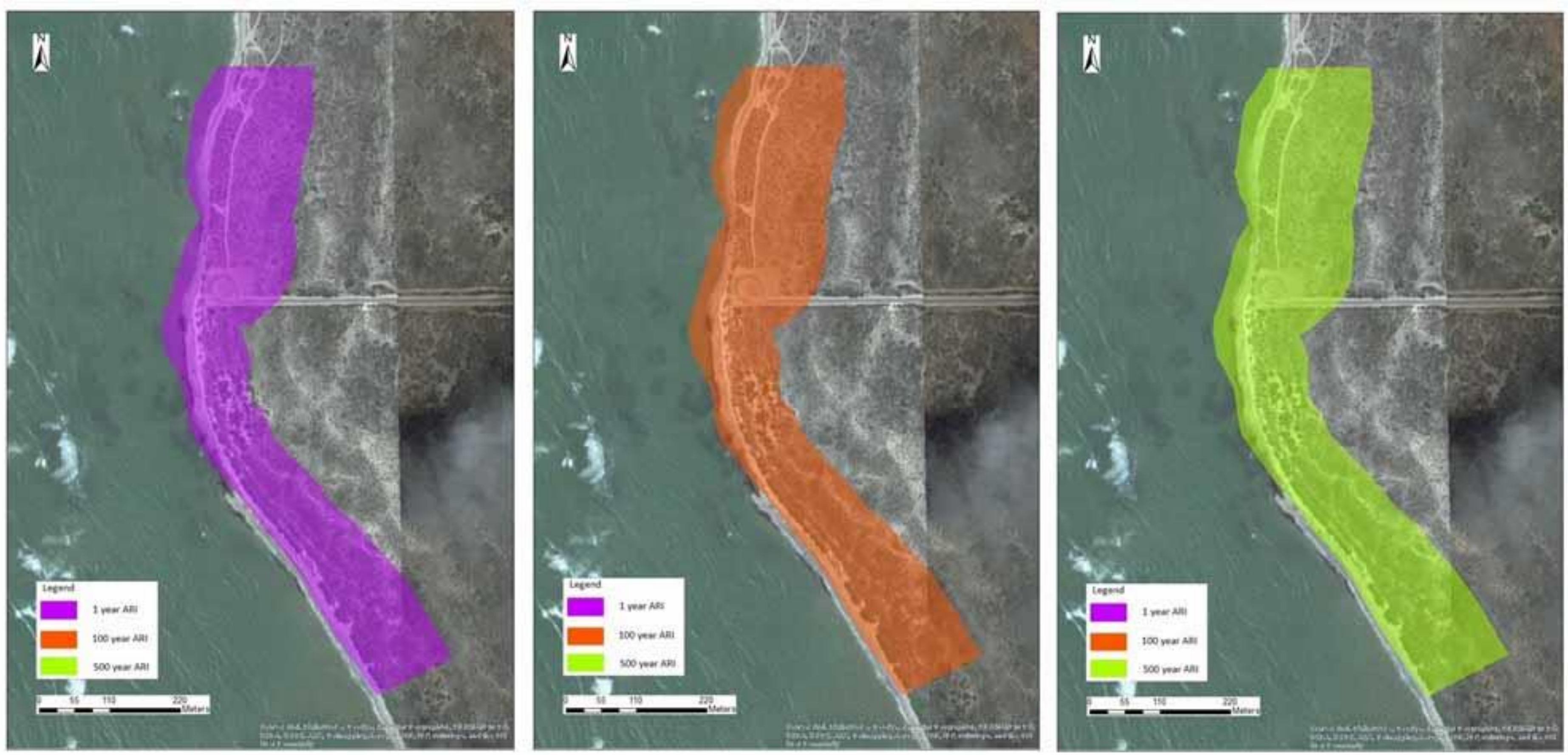

Figure C. 29: Erosion map of Seven Mile Beach- 1, 100 and 500 year ARI in 2110(0.9m SLR) + (Shore line movement + allowance for uncertainty)

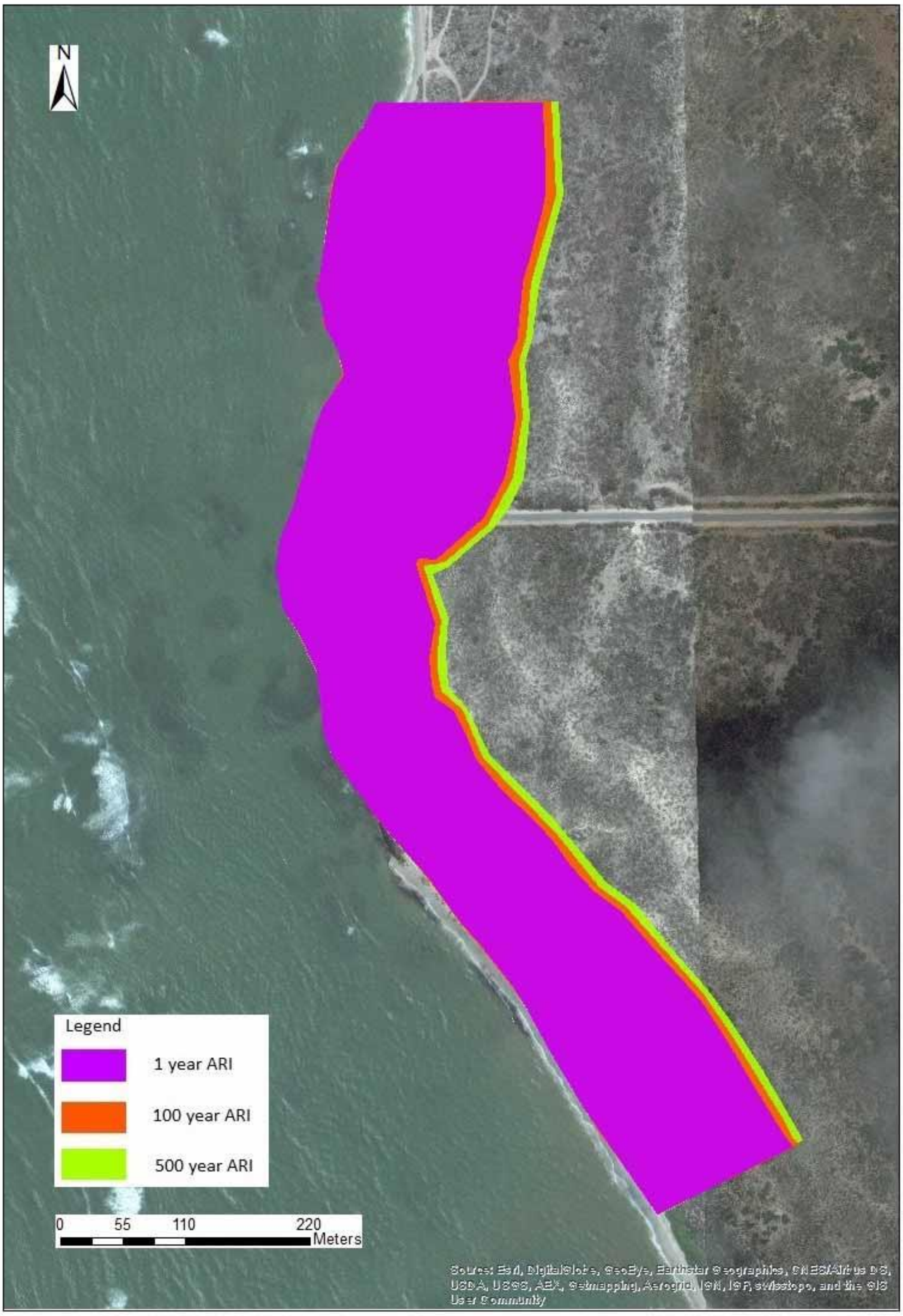

Figure C. 30: Integrated erosion map of Seven Mile Beach in 2110(0.9m SLR) + (Shore line movement + allowance for uncertainty)

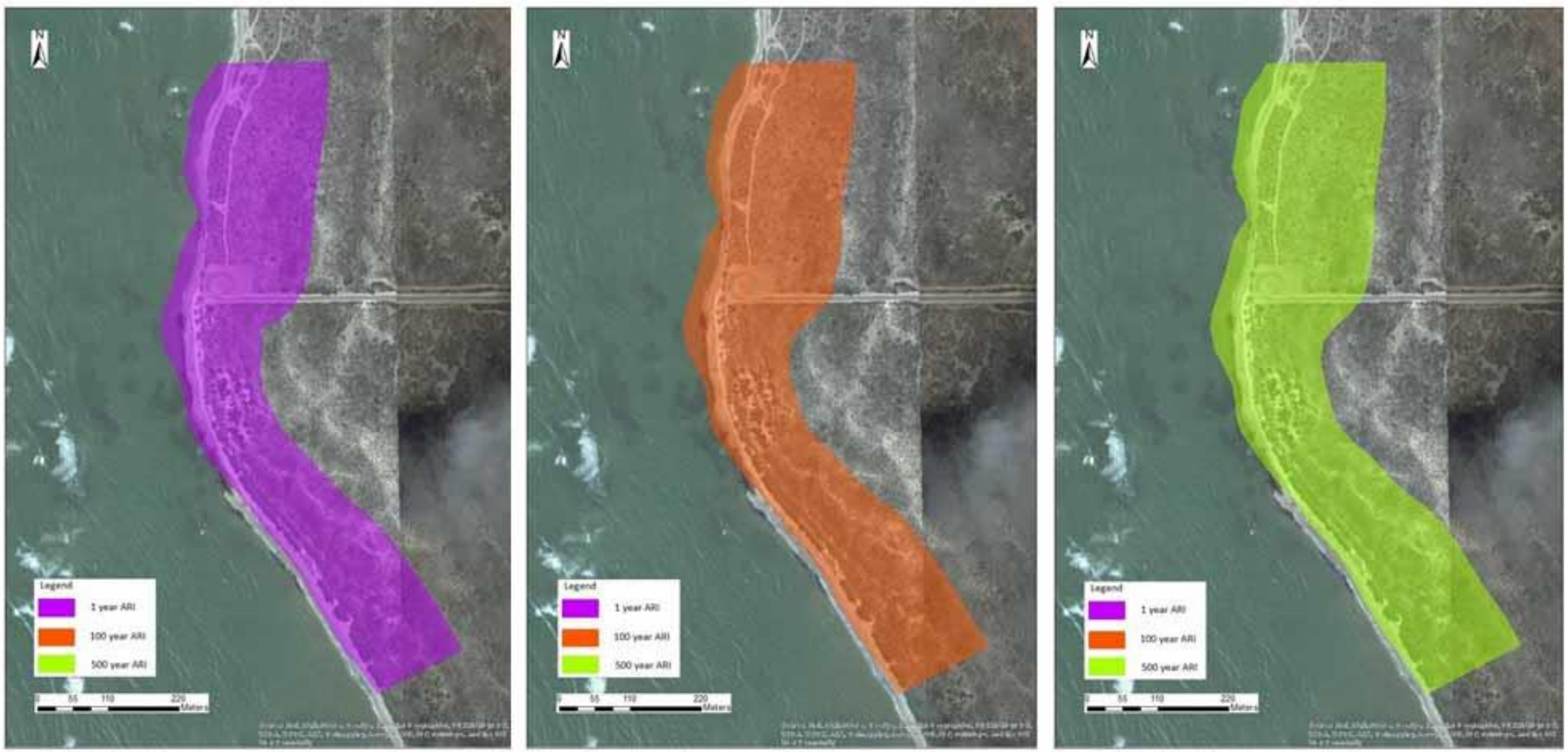

Figure C. 31: Erosion map of Seven Mile Beach- 1, 100 and 500 year ARI in 2110(1.5m SLR) + (Shore line movement + allowance for uncertainty)

Figure C. 32: Integrated erosion map of Seven Mile Beach in 2110(1.5m SLR) + (Shore line movement + allowance for uncertainty)

Freshwater Point

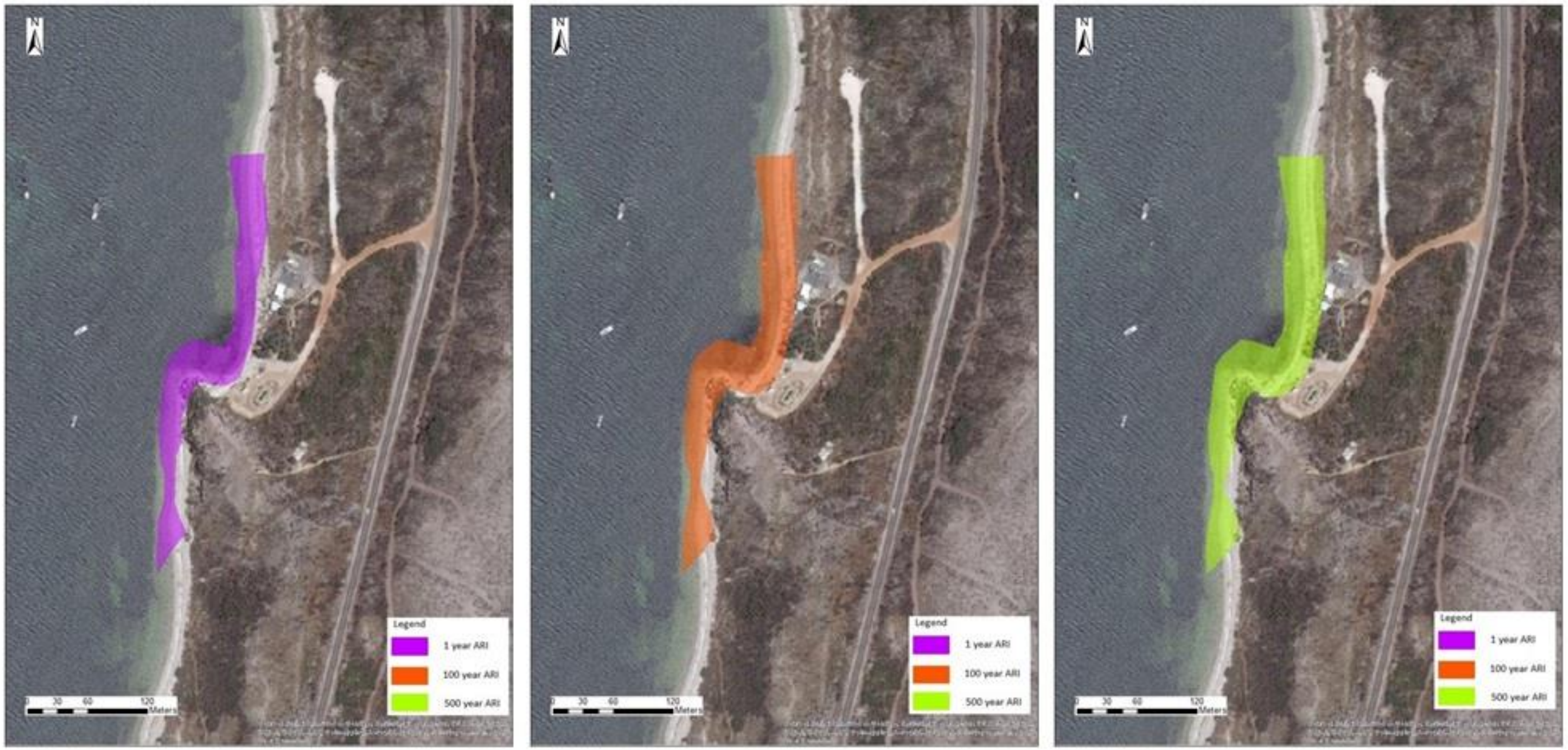

Figure C. 33: Erosion map of Freshwater Point- 1, 100 and 500 year ARI at present (0.0m SLR)

Figure C. 34: Integrated erosion map of Freshwater Point at present (0.0m SLR)

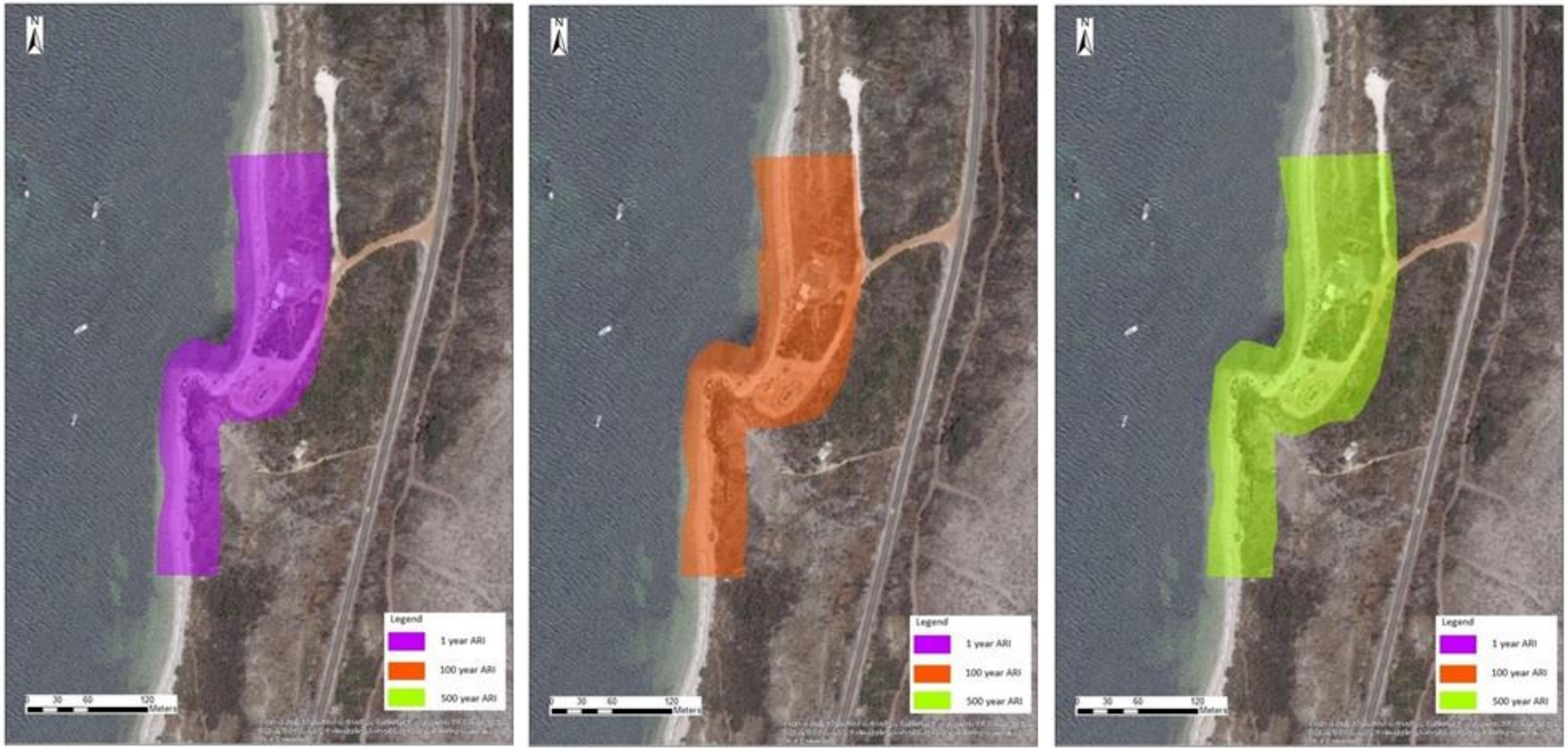

Figure C. 35: Erosion map of Freshwater Point – 1, 100 and 500 year ARI in 2070 (0.5m SLR) + (Shore line movement + allowance for uncertainty)

Figure C. 36: Integrated erosion map of Freshwater Point in 2070 (0.5m SLR) + (Shore line movement + allowance for uncertainty)

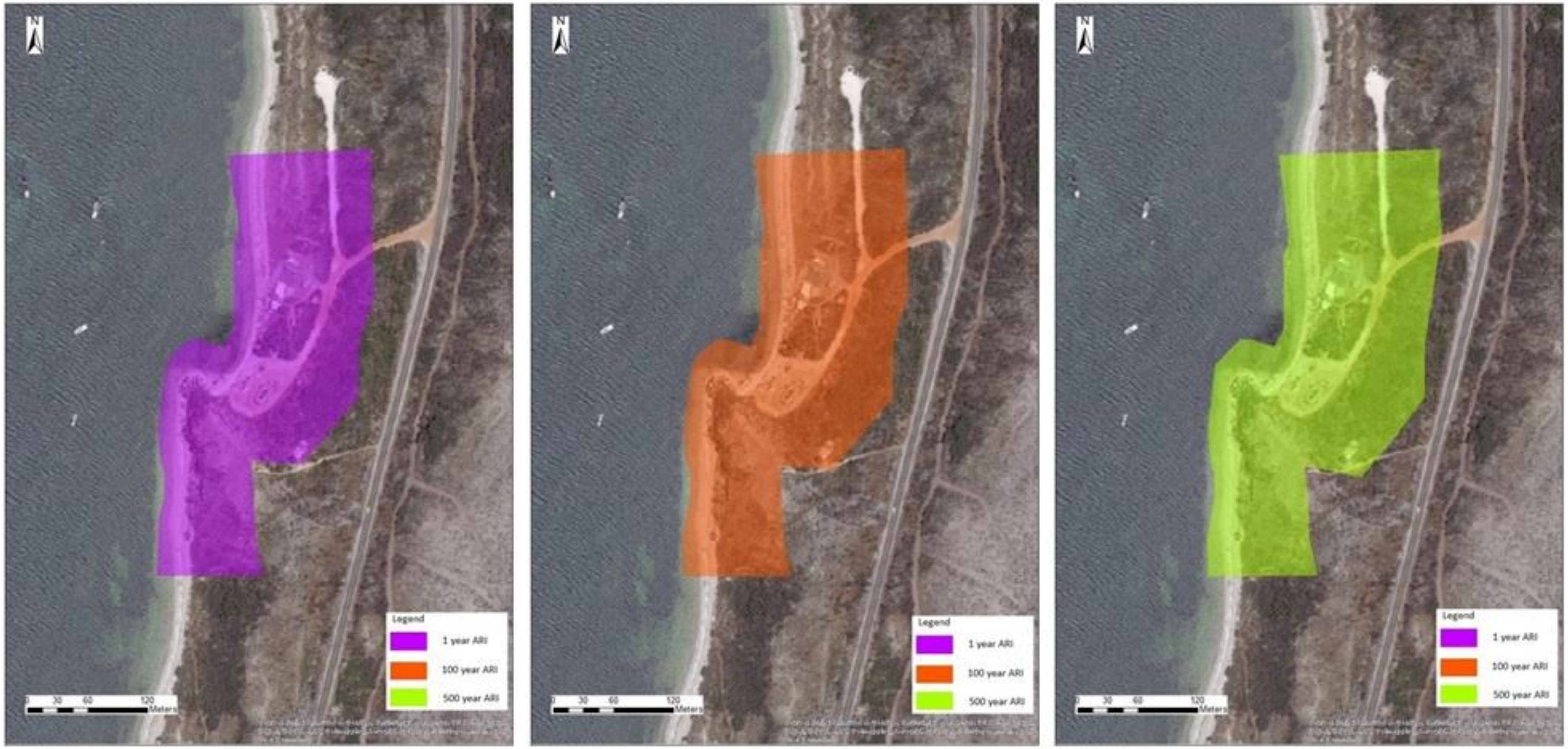

Figure C. 37: Erosion map of Freshwater Point – 1, 100 and 500 year ARI in 2110(0.9m SLR) + (Shore line movement + allowance for uncertainty)

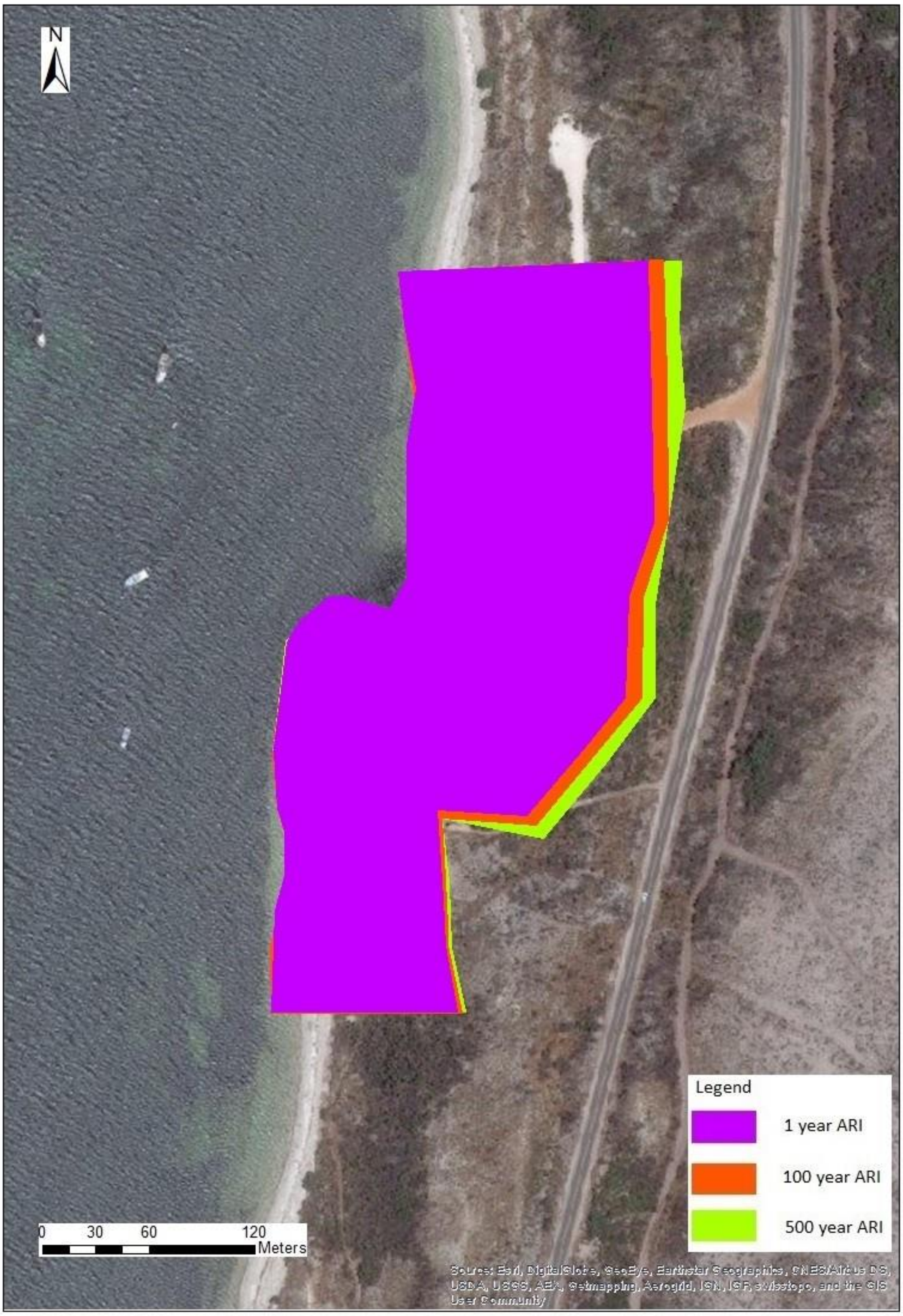

Figure C. 38: Integrated erosion map of Freshwater Point in 2110(0.9m SLR) + (Shore line movement + allowance for uncertainty)

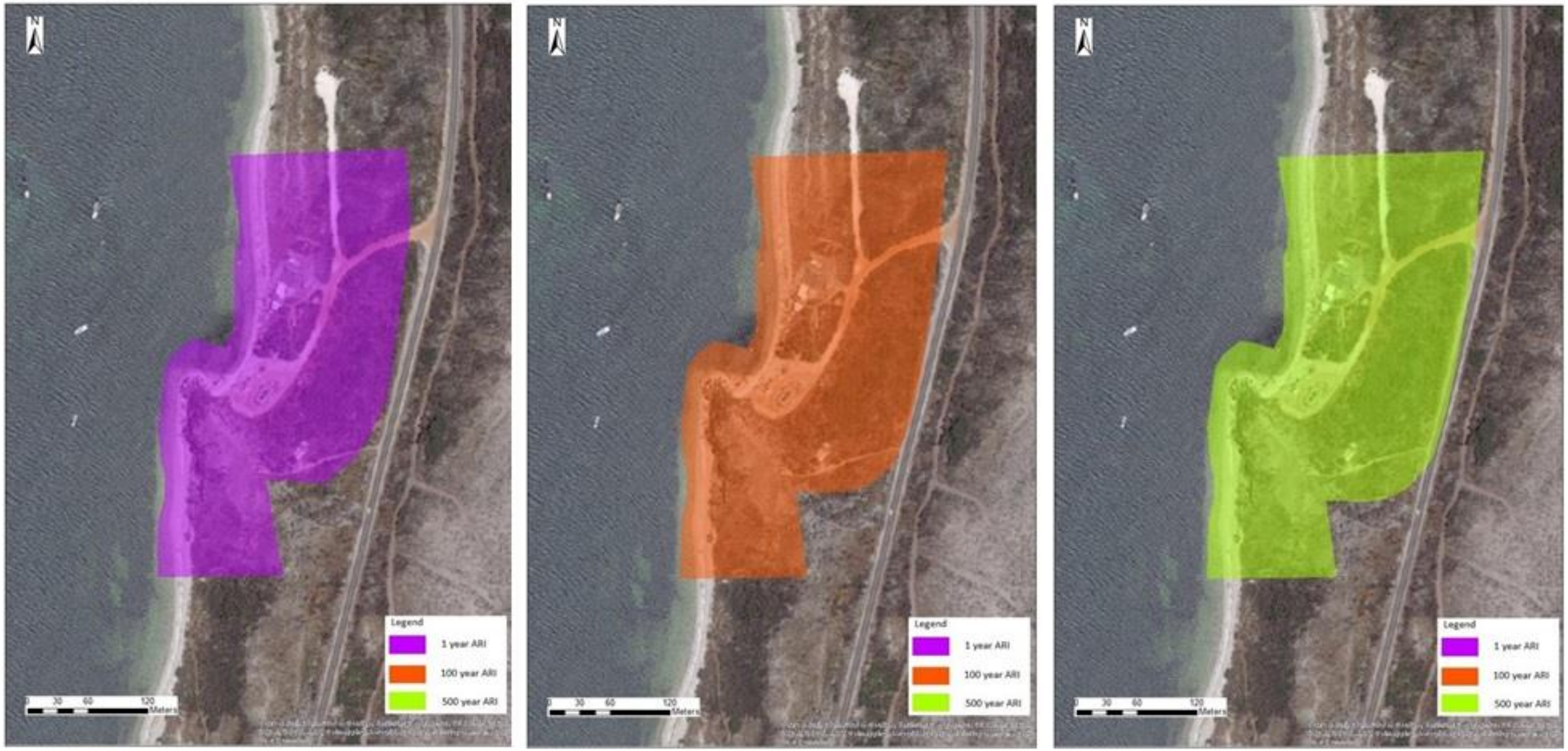

Figure C. 39: Erosion map of Freshwater Point -1, 100 and 500 year ARI in 2110(1.5m SLR) + (Shore line movement + allowance for uncertainty)

Figure C. 40: Integrated erosion map of Freshwater Point in 2110(1.5m SLR) + (Shore line movement + allowance for uncertainty)

Cliff Head (North)

Figure C. 41: Erosion map of Cliff Head (North) -1, 100 and 500 year ARI at present (0.0m SLR)

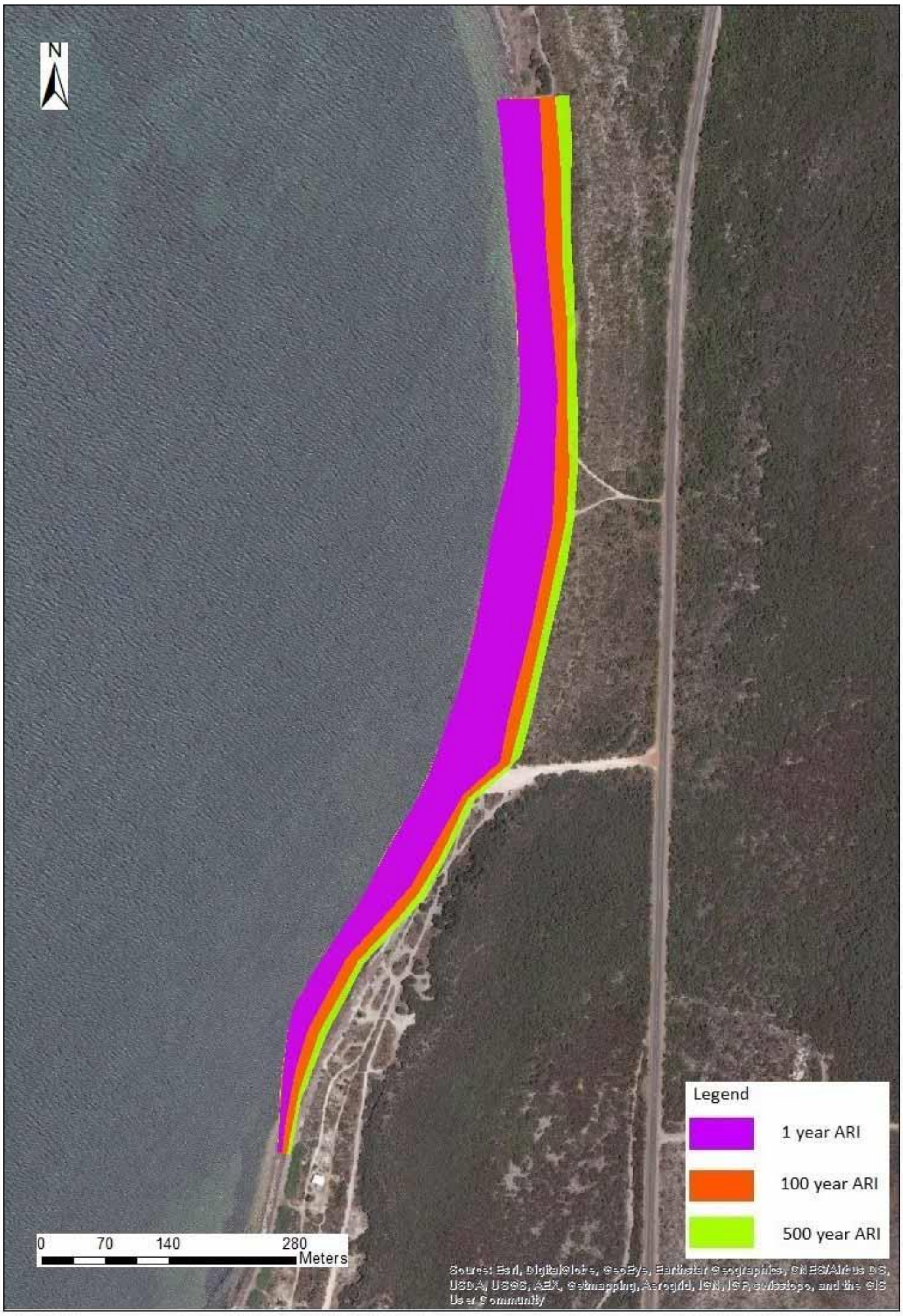

Figure C. 42 : Integrated erosion map of Cliff Head (North) at present (0.0m SLR)

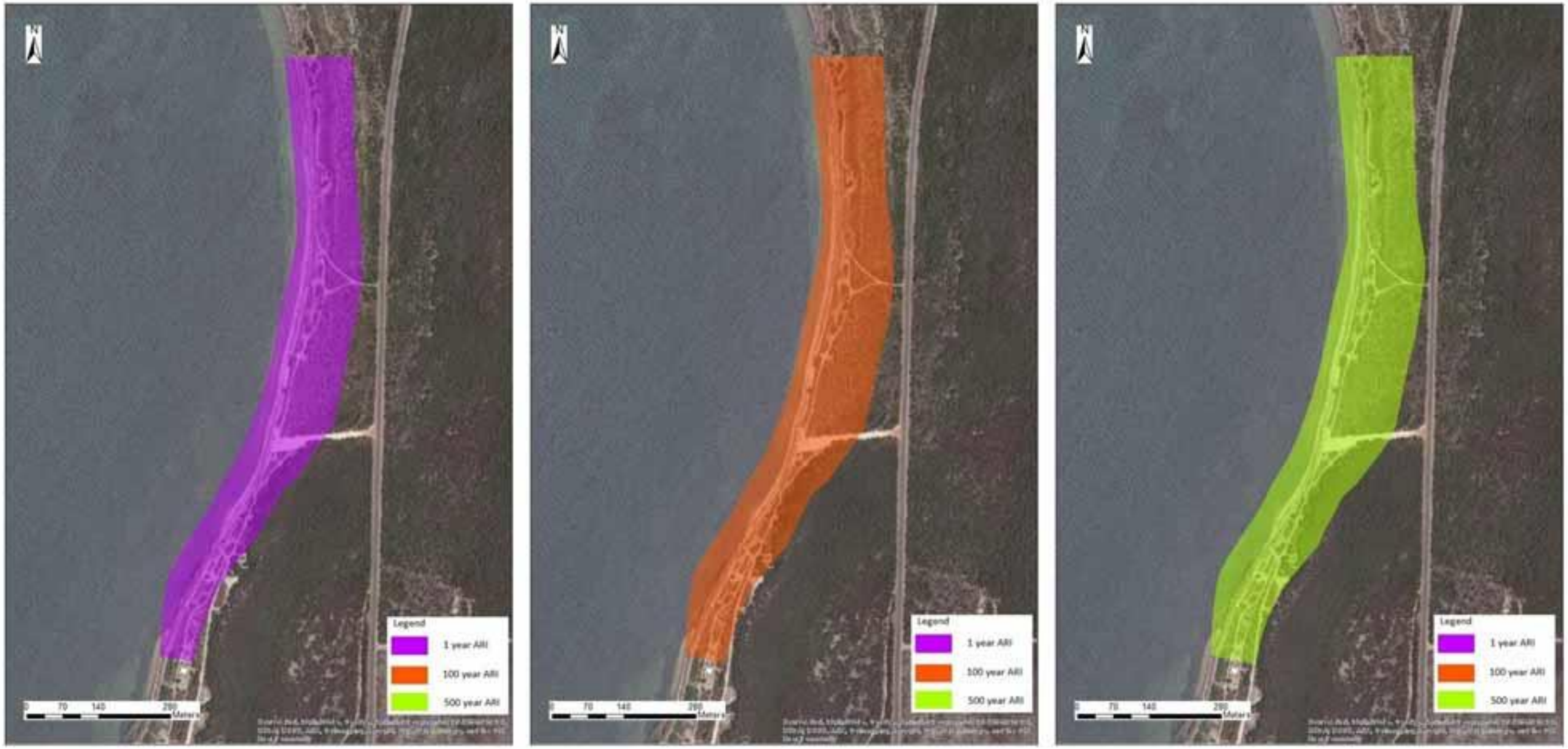

Figure C. 43: Erosion map of Cliff Head (North) -1, 100 and 500 year ARI in 2070 (0.5m SLR) + (Shore line movement + allowance for uncertainty)

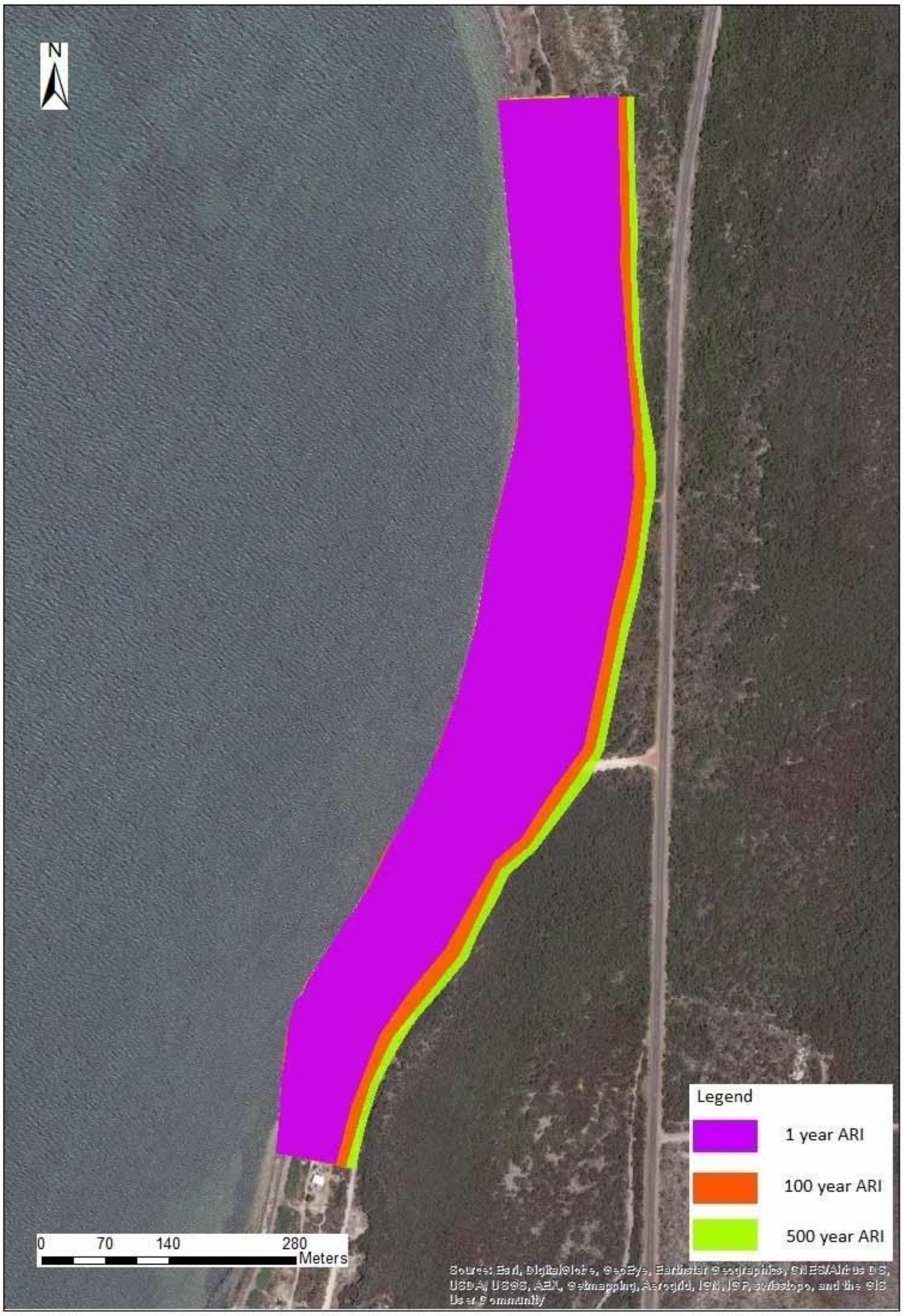

Figure C. 44: Integrated erosion map of Cliff Head (North) in 2070 (0.5m SLR) + (Shore line movement + allowance for uncertainty)

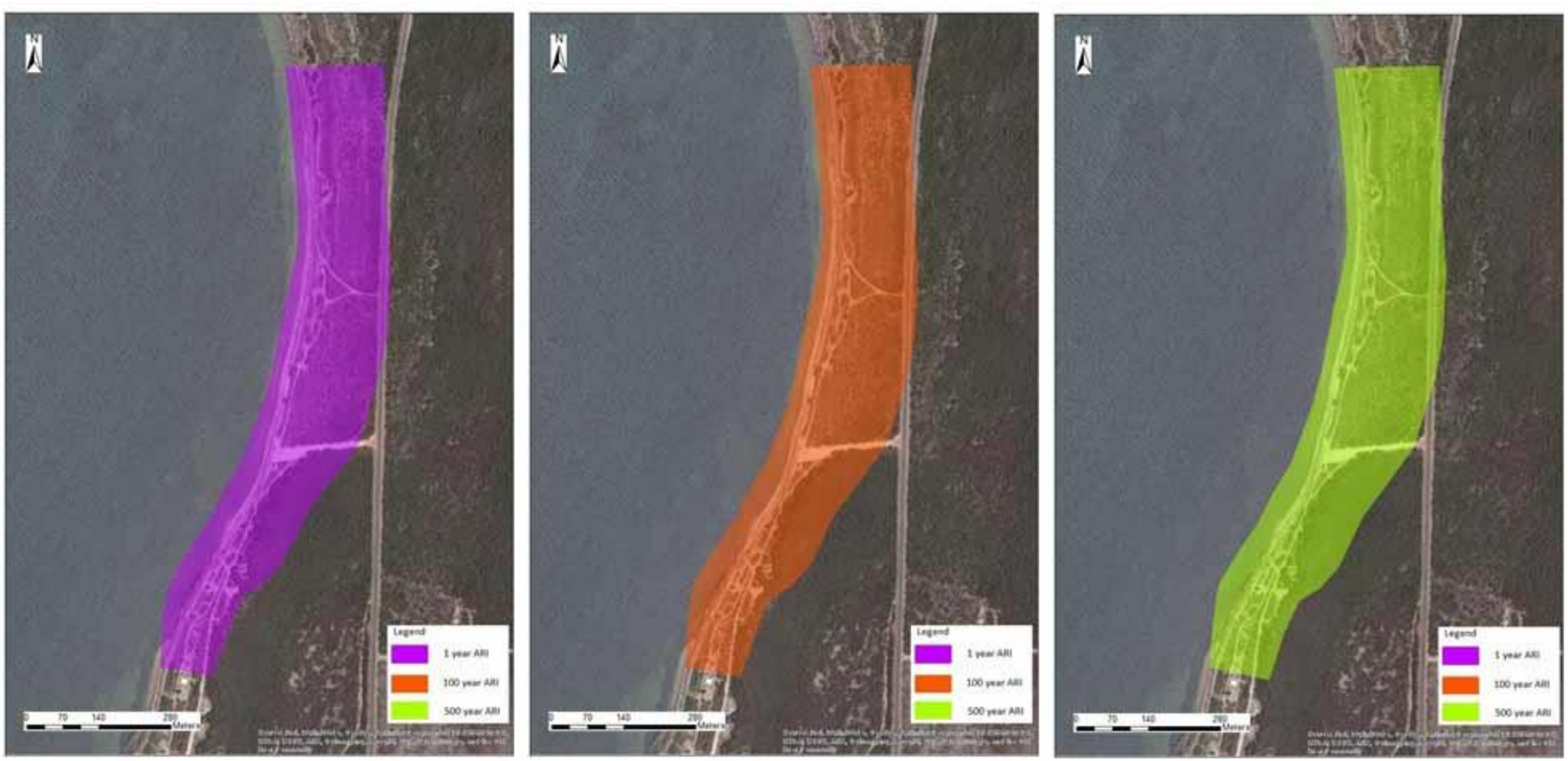

Figure C. 45: Erosion map of Cliff Head (North) 1, 100 and 500 year ARI in 2110(0.9m SLR) + (Shore line movement + allowance for uncertainty)

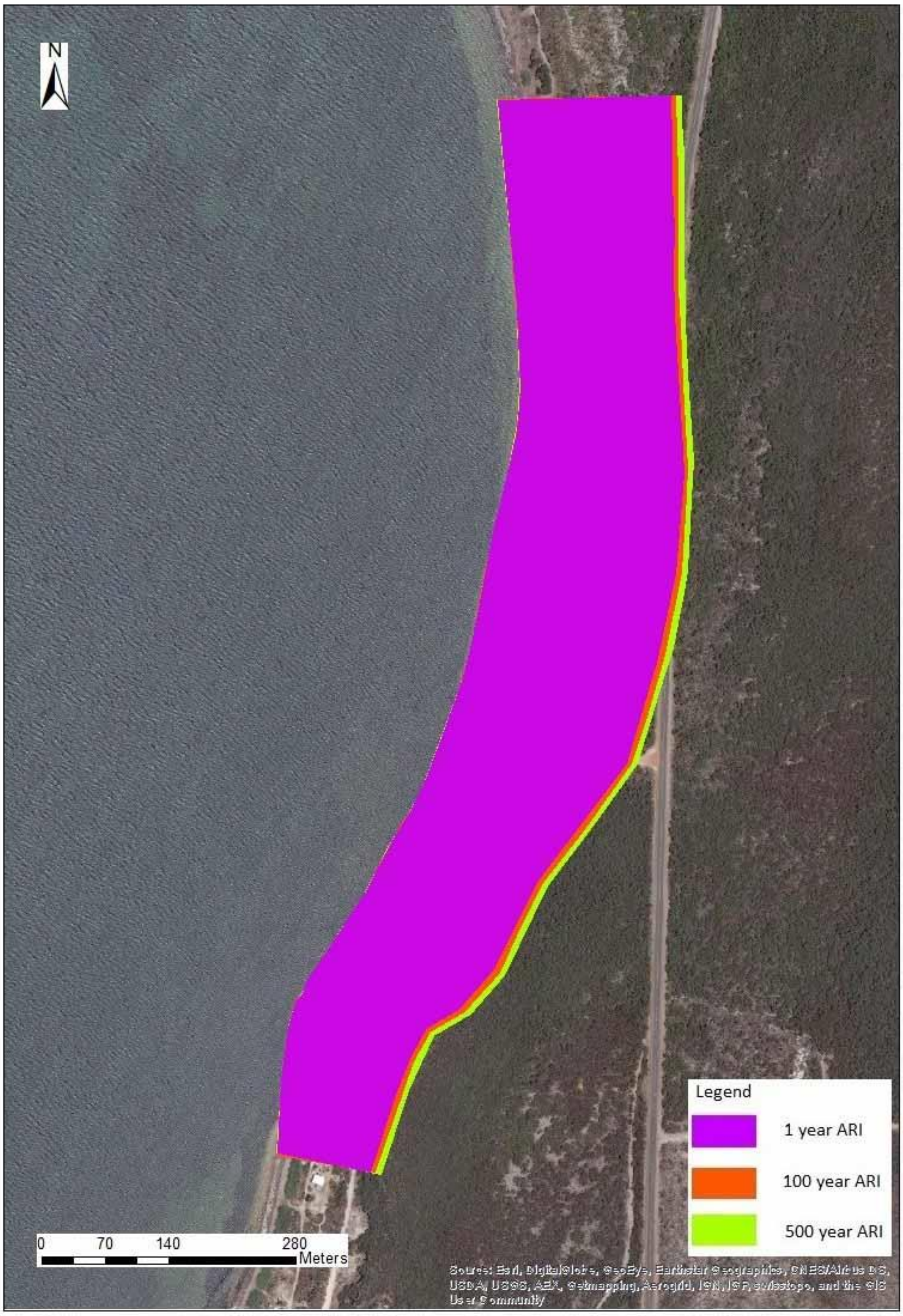

Figure C. 46: Integrated erosion map of Cliff Head (North) in 2110(0.9m SLR) + (Shore line movement + allowance for uncertainty)

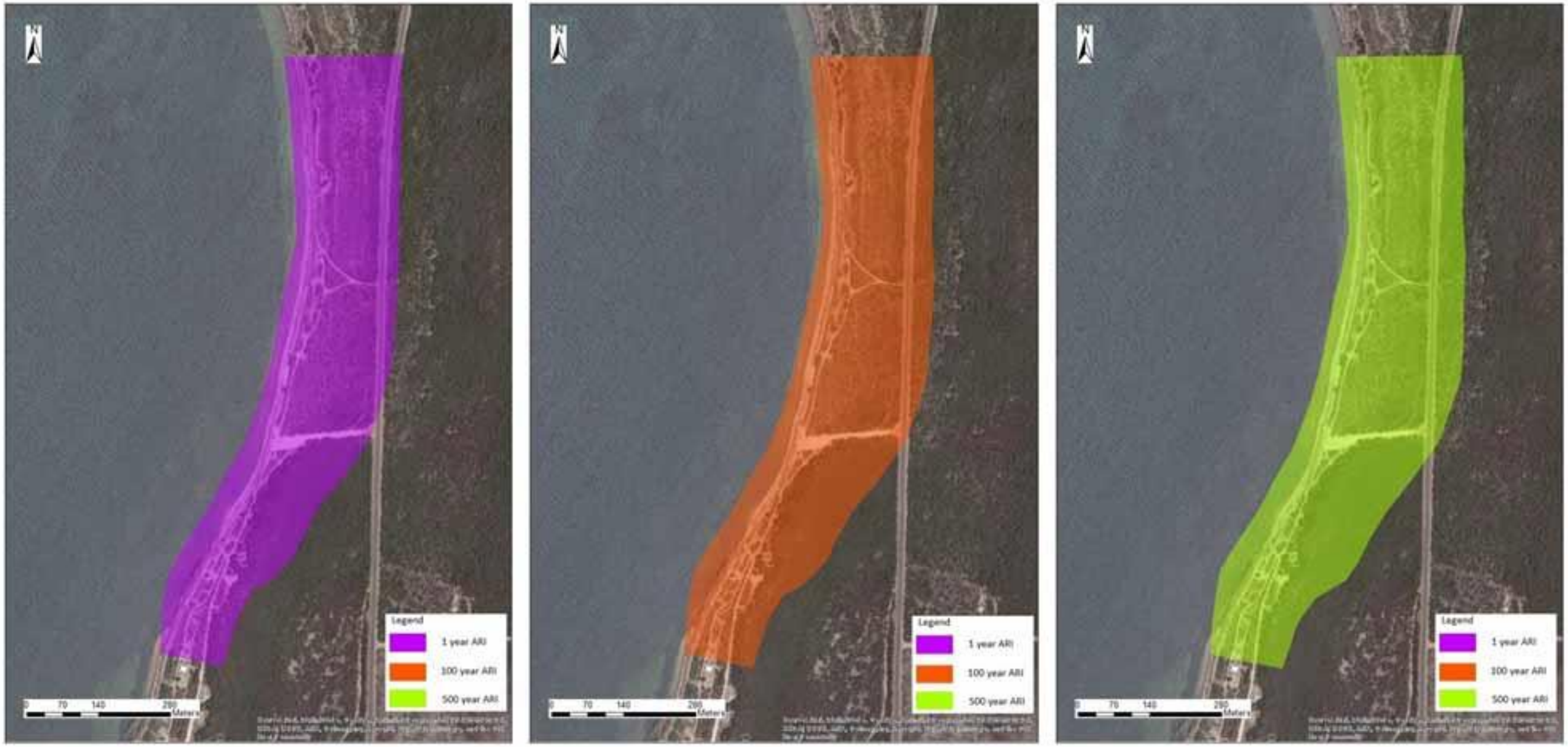

Figure C. 47: Erosion map of Cliff Head (North) -1, 100 and 500 year ARI in 2110(1.5m SLR) + (Shore line movement + allowance for uncertainty)

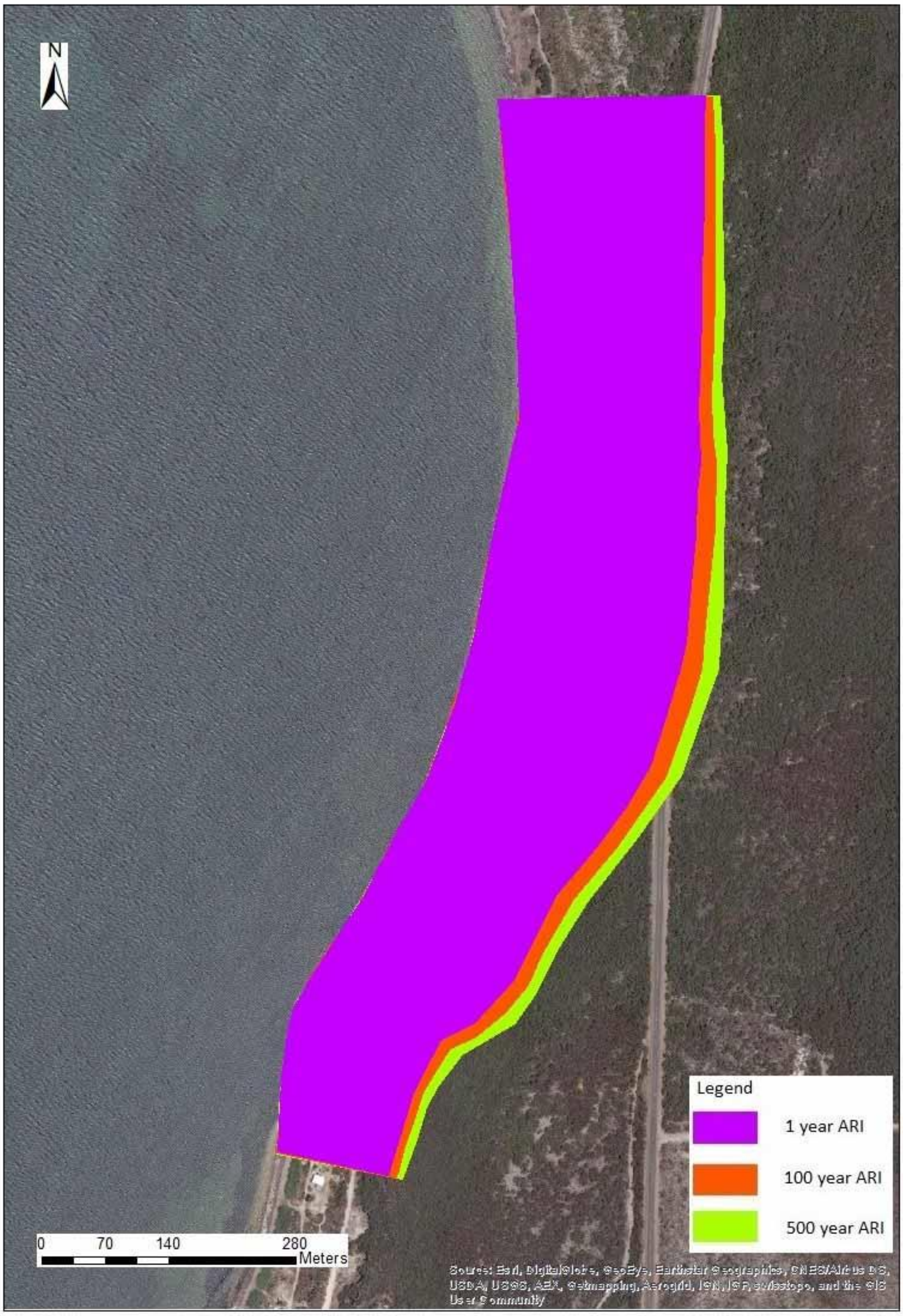

Figure C. 48: Integrated erosion map of Cliff Head (North) in 2110(1.5m SLR) + (Shore line movement + allowance for uncertainty)

Cliff Head (South)

Figure C. 49: Erosion map of Cliff Head (South)-1,100 and 500 year ARI at present (0.0m SLR)

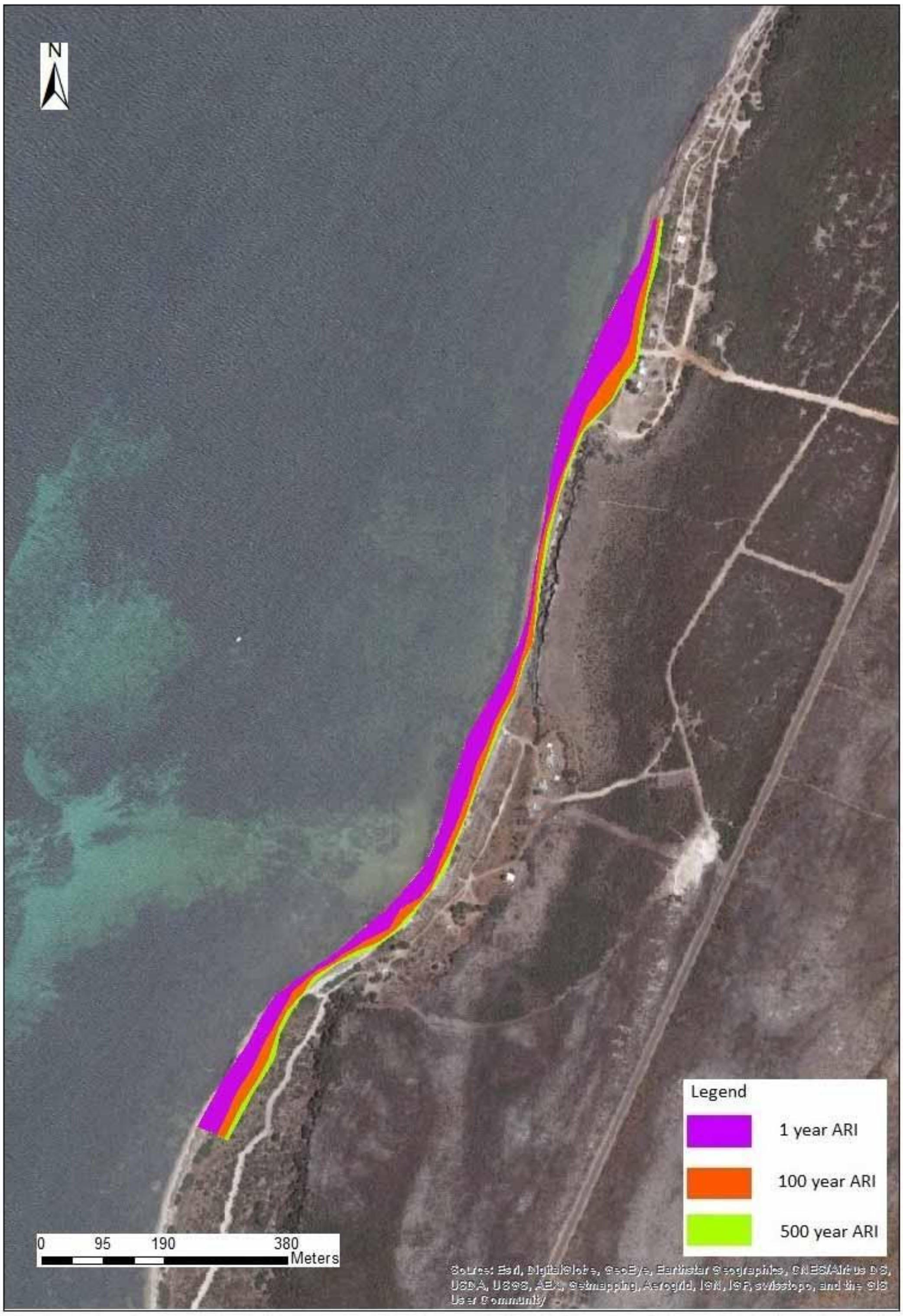

Figure C. 50: Integrated erosion map of Cliff Head (South) at present (0.0m SLR)

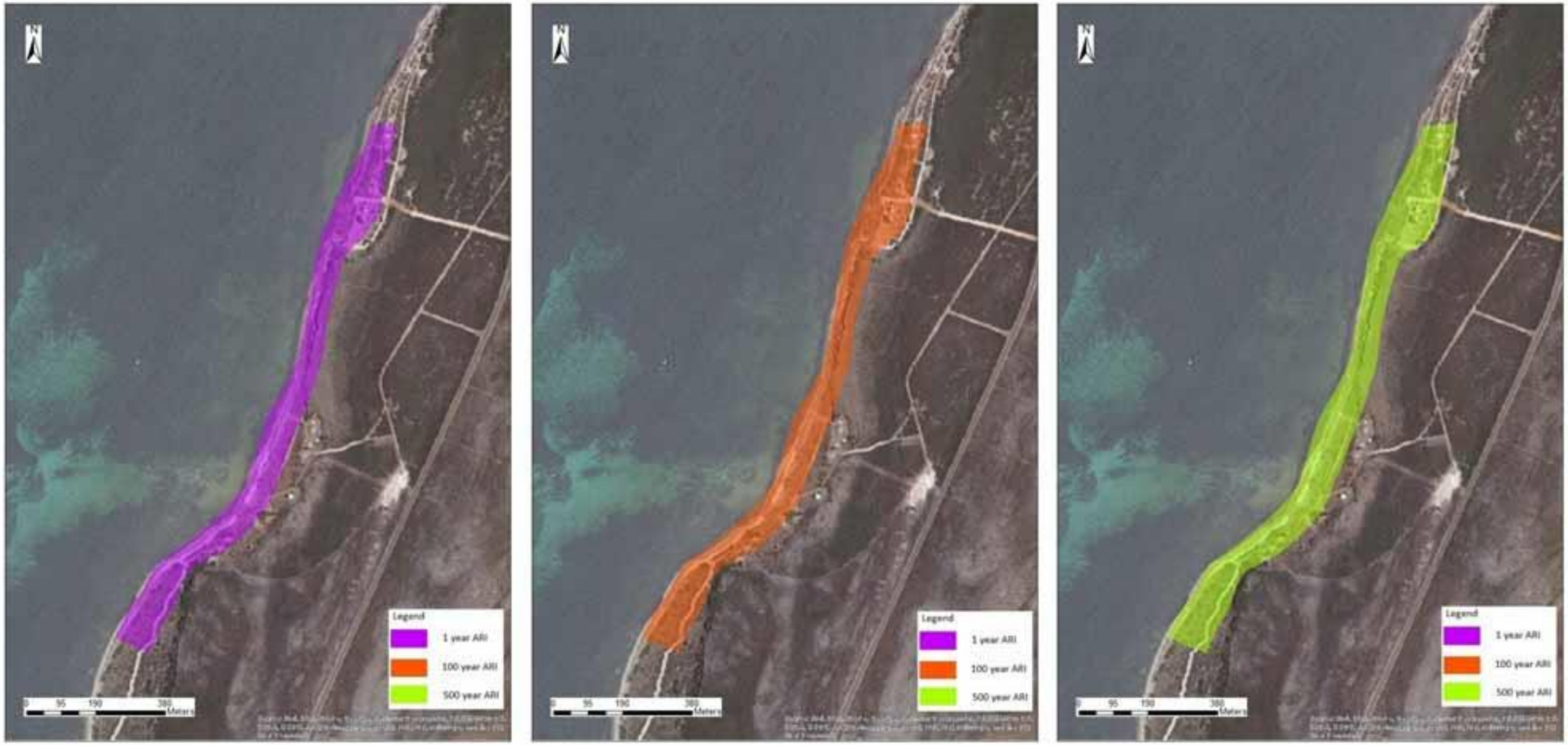

Figure C. 51: Erosion map of Cliff Head (South)- 1, 100 and 500 year ARI in 2070(0.5m SLR) + (Shore line movement + allowance for uncertainty)

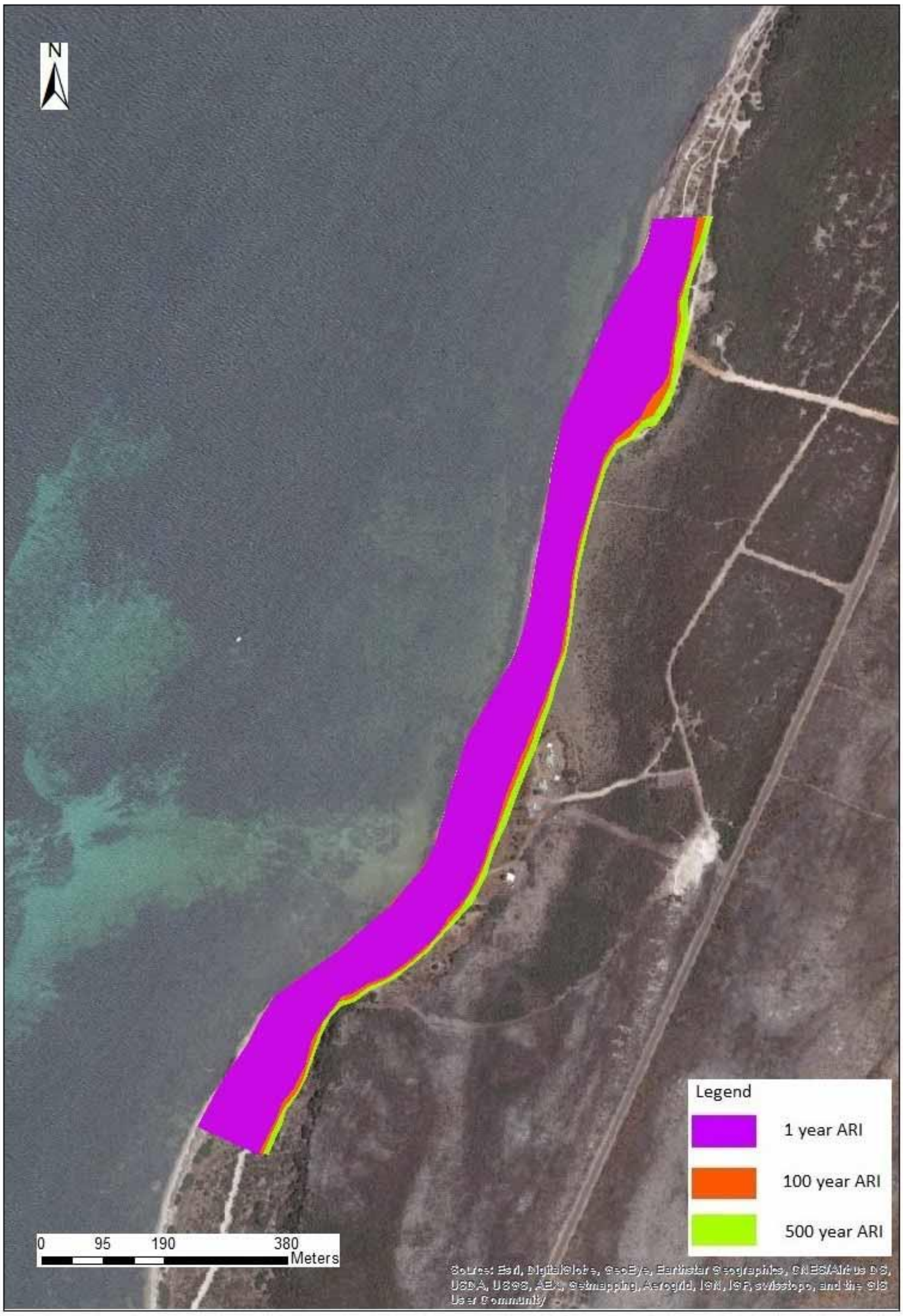

Figure C. 52: Integrated erosion map of Cliff Head (South) in 2070(0.5m SLR) + (Shore line movement + allowance for uncertainty)

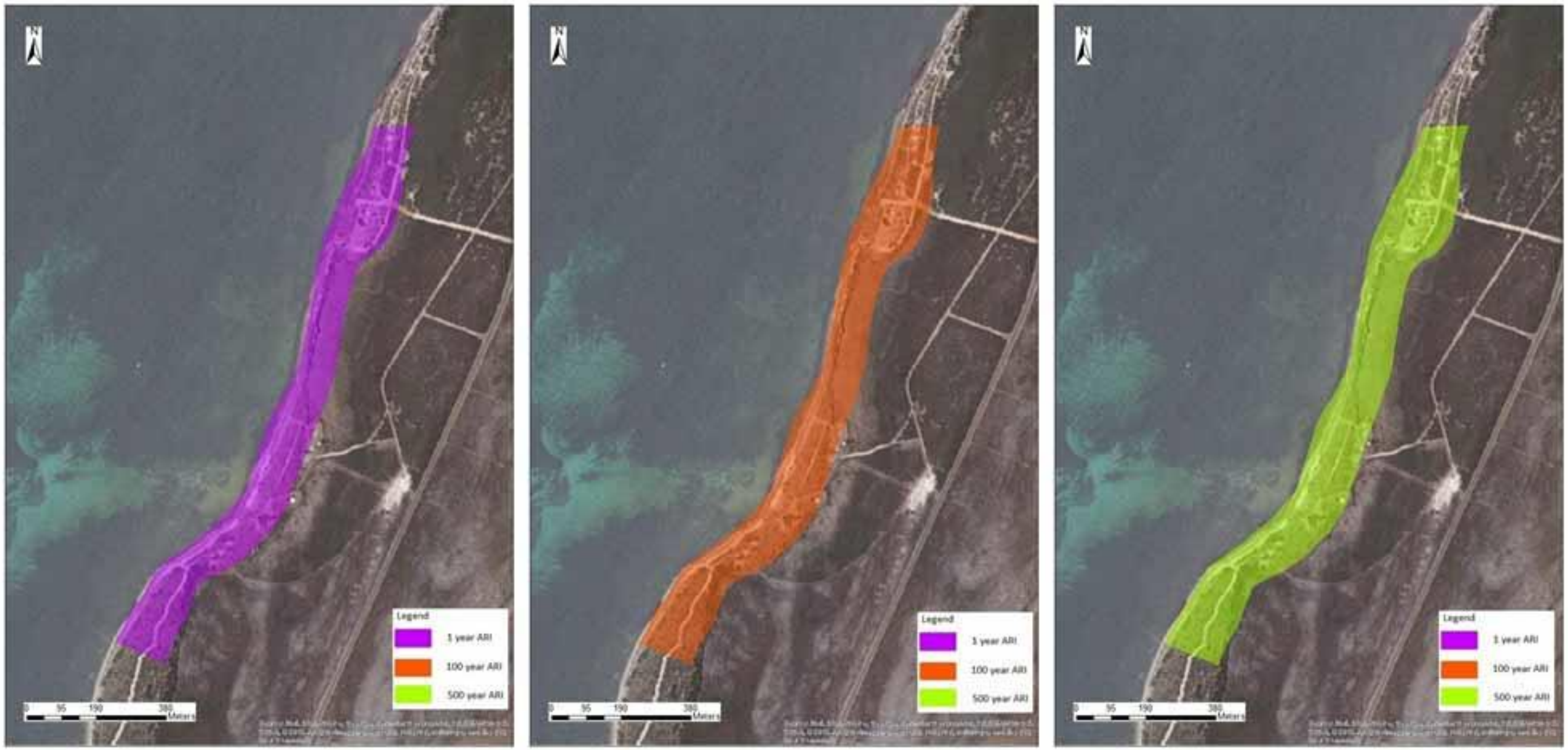

Figure C. 53: Erosion map of Cliff Head (South)- 1, 100 and 500 year ARI in 2110 (0.9m SLR) + (Shore line movement + allowance for uncertainty)

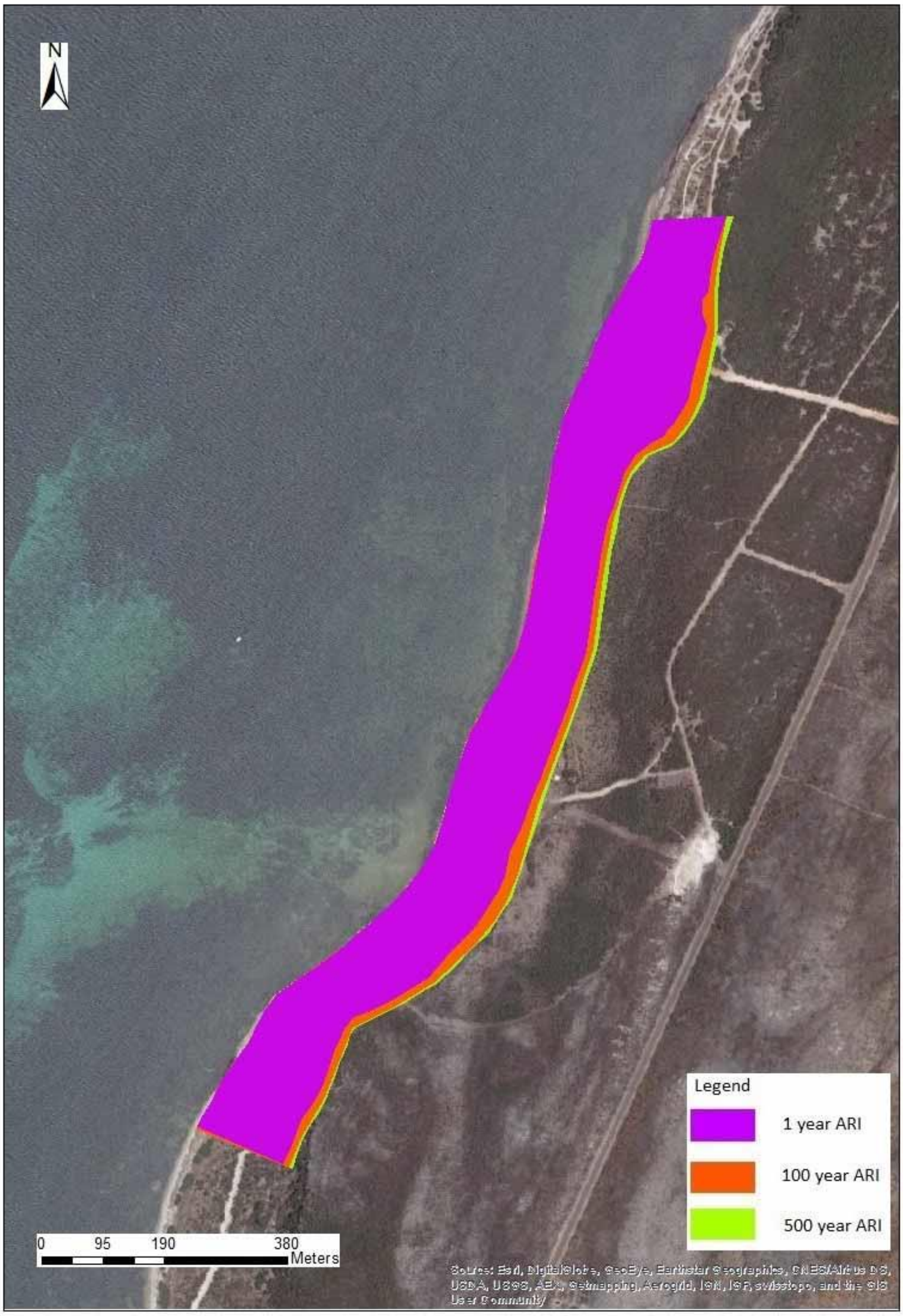

Figure C. 54: Integrated erosion map of Cliff Head (South) in 2110(0.9m SLR) + (Shore line movement + allowance for uncertainty)

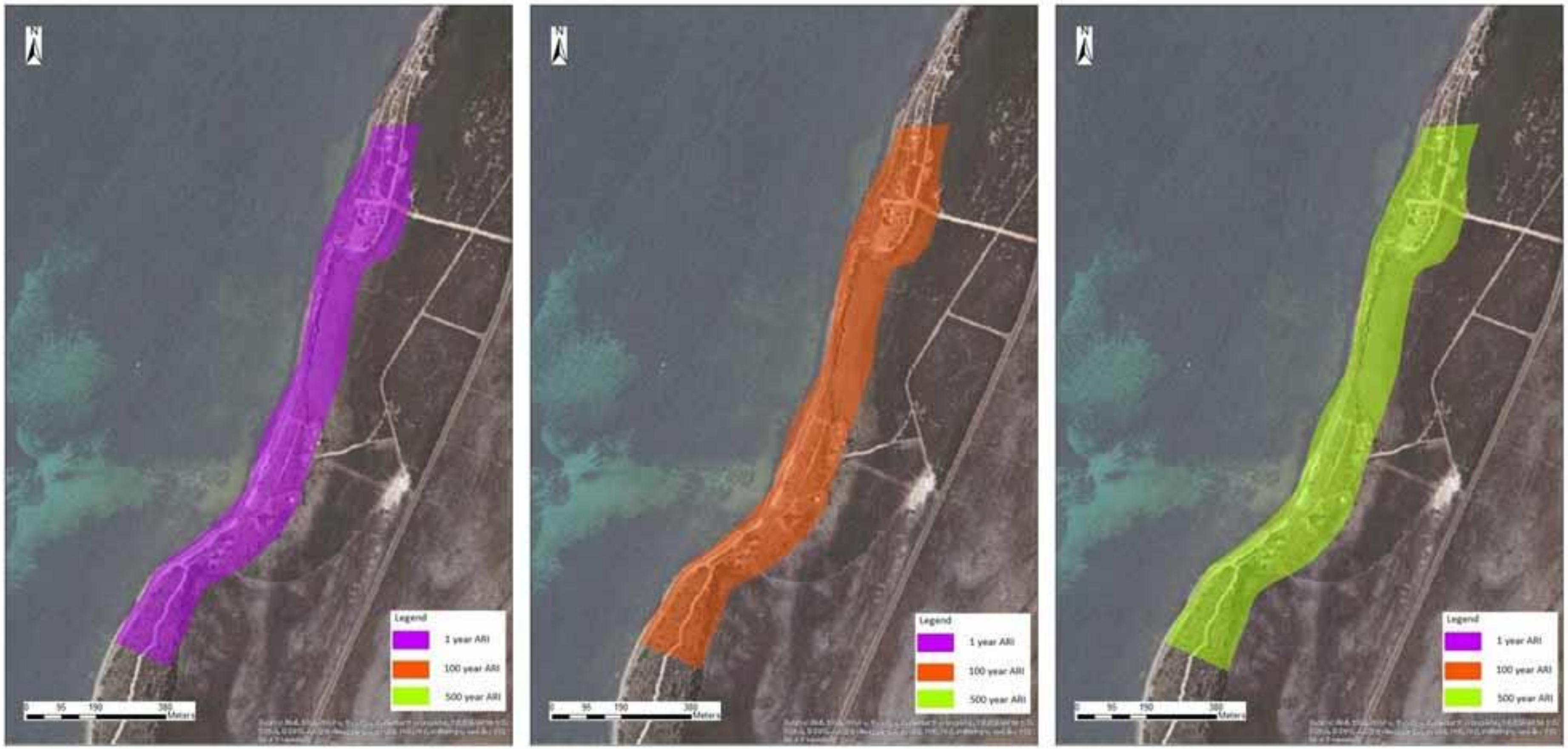

Figure C. 55: Erosion map of Cliff Head (South) – 1, 100 and 500 year ARI in 2110(1.5m SLR) + (Shore line movement + allowance for uncertainty)

Figure C. 56: Integrated erosion map of Cliff Head (South) in 2110(1.5m SLR) + (Shore line movement + allowance for uncertainty)