KARRATHA COASTAL VULNERABILITY STUDY

MAIN REPORT

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Preface

The State Government and the Shire of Roebourne have a shared vision that will see Karratha transformed into a vibrant City of the North with a permanent population of 50,000 by 2035.

Land availability, and in particular developable land above predicted future flood levels, is a clear constraint. In recognition of this the Royalties of Regions program has funded the preparation of the Karratha Coastal Vulnerability Study. The Study considers the combined impact of flood from rainfall and storm surge. The Study was undertaken by JDA Consultant Hydrologists and was overseen by a Steering Committee that included the Department of Water, the Department of Transport and the Department of Planning.

The report is not a statutory document. However, the reports findings will be considered by statutory agencies in assessing future development proposals under the Shire of Roebourne's Town Planning Scheme and the WAPC's Statement of Planning Policy 2.6.

Developers and their consultants may use the report and its data for their own works but must undertake their own independent verification specific to their development proposal.

EXECUTIVE SUMMARY

JDA Consultant Hydrologists was commissioned by LandCorp to undertake the Karratha Coastal Vulnerability Study.

The Karratha Coastal Vulnerability Study has involved a study of the impacts of future climate change (CZM), calculation of the hydrology around Karratha (JDA), assessment of the shoreline stability (Damara), modelling of the flooding from storm surge (GEMS) and modelling of the riverine flooding (JDA).

CLIMATE CHANGE

The specific impacts on the flooding around Karratha include a rise in mean sea level, increases in rainfall intensity and an increase in the frequency and magnitude of cyclones.

Using the National Council for Coastal and Ocean Engineering (Engineers Australia, 2004) guidelines, the following predictions were made for the 2060 and 2110 climate scenarios.

TABLE ES1: CLIMATE CHANGE PREDICTIONS

Climate Component	2060	2110
Mean Sea Level Rise (m)	0.3m	0.9m
Rainfall/Runoff Intensity (mm/hr)	0% to 20% Higher end for ARI >20yr	10% to 30% Higher end for ARI >20yr
Cyclone Frequency	+10%	+10%
Cyclone Magnitude	+10%	+10%

HYDROLOGY

Three large catchments for the Study Area were determined: 7 Mile Creek, Nickol West Tributaries and Nickol River with peak flows assessed using regional methods (Rational and Index Flood Methods from Australian Rainfall & Runoff) and catchment hydrology models (XP-Storm and RORB). It was found that for the 100 year ARI event, the XP-Storm, RORB and Index Flood Methods gave similar results. The verified XP Storm model was used to generate inflow hydrographs for the Hydraulic Model. Runoff within the Karratha Study Area was estimated from the Hydraulic Modelling using the rain-on-grid approach.

COASTAL MOVEMENT

Karratha coastal structure is developed through the interaction of vegetation and sediments, interacting with a significant rock presence. Drivers for change, including water level and wave forcing, are highly episodic within the Pilbara region, and their impacts are strongly influenced by the landform structure. Interactions between landform units have been considered through the application of the sediment budget concept within the domain of Nickol Bay. The methodology for this study included evaluation of historic aerial photography, field reconnaissance, stability assessment using USACE dune criteria and analysis of LiDAR and available metocean data. Four coast types were identified: Western Nickol Bay, West Karratha, East Karratha and the Nickol River Delta. Variable assessment methods have been utilised to investigate coastal change for the different coast types.

STORM SURGE

The storm surge study aimed to provide estimates of the storm surge water levels along the Karratha coastline. Water levels were generated using the GEMSURGE model, a 2D coastal ocean model that determines currents and water levels from specific tidal forcings and meteorological conditions. Wave processes were modelled using SWAN model and cyclone winds were generated using empirical model developed by the Australian Bureau of Meteorology (Holland, 1980). This suite of models was utilised to determine water levels for known cyclone events. To generate water levels for each ARI event a statistical analysis was applied to all of the modelling results.

The model was validated using a number of significant cyclone events in the North West of Western Australia. In particular, a survey of debris associated with cyclone Carlos in February 2011 was used to support the validation.

Future climate scenarios were assessed in the model using results from the climate change study and the shoreline stability estimate. Based on these studies, the model included an increase in water level and cyclone intensity and removal of the mangroves in 2110, including flattening of the topography in mangrove areas.

HYDRAULIC MODELLING

Riverine flooding of Karratha was assessed using DHI's MIKE FLOOD model, a dynamic coupling of the 2D hydrodynamic model MIKE21 and the 1D hydrodynamic model MIKE11. The model is based on the LiDAR survey conducted for Karratha in 2010, converted into a 20m model grid.

The boundary conditions for the model were generated in the Hydrology and Storm Surge studies. Inflow hydrographs have been described in the summary of the Hydrology Study. The sea level boundary condition was generated from the storm surge modelling. The model was validated using observed flood levels from Cyclone Bianca in January 2011 a 2yr to 5yr ARI event. Most of the observation points showed good agreement between observed and simulated levels.

For the design storm simulations joint probability between riverine flood levels and storm surge was assessed, but no obvious correlation found. After assessing available guidelines, a 1:5 probability was adopted for this study, that is, for the 100yr ARI hydraulic model, the results from the 20yr ARI storm surge model were used as a boundary condition. This approach is consistent with other coastal vulnerability studies in the region and Australia.

The hydraulic model accounts for future climate scenarios through changes in inflow hydrographs and storm surge boundary conditions. There is also an increase in rainfall intensities for the internal rain-on-grid runoff generator.

INTEGRATED RESULTS

From the storm surge and hydraulic modelling, a set of maps have been produced for the 2, 10, 100, 200 and 500 year ARI events for the 2010, 2060 and 2110 climate scenarios. These maps show flood extent, depth and levels. These maps show the combined effect of storm surge and riverine flooding taking into account the joint probability.

The 100 year ARI flood extent indicates that a significant proportion of the Study Area is subject to some degree of inundation. The Nickol River tidal flats are impacted by storm surge. To the north of the Karratha townsite, storm surge extent is similar to the Kelly Line. Riverine flooding is generally along 7 Mile Creek and the western tributaries of the Nickol River.

In general, extending development is not impacting by flooding, with most of the existing townsite, Gap Ridge and Baynton West in the west, and the Karratha LIA above the 100yr ARI flood level. The only areas which will be affected are properties along Balmoral Rd between Gawthorne Drive and Warambie Rd, which are subject to some inundation as a result of storm surge.

The road bridges on North West Coastal Highway at Nickol River, Turnoff, Lulu and Hilux Creeks all provide protection against the 10yr ARI event, but the roadway is subject to some inundation in the 100yr ARI event. Other creek crossings along North West Coastal Highway are generally floodways and subject to inundation – length of inundation can vary between 200 m and several kilometres.

The road bridge on Dampier Rd for 7 Mile Creek has a level of service of just under 100yr ARI, with a shallow depth of flow over a short length of roadway occurring.

The area to the south of the Karratha Hills and north of North West Coastal Highway is subject to some inundation, but often flow is shallow and may be developable. Within creek lines a significant depth of flow may occur.

Between Turnoff Creek, Nickol River, North West Coastal Highway and the eastern section of the Karratha Hills, a majority of the area is subject to inundation.

The simulated change in climate results in increased flood levels in all areas of the Study Area. For the 2060 scenario, flood levels generally increase by 0.2 to 0.3 m, with the predicted changed in sea level (0.3 m) accounting for changes adjacent to the coast and increased rainfall intensities accounting for increased flood levels inland. Similarly, flood levels increase further for the 2110 scenario.

Shoreline location is predicted to change as a result of sea level rise and climate change.

In the Western Nickol Bay, it was assumed that the Dampier Salt bunds would continue to be protected by infrastructure with the change in sea level over the 100 year timeframe. The tidal creek expansion is predicted to accelerate as sea level increases. With increased sediment transport from sea level rise, destabilisation of the fringing mangroves will occur, with the result that breaching of the dune adjacent to airport is likely within 100 years.

In the West Karratha section, a tidal flat and mangrove fringe is backed by a high largely continuous coastal dune. The sediment demand of the tidal flat due to sea level rise is unlikely to be met, with the result that the tidal will progressively experience inundation, with subsequent destabilisation of the mangroves. As sea level rise continues the coastal dune may be breached due to zones of focussed erosion. Breaching is likely to occur by 2110.

The East Karratha section of coast has a narrow fringe of mangroves fronting a thin section of low lying sandy foreshore and backed by rocky hinterland. The mangroves will be destabilised due to rising sea levels, however the rock structure provides a significant constraint to potential coastal movement.

Wave run-up in the Karratha area has been estimated based on empirical techniques. The most significant factor impacting wave run-up is the near and onshore slopes. Modelling of the Karratha floodplain areas impacted by the 100 year to 500 year ARI storm surge events indicates that wave run-up is less than 0.3 m. Future development in these floodplain areas may require management where fill is required to provide clearance as this may result in steep batter slopes which will significantly increase wave run-up.

GLOSSARY

Australian Height Datum (AHD)	The datum to which all vertical control for mapping is to be referred to in Australia.
Average Recurrence Interval (ARI)	The average return period or frequency of an event.
Bathymetry	The ocean's surface shape, relief, landforms and features.
Boundary Condition	The conditions of a parameter at the boundary of its domain, for example the water level at the downstream extent of a hydraulic model.
Catchment	The area of land that is drained by a river and its tributaries.
Critical Storm Duration	The storm duration that produces the highest water level or discharge in the river for a given Average Recurrence Interval.
Digital Elevation Model (DEM)	A digital representation of ground surface topography consisting of regularly spaced elevation values.
Flood Frequency Analysis	Statistical method of analysis to estimate the probability, return period or average recurrence interval of a flow or flood event based on historical data.
Floodplain	The area adjacent to rivers, streams and creeks that are subject to inundation from large flows caused by heavy rains.
Foreshore	The area of land that adjoins or directly influences a waterway, including the furthest extent of riparian vegetation, flood prone land and riverine landforms.
GEMSURGE	Two-d storm surge model developed by Global Environmental Modelling Systems Pty Ltd.
HAT	Highest astronomical tide.
Hydraulic Model	A computer model that simulates flow of water through natural channels or engineered structures.
Hydrograph	A graph of discharge in a river throughout a period of time.
Hydrology	The study of the movement, distribution, quality and properties of water of the Earth, including the hydrologic cycle and water resources.
Index Flood Method	A regionalisation technique for estimating peak flow of a catchment for design floods in ungauged catchments or catchments with limited data.
Intensity Frequency Duration (IFD)	The intensity of rainfall for a particular ARI storm event of a particular duration.

Kelly Line	A guideline minimum level for town planning developed in the early 1970's for Karratha and Port Hedland. Defined as 10' (3.05 m) above HAT. At Karratha HAT is 2.5 m AHD, so the Kelly Line is at 5.55 m AHD
Manning's M	A parameter for the resistance of the bed of a channel to the flow of water in it. This parameter is defined as the inverse of the Manning's n.
MIKE11	A 1D Hydraulic model developed by the Danish Hydraulic Institute (DHI) that simulates flow and water levels in rivers and floodplains.
MIKE21	A 2D Hydraulic model developed by the Danish Hydraulic Institute (DHI) that simulates flow and water levels in rivers and floodplains.
MIKEFLOOD	An integrated 1D and 2D Hydraulic model developed by the Danish Hydraulic Institute (DHI) that simulates flow and water levels in rivers and floodplains
Peak Flow	The highest level of discharge that occurs from a river during a storm event. This is represented by the highest point on the hydrograph.
Peak Steady Water Level (PSWL)	Increase in water level incorporating the effects of storm surge, wave set-up and tide.
Rational Method	A method for estimating peak flow of a catchment for design floods in ungauged catchments or catchments with limited data based on rainfall intensity and runoff coefficient.
RORB	RORB is a runoff and stream flow routing program used to calculate flood hydrographs from rainfall and other channel inputs. It calculates runoff as rainfall excess by subtracting losses from rainfall. The rainfall excess is then routed through catchment storage to produce hydrographs.
Storm Surge	Increase in water level due to effects of wind stress and low atmospheric pressure.
Topography	The Earth's surface shape, relief, landforms and features.
Tributary	A stream or river that flows into a larger river.
Wave Set-up	Mean increase in sea level due to the effect of breaking waves near a shoreline.

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1. INTRODUCTION

JDA Consultant Hydrologists was commissioned by Landcorp to undertake a Coastal Vulnerability Study for the townsites of Karratha and Dampier in the Pilbara Region of Western Australia.

1.1 Background

The Pilbara region is significant in Australia for supply of resources to international markets accounting for 35% of the mineral and petroleum production and 23% of exports. Karratha is a major service centre for this activity located in the Shire of Roebourne. It is significant in both providing services and in attracting the workforce required for the expanding activity of the region. The *City Centre Master Plan* has been developed for proposed growth in Karratha. The Town of Karratha is projected to grow to around 50,000 people over the next 20+ years.

Karratha is located 1500km north of Perth. At a sub-regional level, it is the primary centre of the West Pilbara, and forms the hub in a network of nearby towns adjacent to Nickol Bay, including the port town of Dampier, historic town of Cossack, coastal town of Point Samson, and Roebourne, which is a centre for the local Indigenous communities.

The Town of Karratha has grown rapidly in recent years, primarily to accommodate an expanding resources sector. Recent development have expanded the townsite west with the recent Bayton West development and proposed Madigan and Gap Ridge North developments. South of the main townsite is the Karratha Light Industrial Area (LIA) and to the northwest is the Karratha Airport. Significant infrastructure includes the Dampier-Paraburdoo railway line, Dampier Hwy and the North West Coastal Hwy, between Dampier-Paraburdoo railway line and Roebourne townsite.

In 2010, the resident population of Karratha was estimated at 18,000. The town also provides services to an estimated 4000 to 6000 fly-in fly-out workers (Shire of Roebourne, 2010). The Pilbara Cities initiative projects that Karratha's resident population will grow to 50,000 by 2041.

Dampier provides port facilities on the western side of the Burrup Peninsula. Port Dampier is a major export harbour, from which iron ore, salt and hydrocarbons are shipped around the world. It is also in close proximity to a large number of other existing or planned infrastructure projects, which are helping to drive economic activity in the region.

The Pilbara coast is considered to be vulnerable due to the high level of cyclonic activity. Since 1910 there have been 48 cyclones that have caused damaging wind gusts in excess of 90km/h in the Karratha, Dampier and Roebourne region.

The potential for coastal inundation is a significant constraint for future expansion and development of Karratha. This Study is required to provide information for planning and development of Karratha to enable minimisation of risk due to inundation caused by seasonal cyclonic heavy rainfall and associated storm surge. The Study is required to further consider the potential impacts of climate change on the risk of inundation, including change in the intensity of cyclonic activity and rise in sea level. The effect of coastal erosion due to climate change is also to be considered.

The projected shoreline erosion and coastal inundation level and its sensitivity to climate change over the next century are required to make informed decisions when allocating set back distances, assigning infrastructure corridors, preparing emergency response plans and improving the land value in any future development of Karratha.

1.2 Study Objectives

To purpose of the Study is to evaluate the combined effects of storm surge, coastal inundation and shoreline stability on the future expansion of the townsite for development of Karratha. The Coastal Vulnerability Study is to provide quantitative answers to the following:

- Areas in Karratha and Dampier are likely to be affected by floods at present, in 50 years (2060) and in 100 years (2110),
- The most likely shoreline position for Karratha for the above dates,
- The accuracy of these predictions, and
- A model/process that outlines the monitoring and tracking of any changes.

1.2.1 Project Objectives

The two Project Objectives are:

(A) To evaluate the combined effects of storm surge, coastal inundation and shoreline movement on the future expansion of the townsite for Karratha (including Dampier townsite)

(B) To provide estimates of the storm surge components and total water levels for a range of design return periods along Karratha coastline. (A hydraulic model is required as a part of this study).

1.3 Study Components

To address these objectives, the Study was divided into five components. A brief summary of each component is presented below.

1.3.1 Storm Surge Assessment

The requirement was for the assessment of extreme storm surge is to determine the corresponding peak steady water level resulting from the combined effects of tide, storm surge and wave set-up. The dynamic effects of wave set-up and overtopping are also to be determined.

Storm surge levels are required to address at least five Average Recurrence Intervals (2yr, 10yr, 100yr, 200yr and 500yr) showing model calibration and validation within the modelled area.

Assessment of Cyclonic Conditions is required to include provision for surge-induced water levels for different return periods along the entire Karratha Study Area shoreline. Sea surface elevation maps showing the areas of inundation are also required.

1.3.2 Hydrological Assessments

Modelling for hydrologic assessment is for design flows of 2yr, 10yr, 100yr, 200yr and 500yr ARI for rivers and watercourses at key locations and any break-out flows from adjacent rivers.

Consideration of climate change on rainfall and flow estimates is further required.

1.3.3 Hydraulic Modelling

Hydraulic modelling was required to show the combined influence of tidal surge and rainfall/runoff flood mechanisms. The hydraulic model was required to show floodplain mapping for the range of design flood events. From this, mapping of the 100yr ARI floodplain that may be developed without detrimentally impacting the general flooding regime of the area was required.

The relative timing (co-occurrence probability) of the storm surge and riverine flooding events was required.

The hydrodynamic model was to incorporate drainage networks and respective catchment information to a degree of vertical accuracy ranging from +/- 0.2m, and to a lower accuracy for the rest of the catchments.

1.3.4 Shoreline Assessment

The Study was required to report on potential acute erosion arising from pre-determined storm events as well as long-term trends in shoreline movement (accounting for sea level rise). It was further required to provide an assessment of shoreline changes for the beach system. The results of analysis were required to be provided as geo-referenced images, mapping and analysis (i.e. for shoreline positions and trends).

Further consideration was required of sea level rise and climate change by assessing sensitivity of long-term hazard lines to water level and wave effects. Hazard lines for immediate 2060 and 2110 conditions were required.

1.3.5 Climate Change

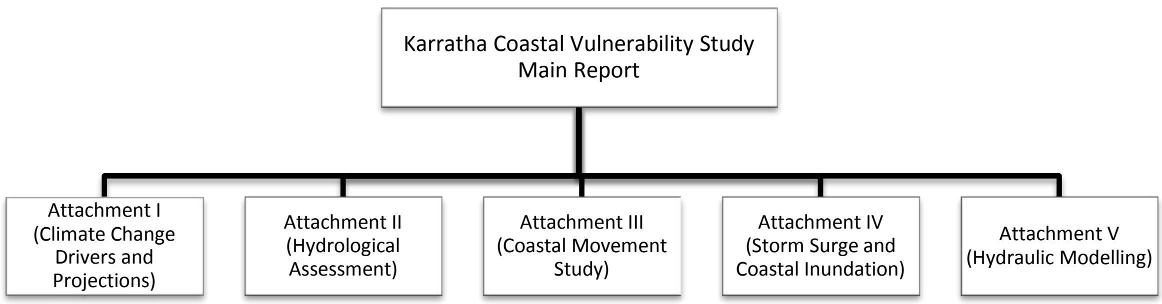
The potential changes to annual rainfall totals, rainfall intensity, mean sea level and cyclone incidence from broader global climate change was also examined. Predictions for these parameters for 2060 and 2110 were determined based on a literature review.

1.4 Report Structure

This Study has been reported in six parts, reflecting the separate components. This document is the Main Report, including a brief summary of previous studies and methodology and a detailed description of the scenarios that have been analysed and presentation of integrated results.

There are five Attachment Reports, each documenting a separate component of the Study. These Attachment Reports present a comprehensive description of the background, relevant studies and methodology. Details of the outcomes of each Study are also presented.

The flow chart below presents the reporting structure.



2. PROJECT AREA

The Study Area for this project includes the Karratha Townsite and areas that are being considered for future development. A description of this area is provided below, including an outline of the key components that contribute to flooding; the existing waterways and climate. Each of the Attachment Reports outlines the in more detail the individual environmental factors that influence the respective studies.

2.1 Study Area Location

The boundary for this Study is broadly based upon the collection of LiDAR data that was collected in November 2010. As shown in Figure 2, the Study Area includes the main Karratha townsite and the LIA. It extends southwards to include the North West Coastal Hwy. The topography within the Study Area ranges from sea level up to 130mAHD on the escarpment immediately south of the Townsite. Most of the Study Area is less than 25mAHD (Figure 3).

Apart from the developed areas, a large of the Study Area consists of native vegetation including low tussock and spinifex grass, particularly the area south of the Karratha Hills. The coastal areas consist of fringing mangrove swamps and tidal flats, particularly at the mouth of the Nickol River. These areas and the Townsite can be seen in the aerial photograph in Figure 4.

The coastal environment within the Study Area includes four coast types; tidal flats to the west and north of the townsite (Western Nickol Bay & West Karratha), and a rocky shore on the eastern edge of the Townsite (East Karratha). Further east is the Nickol River Delta (Figure 4).

The Study Area is approximately 33,500ha.

2.2 Climate

Karratha features hot summers with periodic heavy rain and mild winters with occasional rainfall. Annual average rainfall for Karratha is approximately 280mm a year (Figure 5). The maximum recorded annual rainfall is 855 mm based on records taken between 1974 and 2009 at Karratha airport (BoM, 2011). The average annual pan evaporation is approximately 3,590 mm (Luke et al, 1988). Rainfall intensity frequency duration (IFD) data for Karratha Airport is shown in Figure 6.

Most of the recorded precipitation is received during the wet season, as a result of tropical cyclones and local thunderstorms. Along the central Pilbara coast, the cyclone season runs from December to April peaking in February. A tropical cyclone is characteristically a large area of convective cloud with associated heavy rain. In the more intense tropical cyclones there may also be a clear region, the ‘eye’, situated near the cyclone centre. The strongest winds are located in a band surrounding this eye although, within the eye itself, winds are usually very light.

The Pilbara coast experiences more cyclones than any other part of Australia. Since 1910, there have been 48 cyclones that have caused damaging wind gusts in excess of 90km/h in the Karratha region. On average this equates to about one every two years. About half of these cyclones have an impact equivalent to a Category One cyclone. Ten of these: 1925, 1939, 1945, 1954, 1966 (Shirley), 1971 (Sheila-Sophia), 1975 (Trixie), 1984 (Chloe), 1989 (Orson) and 1999 (John) have caused very destructive wind gusts in excess of 170km/h (BoM, 2010).

There is significant rainfall associated with these cyclone systems. Cyclone Glenda and Claire produced 140mm and 190mm of rainfall in 2006 (BoM, 2010).

2.3 Waterways

The Study Area has numerous rivers and creeks that drain towards Nickol Bay. These waterways include Nickol River, 7 Mile Creek, Lulu Creek, Turnoff Creek and Hilux Creek as shown in Figure 7.

The major waterway is Nickol Creek to the east of the townsite. The main channel extends south of the North West Coastal Hwy beyond the extent of the Study Area, approximately 22km from the Townsite. The width of the Nickol River main channel up to is 600m near the mouth. West of the main channel are a number of large tributaries, including around the Karratha LIA and south of the Karratha Hills. The tributaries include Turnoff Creek, Lulu Creek and Hilux Creek.

The 7 Mile Creek catchment to the west of the Karratha Townsite is a secondary drainage feature (compared to the size of Nickol River catchment). The catchment for 7 Mile Creek also extends beyond the Study Area, south of North West Coastal Hwy. The catchment also includes the tributary Madigan Creek.

The Karratha Hills act as a watershed causing water to drain from the northern portion of the hills through the Karratha Townsite. There are approximately 19 catchments (GHD, 2010) and creek lines (and storm water infrastructure) which discharge flow towards Nickol Bay.

Within mudflat areas west of Karratha there is an extensive complex of mangals fringing tidal creeks (Figure 7).

3. PREVIOUS STUDIES

This is the first holistic assessment of coastal and riverine flooding in the Karratha region.

The other major Study to assist with development of Karratha was the development of the Kelly Line in the 1960s. The Kelly Line is based on an assessment of the storm surge and topography of the site and is roughly estimated as 3m above the highest recorded Astronomical Tide. The line follows Searipple and Balmoral Roads on the northern boundary of the townsite. Whilst being a useful concept to determine the northern extent of the townsite, it is limited as it only considers storm surge impacts (not riverine flooding). Significantly more meteorological and oceanographic data and modelling techniques are now available.

There have been several flood studies undertaken within the Karratha Study Area in support of local development, but not on the regional scale. Similarly there have been a number of initial studies on storm surge impacts but not with amount of data available for this assessment. A brief review of these studies is provided in this section of the report.

3.1 Climate Projections

Climate change projections in this Study have been based on a number of large peer-reviewed scientific studies. These documents are summarized in Table 1.

TABLE 1: SUMMARY OF PREVIOUS CLIMATE STUDIES

Study	Client	Year	Author	Overview
IPCC Fourth Assessment Report	-	2007	Intergovernmental Panel on Climate Change (IPCC)	This document is a review of peer-reviewed scientific, technical and socio-economic information relevant to the understanding of climate change. The Physical Science Basis, in particular Chapter 11 Regional Climate Projections presents projected change in mean precipitation, extreme rainfall and tropical cyclone activity across Australia and New Zealand.
Climate Change in Australia	-	2007	CSIRO	The CSIRO Climate Change in Australia report presents the most current climate change predictions for Australia. The report outlines predicted changes for a range of parameters including temperature, rainfall and sea level rise for scenarios at 2030 and 2070. The report advances the information presented in IPCC 2007 as it downscales the projections to generate climate change ‘futures’ by bioregion
Sea Level Change in Western Australia: Application to Coastal Planning	-	2010	Department of Transport	The report reviewed the current information on mean sea level variation along the Western Australian coastline, and provided recommendations on an appropriate allowance for mean sea change to be used in coastal planning.

The Coastal Vulnerability Study has included the information in these documents in projections for future climate scenarios. There has also been a consideration of unpublished data through consultation with experts from the Centre for Australian Weather and Climate Research (CAWCR) and the Centre for Marine and Atmospheric Research (CMAR).

3.2 Hydrology

Example hydrological studies that have previously been carried out for the Karratha region are summarized in Table 2.

TABLE 2: SUMMARY OF PREVIOUS HYDROLOGY STUDIES

Study	Client	Year	Author	Overview
Surface Water Hydrology of the Pilbara Region	-	2000	WRC	Describes the surface hydrology of the Pilbara region including an overview of the drainage basins, stream flow and water quality. Peak flow for five selected rivers were estimated using Log Person Type III and GEV.
Maitland Industrial Estate Hydrology Study	LandCorp	2009	JDA Consultant Hydrologists	Hydrological investigation for Maitland Industrial Estate Karratha was performed to estimate 100yr ARI flow using available record of Maitland River and other rivers in the region. Frequency curves were fitted to the historical data, using Log person III
7 Mile Creek Flood Study	LandCorp	2009	GHD	GHD used the Urban B Mike11 Hydrology sub-model to determine the overland flow from the catchments. The model was calibrated using the Rational Method based on local gauged catchments
Madigan Creek Flood Study	LandCorp	2010	JDA Consultant Hydrologists	Runoff was estimated for the Madigan Creek catchments for input into hydraulic modelling. It was estimated using the RORB model with validation using the Rational Method and Index Flood Methods

There have been a number of different approaches to hydrological assessment within the Karratha region. These studies have been limited to a small number of catchments and have utilised different methods.

The current Study improves the previous work because of these factors:

- Examining the hydrology a regional scale;
- Using multiple methods for comparison.

3.3 Coastal Movement

The extensive field and research studies required to describe the relationships between environmental drivers and geomorphic response (coastal movement), in a Western Australian context, have not been fully resolved. Although significant research and data sets have been accumulated, much of the relevant information remains fragmented. Assessment of these studies is provided in the Attachment III Report.

3.4 Storm Surge

Two comprehensive Storm Surge studies have previously been carried out for the Karratha Region. These are summarized in Table 3.

TABLE 3: SUMMARY OF PREVIOUS STORM SURGE STUDIES

Study	Client	Year	Author	Overview
Karratha Storm Surge Study	Shire of Roebourne	1997	Bureau of Meteorology	Original Karratha Study reporting surge levels at selected locations
West Pilbara Cyclonic Storm Surge Study	Shire of Roebourne (Study No G06/0506)	2009	GEMS	1997 study results converted to GIS layers Worst 'track' inundation estimates computed consistent with WA SPP 2.6

The 1997 study was carried out by the Bureau of Meteorology Special Services Unit, using the pre-cursor model to the GEMSURGE model. Storm levels in this study were reported for spot locations, rather for the entire model grid. The West Pilbara Cyclonic Storm Surge Study completed in 2009 was primarily focussed on the Cape Lambert area but included some work undertaken to update the 1997 study. A noted limitation of the earlier studies was the lack of a comprehensive high resolution DEM for the area.

The current Study improves the accuracy of the previous work because of these factors:

- improved definition of the topography through application of a new Digital Elevation Model based on recent LIDAR surveying for the area;
- a more extensive cyclone database;
- improved modeling techniques in relation to the treatment of wave set-up, and
- the ability to undertake a higher number of model simulations due to increased computing speed.

3.5 Hydraulics

There are several flood studies within the Study Area. Although these reports lack the accuracy of data available in the current Study, and do not analyse future climate predictions they provide data for comparison.

TABLE 4: SUMMARY OF PREVIOUS FLOOD STUDIES

Study	Client	Year	Author	Overview
7 Mile Creek Flood Study	LandCorp	2009	GHD	Investigated flood levels in support of a proposed development
Karratha Drainage Assessment	Shire of Roebourne	2010	GHD	The study examined the existing stormwater drainage network with the Karratha townsite. Nineteen drain systems were identified and a site investigation defined drain type, cross section description and vegetation for each
Madigan Creek Flood Study	LandCorp	2010	JDA Consultant Hydrologists	Madigan Creek was modelled using a 1D Mike11 Model to determine flood levels in support of a number of developments along the creek

These studies are examples of some of the various flood studies that have been conducted for the Karratha Area. None of these studies have been performed using a coupled 2D and 1D Hydraulic Model and they have been based on limited survey information. The scope of these studies has also been limited to a local scale approach in support of particular developments.

The current Study improves the accuracy of the previous work because of these factors:

- Taking a regional scale approach to identify major flow paths and tributaries
- Improved definition of the topography through application of a new Digital Elevation Model based on recent LIDAR surveying for the area;
- 2D modeling coupled with a 1D model utilizing the improved topography data.

3.6 Anecdotal Evidence

Validation of the Storm Surge and Hydraulic Modelling requires observed flood levels for comparison with modelled flood levels. A request was made for historical flood level within the Study Area. The Department of Water does not have any information within the Study Area with the only data available at the Maitland River gauging station (outside of the Study Area). Main Roads was able to provide flood levels along the North West Coastal Hwy for Cyclone Connie (1987); however this data precedes the construction of bridges along the highway and could not be used for validation. There is also no historical information available from the Shire of Roebourne.

During flooding from TC Bianca in January 2011, Craig Davey, the Shire Surveyor, took a number of photographs at various sites within the Study Area. From these photographs, flood level locations were identified, which were later surveyed by Whelans. Flood level locations included the Karratha Rd floodway by the LIA, a floodway on North West Coastal Highway, and 7 Mile Creek at Dampier Hwy. These flood levels were used to validate the Hydraulic model and further details are provided in Attachment Report V.

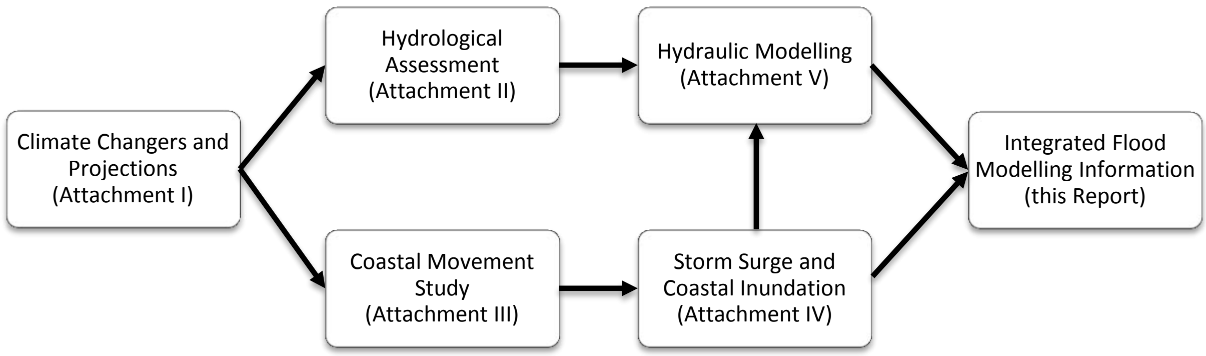
A survey of debris from Tropical Cyclone Carlos in February 2011 was also undertaken for validation of the Storm Surge model. Although a relatively weak storm, with mean wind speeds reaching 60-70 mph at Karratha Airport, ‘Carlos’ produced an abnormal increase in water levels in Nickol Bay.

4. METHODOLOGY

A Coastal Vulnerability Study involves a multi-disciplinary approach with a varied methodology. A description of the conceptual approach is outlined below. Each of the Attachment Reports details the methodology applied for the respective Study but a brief summary of each approach is also provided in this section of the report.

4.1 Conceptual framework

The broad methodology of this Study is to establish the flooding conditions for the Study Area and then determine the impacts with under future climate scenarios. The outcomes of each Study are integrated and outlined conceptually in the flow chart below.



Attachment I, Climate Change Drivers and Projections, examined the predicted climate change. The results of this Study component feeds into the each of the other four Study components. The Hydrology Study (Attachment II) produces hydrographs that are used for Hydraulic Modelling. The Shoreline Stability Study (Attachment III) examines predicted shoreline locations and provides inputs for the Storm Surge Modelling. Storm Surge Modelling (Attachment IV) produces maximum water levels and boundary conditions for the Hydraulic Modelling. The Hydraulic Modelling (Attachment V) utilises climate change projections, inflow hydrographs and storm surge boundary conditions along with topographic data to determine maximum riverine flood levels.

Outputs for the Shoreline Stability, Storm Surge Modelling and Hydraulic Modelling are then integrated to determine the risk of flooding within the Karratha Study Area.

4.2 Climate Change

Flooding within Karratha is generally associated with extreme climate events and rising sea levels. Climate change is expected to affect temperature, global circulation, synoptic weather systems, rainfall, sea level and wave climate (IPCC, 2007). The specific impacts on the flooding around Karratha include a rise in mean sea level, increases in rainfall intensity and an increase in the frequency and magnitude of cyclones.

These three factors have been addressed within this Study through a review of relevant studies for the Pilbara including local and global studies. Reviewed documents include Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (2007), Climate Change in Australia (CSIRO, 2007) and Sea Level Change in Western Australia: Application to Coastal Planning (Department of Transport, 2010). Consultation with climate researchers was also undertaken to include any current research.

Predictions were made for the 2060 and 2110 climate scenarios based on a framework from the National Council for Coastal and Ocean Engineering (Engineers Australia, 2004).

4.3 Hydrological Assessment

The hydrology has been investigated, including all catchments discharging through the Karratha Study Area. Three large catchments for the Study Area were determined; 7 Mile Creek, Nickol West Tributaries and Nickol River (Figure 8).

Hydrologic analysis of the contributing catchments was performed to estimate peak flows and design hydrographs for the various design ARI storm events. Techniques include:

- Flood frequency analysis,
- Regional methods from Australian Rainfall and Runoff (IEAust, 1997) such as the Rational Method and Index Flood Method,
- Hydrologic catchment modelling.

Hydrograph generation was an important requirement of the Hydrologic Assessment as the Hydraulic Modelling Assessment incorporates flow from the catchments to the south of the Study Area and routes runoff through the Study Area.

Therefore two hydrologic catchment models were assessed. These were the RORB and XP-Storm software models. These models were compared and validated against peak flows estimates from Rational and Index Flood Methods and regional stream flow gauging data analysis.

Although two hydrograph methods were assessed only one was required for generating the hydraulic model input. The XP-Storm model was selected as this model allowed greater control of hydrograph time step data.

4.4 Coastal Movement Study

The Coastal Movement Study investigated the predicted shoreline locations based on projected sea levels and increase cyclone activity. The approach has included field reconnaissance and survey; interpretation of aerial imagery and desktop analysis of available metocean data. Aerial imagery analysis was undertaken with aerial photography from 1942, 1968, 1976, 1992, 2001 and 2008. The interval between imagery is longer than the typical 5 years suggested for sandy coasts in SPP No. 2.6 (WAPC 2003), but is sufficient to demonstrate that the mangrove and rocky coast is not subject to short-term storm erosion and recovery that may bias aerial photograph interpretation on softer coasts.

Karratha's coastal structure is developed through the interaction of vegetation and sediments, interacting with a significant rock presence. Drivers for change, including water level and wave forcing, are highly episodic within the Pilbara region, and their impacts are strongly influenced by the landform structure. As a consequence, a Study methodology has been developed with variable assessment methods for coastal change with different shore types. Four coast types were identified; Western Nickol Bay, West Karratha, East Karratha and Nickol River Delta. Interactions between landform units have been considered through the application of the sediment budget concept within the domain of Nickol Bay.

This Study has derived process-based models for four different shore types, targeting the key elements of possible future climate impacts. It should be recognised that these models are preliminary and empirical in nature, as the extensive field and research studies required to describe the relationships between environmental drivers and geomorphic response, in a Western Australian context, have not been fully resolved. Conceptual methods used to undertake assessment across the range of different shore types are outlined in Attachment Report III.

Projection of future coastal change has considered the existing active processes, in the context of the regional geomorphology and the presence of rock features.

4.5 Storm Surge and Coastal Inundation

A major component of flooding for Karratha is inundation from the ocean caused by storm surges. The storm surge Study aimed to provide estimates of the storm surge water levels along the Karratha coastline. Water levels were generated using the GEMSURGE model, a 2D coastal ocean model that determines currents and water levels from specific tidal forcings and meteorological conditions. Wave processes (regional wave set-up and regional wave run-up) were modelled using SWAN model and cyclone winds were generated using empirical model developed by the Australian Bureau of Meteorology (Holland, 1980). This suite of models was utilised to determine water levels for known cyclone events. To generate water levels for each ARI event a statistical analysis is applied to all of the modelling results. Wave run-up is further estimated using empirical techniques to estimate wave run-up for existing coastline (Appendix E).

The model was validated using a number of significant cyclone events in the North West of Western Australia. In particular, a survey of debris associated with cyclone Carlos in February 2011 was used to support the validation.

Future climate scenarios were assessed in the model using results from the Climate Change Study and the Coastal Movement Study. Based on these studies, the model included an increase in water level and cyclone intensity and removal of the mangrove areas by 2110, including flattening of the topography in mangrove areas.

4.6 Hydraulic Modelling

Riverine flooding of Karratha was assessed using DHI's MIKE FLOOD model, a dynamic coupling of a MIKE21 model (in this case a 2D representation of the Study Area) and a MIKE11 model (predominantly used to represent 1D structures). The MIKE21 model comprises a bathymetry file (topography), a roughness coefficient (resistance), boundary conditions (inflows and water levels), initial water levels and secondary model parameters (simulation parameters, eddy viscosity and wetting/drying parameters).

The topography is generated from the LiDAR survey conducted for Karratha in 2010. The survey data was converted into a 20m grid to cover the Study Area shown in Figure 3. Further survey information was added to the east of the Study Area to allow for the modelling of eastern tributaries of the Nickol River. This additional survey information is based on Landgate 10m Contours.

The boundary conditions for the model were generated in the Hydrology and Storm Surge studies. Inflow hydrographs have been described in the summary of the Hydrology Study. The sea level boundary condition was generated from the storm surge modelling, however, owing to joint probabilities a lower storm surge ARI was used for the hydraulic modelling. A 1:5 probability was used for this Study, that is, for the 100yr ARI hydraulic model, the results from the 20yr ARI storm surge model were used as a boundary condition. This approach is consistent with other coastal vulnerability studies in the region and Australia.

The model was validated using observed flood levels from Cyclone Bianca in February 2011. Cyclone Bianca was between a 2yr ARI and 5yr ARI event. Observed water levels were surveyed and compared against modelling output. Sensitivity analysis was also conducted for changes in resistance values

(Manning's M) and changes in inflow hydrographs. The sensitivity analysis demonstrates that the model is not significantly sensitive to either parameter for the Cyclone Bianca event.

The hydraulic model accounts for future climate scenarios through changes in inflow hydrographs and storm surge boundary conditions. There is also an increase in rainfall intensities for the internal rain-on-grid runoff generator.

5. SCENARIOS FOR ANALYSIS

The objectives of this Study were to determine the extent of flooding for the 2yr, 10yr, 100yr, 200yr and 500yr ARI storm events as described in Section 1. For each of these ARI events, three climate conditions were analysed; the 2010 (current) climate and projected 2060 and 2110 climates. A description of these scenarios is provided in this section.

5.1 Baseline Information

The baseline information for this Study is the mean sea level and current climate information including cyclone frequency and rainfall intensity. The current rainfall intensity is represented in the IFD data in Figure 6.

Cyclone frequency and intensity was analysed by GEMS as part of the Storm Surge and Coastal Inundation (Attachment IV) component of this Study. The aim of this analysis was to quantify recurrence intervals for water levels resulting from cyclone activity. Data for cyclones impacted on the Karratha area between 1950 and 2010 were examined to produce synethic storms based on actual storm tracks. Further information about this approach is provided in the Attachment Report IV.

5.2 Climate Change Projections

Following a literature review (as outlined in Sections 3 and 4), climate projections were made for the 2060 and 2110 scenarios. Recommendations were made on sea level rise, rainfall intensity and cyclone activity and are shown in Table 5. Further detail is provided in Attachment Report I.

The key outcomes of the Study are an increase in sea level of 0.3m by 2060 and 0.9m by 2110. Both cyclone frequency and intensity is predicted to increase by 10% and rainfall intensity increases up to 20% by 2060 and up to 30% by 2110 for larger ARI events (>20yr ARI).

TABLE 5: CLIMATE CHANGE DATA

Time frame	Mean Sea Level (m)	Rainfall / Runoff Intensity (mm/hr)	Cyclone Incidence	
			Frequency	Intensity
2010	0	-	-	-
2060	**0.3**	**0% to 20% Higher end for ARI >20 yr**	**+10%**	**+10%**
2110	**0.9**	**10% to 30% Higher end for ARI >20 yr**	**+10%**	**+10%**

These projected climate scenarios have been adopted throughout the Study, including Hydrological, Storm Surge and Hydraulic Modeling and analysis of the Coastal Movement.

The Hydrological models, RORB and XP-Storm, implement the projected change in rainfall intensities by increasing the current Intensity-Frequency-Duration data by the projected increase within the input sections of the models. The model then calculates the new hydrograph for each catchment. The Hydrology Study identified that increasing rainfall intensity by 20% will result in a greater than 20% increase in peak flow (Figure 9).

The Storm Surge modelling implements change in cyclone intensity by converting cyclone pressure to a deficit to the background pressure, increasing the deficit by 10% and then converting back to its absolute pressure (see Attachment IV, Section 3.7.1 for more detail). Cyclone frequency was addressed by increasing the storm rate of occurrence by 10%. For details of the return period calculation, see Attachment IV, Section 3.6.

The Hydraulic modelling utilised the climate change adjusted inputs (inflow hydrographs and sea level boundary condition) as well as direct rainfall intensities adjusted for climate change as for the Hydrologic modelling.

5.3 Scenarios

For the Study, sixteen scenarios were analysed. Fifteen scenarios represent the five ARI events and three climate scenarios. Hydrological, storm surge and hydraulic modelling was performed for the 2yr, 10yr, 100yr, 200yr and 500yr ARI storm events. This was performed for the current climate scenario (2010), 50 year projected climate scenario (2060) and 100 year projected climate scenario (2110). Table 6 below outlines these fifteen modelled scenarios.

TABLE 6: CLIMATE CHANGE SCENARIOS

ARI	2010 Climate	2060 Climate	2110 Climate
2yr	✓	✓	✓
10yr	✓	✓	✓
100yr	✓	✓	✓
200yr	✓	✓	✓
500yr	✓	✓	✓

The sixteenth scenario represents a mix of climate scenarios. The predicted increase in sea levels is generally accepted in Western Australia, and planning of coastal regions requires that sea level change is taken into account. However the predicted change in rainfall intensities is less conclusive, and as yet has not been adopted for future planning. Department of Water therefore requested a scenario where the 2110 storm surge was applied with runoff generated from 2010 rainfall conditions.

6. INTEGRATED RESULTS

Results from each separate component of this Study have been integrated to provide an indication of flooded areas within the Study Area. As shown in Section 1.4, outputs from the Climate Projection Study (Attachment I), Hydrological Study (Attachment II) and Coastal Movement Study (Attachment III) have been used to generate maximum water levels through Storm Surge Modelling (Attachment IV) and Hydraulic Flood Modelling (Attachment V). The results from Storm Surge and Hydraulic Modelling have been integrated to determine the maximum flood levels across the site. The predicted shoreline locations are also presented below. Wave run-up has also been detailed to provide run-up levels as storm surge modelling includes wave set-up and regional wave run-up. Further details of each Study component are presented in the respective reports.

6.1 Shoreline Location

Projected coastal change was developed for each of the four coast types; Western Nickol Bay, West Karratha, East Karratha and Nickol River Delta. A brief summary of these projected coastal changes is provided below. The projected coastal changes and breaching hazard have been combined to develop a coastal development plan for a sea level rise scenario of 0.9m, nominally for 2110 (Figure 10). The plan identifies four different components:

1. Shoreline changes projected to occur by 2110 including tidal creek expansion. Construction undertaken seaward of this zone will be subject to significant erosive pressure;
2. Existing coastal dunes. These should not be subject to excavation, trimming or lowering, as they form the major natural protection for Karratha Townsite. As the dunes are not continuous, storm surge can pass through the gaps, however the dunes reduce water energy transmitted past the dune, limiting structural loading;
3. A 500m width protective buffer of land below 9m AHD, landward of dunes from the airport to the dune ridge east of Karratha golf course, which may potentially be subject to breaching;
4. An area subject to occasional marine influence, within which development requires management to mitigate inundation risk and structural design suitable to cater for wave impact, flooding and drainage.

6.1.1 Western Nickol Bay

Approximately 50% of the shoreline along western Nickol Bay is determined by the Dampier Salt bunds. For assessment purposes, it has been assumed that this facility will be morphologically isolated from the Karratha mudflats over the 100 year planning time frame. This requires that levees will be progressively upgraded when subject to overtopping damage, and will be reinstated in the event of breaching. Under the projected sea level rise scenario, the following changes have been determined:

- Tidal creek expansion will accelerate in response to sea level rise, with a 60% expansion of width and length projected by 2060 and potential for a 180% expansion by 2110;
- Destabilisation of the fringing mangroves will occur due to increased sediment transport for a sea level rise of 0.4 to 0.7m, which is projected to occur from 2070 to 2090;
- Following destabilisation of the fringing mangroves, there is insufficient material storage in the dune adjacent to the airport, such that breaching due to overtopping is likely.

6.1.2 West Karratha

The majority of Karratha townsite is landward of a high, largely continuous coastal dune, which in turn is fronted by a tidal flat and mangrove fringe. Present-day dynamics suggests that the tidal flat is experiencing accumulative behaviour, and will continue to actively demand sediment in response to increasing sea level. Existing available sediment supply, principally through marine sources, is inadequate to keep pace with sea level rise, suggesting that the tidal flat will progressively experience inundation, commencing with development of a tidal creek network, and moving towards formation of a coastal lagoon with sea level rise in the order of 0.3-0.5m. Subsequent destabilisation of the fringing mangrove is projected to occur from 2070 to 2090. Sediment demand from the coastal dune will occur and is likely to result in general scarp formation, with more focused erosion adjacent to tidal creeks.

As sea level rise continues, zones of focused erosion will facilitate breaching of the coastal dune during extreme cyclone events. The level of protection afforded by the dune increases towards the east due to the higher and wider dune structure. From the airport to the dune ridge east of Karratha golf course, breaching of the dune is likely to occur by 2110. Seaward of Town Beach, breaching is unlikely (~10% likelihood), and there is considered negligible risk of breaching the high dune in front of the golf course for the next 100 years.

6.1.3 East Karratha

This section of coast has a narrow fringe of mangroves, fronting a thin section of low lying sandy foreshore and backed by rocky hinterland. Extensive rock features are present above existing high water level, characteristic of a previous coastal position.

The landform features in front of the rock will provide mild resistance to the pressure of rising sea level, but ultimately, a 0.3-0.5m sea level rise is sufficient to overwhelm the fringing mangroves, which is projected to occur from 2060 to 2080. The rocky structure at the back of the coast provides a significant constraint to potential coastal movement, and may be considered largely a stable configuration. For mapping purposes, the coastline has been considered the +3.5m AHD contour, taking into the highest astronomical tide, plus 1.0m sea level rise.

6.1.4 Nickol River Delta

The predicted response to climate change for the Nickol River Delta is gradual drowning under projected sea level change. The Nickol River delta is supplied by sediment from both marine and fluvial sources. A recommended setback position has been determined through consideration of maximum sediment demand from the tidal flats, if they were to keep pace with the sea level rise.

6.2 Flooding

The 100yr ARI flooding results are presented for the 2010, 2060 and 2110 climate scenarios. This ARI event has been highlighted as the 100yr ARI event is widely adopted as the basis for land use planning in Western Australia. Results for the 2yr, 10yr, 200yr and 500yr ARI events are shown in Appendices A to D.

6.2.1 100yr ARI 2010 Climate Scenario

The 2010 Climate Scenario represents the current baseline climate conditions. As discussed previously, the 100yr ARI hydraulic model was simulated using a downstream boundary condition set to the 20yr ARI storm surge level. The results of this modelling were integrated with the results for 100yr ARI Storm Surge modelling to determine the maximum water levels for the 100yr ARI event. This approach has been used for all the modelled scenarios.

Tag points have been selected within the Study Area for comparison of flood levels with peak levels shown in Table 8 and tag point locations shown in Figure 11.

The integrated results of the 100yr ARI (2010) modelling are presented in following figures:

- Figure 11: 100yr ARI (2010) Flood Depth (m)
- Figure 12: 100yr ARI (2010) Flood Levels (mAHD)

Figure 12 has been split over six plans to provide better clarity of results. The flooding shown in these figures indicates that a significant amount of inundation occurs within the Study Area. Storm Surge impacts are focused generally east of the townsite with the Nickol River tidal flats and northwest of the townsite. The Kelly Line, which follows the northern edge of the townsite, generally represents the extent of flooding.

In the west, 7 Mile Creek experiences major riverine flooding. Where North West Coastal Highway (NWCH) crosses the 7 Mile Creek tributaries, these crossings are all subject to significant inundation. The eastern tributary downstream of NWCH shows a large width of flooding, however most of this is less than 0.25 m depth. At Dampier Rd, flow is constrained by the bridge structure resulting in a depth of flow behind Dampier Rd. Downstream of Dampier Rd, storm surge influence becomes predominant, with significant flooding across the mouth of 7 Mile Creek.

Madigan Creek, to the east of 7 Mile Creek, is also constrained at Dampier Rd, with significant flow over the floodway at this location. There is also flow westward across Madigan Rd to 7 Mile Creek, upstream of Dampier Rd.

In the southern section of the Study Area, the Nickol River tributary east of Karratha Rd shows up to 500 m width of flooding with flood depth of up to 1 m. The creeks at the western extent of the tributary are generally less than 0.25 m depth. The contributing creeks to the south of the NWCH all discharge across the highway at floodways and at peak level result in up to 200 m of inundated roadway.

The other contributing tributaries of the Nickol River to the south of NWCH (east of Karratha Rd) show significant inundation of the highway at each crossing point. Turnoff Creek shows greatest depth of flow, and is generally the most channelized. At NWCH, the width of flooding is approximately 400 m. Lulu Creek shows breakouts of flow downstream of NWCH to the east and west. At NWCH, approximately 500 m of roadway is inundated at peak levels. Eastward from Lulu Creek, the unnamed creeks often combine and pool behind NWCH with flows at floodways. Hilux Creek is relatively channelized with flow interact with other creeks immediately upstream of NWCH. The Nickol River crossing of NWCH results in significant inundation along several kilometres of highway.

The Karratha LIA is mostly protected from flooding, flood waters to the south of Anderson Rd and north of Mooligunn Rd. The creek crossing of Coolawanyah Rd adjacent to Mooligunn Rd is subject to significant inundation with several hundred metres of road under water. The eastern section of the LIA is not subject to flooding also.

Within the townsite, terrestrial runoff is generally confined to existing stormwater channels and roads. As discussed in Section 7, the scale of the modelling needs to be considered for these results. The townsite is generally at greater risk from storm surge. The section of Balmoral Rd between Gawthorne Drive and Warambie Rd is subject to some inundation at peak surge levels.

6.2.2 100yr ARI 2060 Climate Scenario

The 2060 Climate Scenario was modelling using the climate projects of 0.3m rise in sea level, 10% increase in cyclone frequency and intensity and a 20% increase in rainfall intensity, consistent with the Attachment I Report.

The integrated results of the 100yr ARI (2060) modelling are presented in following figures:

- Figure 13: 100yr ARI (2060) Flood Depth (m)
- Figure 14: 100yr ARI (2060) Flood Levels (mAHD)
- Figure 15: 100yr ARI (2010 and 2060) Flood Extent Comparison

The impact of climate change is discussed below in Section 6.3.

6.2.3 100yr ARI 2110 Climate Scenario

The 2060 Climate Scenario was modelling using the climate projects of 0.9m rise in sea level, 10% increase in cyclone frequency and intensity and a 30% increase in rainfall intensity, consistent with the Attachment I Report.

The integrated results of the 100yr ARI (2110) modelling are presented in following figures:

- Figure 16: 100yr ARI (2110) Flood Depth (m)
- Figure 17: 100yr ARI (2110) Flood Levels (mAHD)
- Figure 18: 100yr ARI (2010, 2060 and 2110) Flood Extent Comparison

The impact of climate change is discussed below in Section 6.3.

6.2.4 100yr ARI 2010 Runoff / 2110 Storm Surge Scenario

This Scenario was modelling using the climate projects of 0.9m rise in sea level, and 10% increase in cyclone frequency and intensity for storm surge, consistent with the Attachment I Report.

The integrated results of the 100yr ARI (2010/2110) modelling are presented in following figures:

- Figure 19: 100yr ARI (2010/2110) Flood Depth (m)
- Figure 20: 100yr ARI (2010/2110) Flood Levels (mAHD)

The results of this Scenario are essentially a combination of previous Scenarios. The terrestrial peak flood levels are identical to the 2010 results, while the storm surge levels are identical to the 2110 results.

6.2.5 Other ARI Results

Further integrated modelling results for other ARI are presented in Appendices A to D. Modelling was undertaken for the 2yr, 10yr and 200yr ARI events for each of the climate scenarios. A list of the outputs that are presented in Appendices A to D are shown in Table 7.

The 500yr ARI event represents the largest flooding event modelled for the 2010 climate in this Study. The flooding extent and levels in Figures D1 and D2 (Appendix D) shows an increase in flooding compared to the 100yr ARI flooding. Flood levels for the tag points indicate an increase of between 0.4m and 1.2m (Table 8) compared to the 100yr ARI event.

The increased flood levels result in increased extent of flooding compared to the 100yr ARI. The majority of the area between Turnoff Creek and Hilux Creek now shows inundation greater than 0.1 m, and the area immediately west of Nickol River shows greater depth of flooding. The tributary west of Karratha Rd shows increased width of flow, particularly in the upper catchment. The width of flooding in 7 Mile Creek has increased, with longer lengths of roadway inundation for North West Coastal Highway. There is also greater extent of inundation of land on the western bank of the 7 Mile Creek mouth.

Within the townsite, the greater storm surge levels result in increased inundation of coastal properties along Balmoral Rd. There is also increased inundation of the golf course and land south to Searipple Rd, with some flooding of the vacant land north of Richardson Way, and properties on Dugald Way.

TABLE 7: OTHER ARI RESULTS

ARI	2010 Climate	2060 Climate	2110 Climate
2yr Flood Depth	Appendix Figure A1	Appendix Figure A3	Appendix Figure A6
2yr Flood Level	Appendix Figure A2	Appendix Figure A4	Appendix Figure A7
10yr Flood Depth	Appendix Figure B1	Appendix Figure B3	Appendix Figure B6
10yr Flood Level	Appendix Figure B2	Appendix Figure B4	Appendix Figure B7
200yr Flood Depth	Appendix Figure C1	Appendix Figure C3	Appendix Figure C6
200yr Flood Level	Appendix Figure C2	Appendix Figure C4	Appendix Figure C7
500yr Flood Depth	Appendix Figure D1	Appendix Figure D3	Appendix Figure D6
500yr Flood Level	Appendix Figure D2	Appendix Figure D4	Appendix Figure D7

6.3 Impacts of Climate Change

There is a clear increase in flooding associated with the projected climate change scenarios. As discussed in Section 5, the projected climate includes increases in rainfall intensity (20% by 2060 and 30% by 2110), cyclone frequency (10% for both 2060 and 2110) and sea level (0.3m by 2060 and 0.9m by 2110). The impact of these changes can be seen in Figures 15 and 18.

Table 8 below indicates the water levels associated with each climate scenario at the tag points for the 100yr and 500yr ARI events.

Projected coastal change as a result of climate change varies for each of the four coast types. Changes include tidal creek expansion, tidal flat and mangrove destabilisation and breaching of coastal protection systems including dunes, rock features and bunding.

Tidal creek expansion is significant for the Western Nickol Bay and Nickol River Delta where expansion is accelerated in response to sea level rise. Western Nickol Bay has a project expansion in length and width of 60% by 2060 and a potential 180% by 2110. The Nickol River Delta has a projected gradual drowning due to sea level rise.

Tidal flat and mangrove destabilisation is significant for the Western Nickol Bay and West Karratha areas. Destabilisation of fringing mangroves at Western Nickol Bay will occur due to increased sediment transport projected to occur between 2070 and 2090. Destabilisation at this location is likely to result in a breach of the dune system adjacent to the airport due to insufficient material (sediment) storage. The West Karratha area includes the majority of the Karratha townsite which is protected by a highly, largely continuous coastal dune. Destabilisation of the fringing mangrove seaward of the dune system and sediment demand from the coastal dune will occur and is likely to result in general scarp formation, with more focused erosion adjacent to tidal creeks. Zones of focused erosion will facilitate breaching of the coastal dune during extreme cyclone events and between the existing creek channels likely by 2110.

The East Karratha area is protected by the extensive rock features present above the existing high water level. While destabilisation of the seaward fringing mangroves the feature provides a stable configuration above the mapped coastline landward of the formation (Section 6.2.1).

A comparison of flood extent for the 100yr and 500yr ARI between current and 2060 climate scenarios is shown in Figure 15 and Appendix D Figure D5 respectively. It can be seen there is only a marginal increase in flood extent for both the 100yr and 500yr ARI events. Table 8 indicates that there is a maximum increase of 0.5 m for the 100yr ARI with an average of 0.2 m increase. Most of the increase occurs at the coast where the predicted 0.3 m increase in sea level occurs. This can be seen in Figure 15, which shows little change in flood extent in 7 Mile Creek upstream of Dampier Rd and the Nickol River and tributaries.

Comparing the 2010, 2060 and 2110 flood extents for the 100yr ARI event (Figure 18) shows that the flooding extent for the 100 year ARI 2110 scenario is much greater than for 2010 and 2060 scenarios.

The largest increase in flood levels occurs in the coastal areas with increases of up to 1.9m between 2010 and 2110. The largest increase occurs in the mouth of 7 Mile Creek with tag points T8 and T27 both showing increases greater than 1 m. Along the coast flood levels increase by 0.7 to 1.0 m. In the tributaries of 7 Mile Creek and Nickol River flood levels increase by 0.3 to 0.4 m. An average of 0.5 m increase is seen over all tag points.

The increase at the mouth of 7 Mile Creek is a result of the change in coastline, increase in sea level, location within Nickol Bay (concentration of storm surge) and increase in runoff from the 7 Mile Creek catchment. This is seen in the increase in flood extent along the western bank of 7 Mile Creek, particularly so downstream of Dampier Rd.

The coastline between 7 Mile Creek and the townsite sees increased inundation of the vacant land north of Balmoral Rd. Flood extent within the tributaries of 7 Mile Creek and Nickol River has increased, although this will have little impact on existing infrastructure.

The 500yr ARI (Appendix D Figure D8) comparison shows similar impact of climate change, with similar increases in flood levels to the 100yr ARI impact. Almost all of the area between Turnoff Creek and Nickol River downstream of NWCH is subject to inundation. Inundation at the mouth of 7 Mile Creek increases. Overall flood levels increase by 0.4 m compared to the 2010 climate scenario.

6.4 Wave Run-Up Estimation

Wave run-up along the Karratha coastline was estimated based on empirical technique methods as defined in coastal engineering texts. These methods are based on physical model testing and field observations indicate that this may exaggerate run-up compared to field data. Appendix E provides a summary of wave run-up methods, influencing factors and estimation for Karratha.

There are a number of factors influencing wave run-up, which include near and onshore slopes, near and onshore roughness, permeability, nearshore transition depth, near and offshore wave conditions and wave direction. Of these factors, it is the near and onshore slopes which are the most significant.

The storm surge levels associated with the 100 year to 500 year ARI events are between 6 mAHD and 9 mAHD. These levels correspond to natural surface levels within the floodplain area located between the Karratha townsite and the coastal dunes, and the floodplain areas of 7 Mile Creek and Nickol River. These areas have gradients in the range of 1 in 60 to 1 in 300. Waves approaching across this gradually sloping area are strongly damped by friction, resulting in energy loss. Wave run-up levels are estimated to be between 0.1 m and 0.3 m within the Study Area.

Future development of floodplain areas affected will need to manage wave run-up, as run-up levels can be significantly increased when fill is brought in to provide clearance and a steep batter slope to natural surface is created. Management to minimize batter slope or provide structural design to accommodate some overtopping may be required in these cases.

TABLE 8: WATER LEVELS AT TAG POINTS (mAHD)

Tag Points	2010 100y ARI Water Level (mAHD)	2060 100y ARI Water Level (mAHD)	2110 100y ARI Water Level (mAHD)	2010 500y ARI Water Level (mAHD)	2060 500y ARI Water Level (mAHD)	2110 500y ARI Water Level (mAHD)
T1	11.0	11.2	11.2	11.4	11.6	11.7
T2	8.6	8.9	9.0	9.2	9.5	9.6
T3	5.9	6.2	6.7	6.9	7.1	7.5
T4	5.9	6.2	6.7	6.7	7.0	7.5
T5	5.5	5.8	6.3	6.7	6.7	7.1
T6	7.6	7.9	8.0	8.2	8.4	8.5
T7	13.5	13.5	13.6	13.6	13.7	13.7
T8	7.3	7.6	8.4	8.4	8.8	9.0
T9	10.6	10.9	11.0	11.1	11.3	11.4
T10	13.5	13.7	13.8	14.0	14.2	14.4
T11	10.0	10.1	10.1	10.2	10.2	10.3
T12	12.9	13.0	13.0	13.1	13.2	13.2
T13	11.0	11.2	11.3	11.5	11.7	11.8
T14	13.9	14.1	14.2	14.4	14.6	14.7
T15	10.9	11.1	11.2	11.2	11.5	11.6
T16	15.9	16.1	16.1	16.1	16.2	16.2
T17	12.1	12.3	12.4	12.5	12.7	12.8
T18	15.2	15.2	15.3	15.3	15.3	15.3
T19	14.3	14.5	14.5	14.6	14.8	14.9
T20	16.8	16.9	16.9	17.0	17.1	17.1
T21	17.6	17.7	17.7	17.8	17.9	18.0
T22	21.8	21.9	21.9	21.9	22.0	22.0
T23	17.8	17.9	18.0	18.1	18.3	18.4
T24	19.9	20.0	20.1	20.2	20.4	20.5
T25	16.9	17.1	17.3	17.5	17.8	17.9
T26	8.9	9.1	9.8	9.4	9.7	10.2
T27	7.4	7.6	9.3	9.0	9.6	9.9
T28	18.9	18.9	19.0	19.0	19.0	19.0
T29	9.5	9.7	9.9	10.1	10.4	10.5
T30	7.2	7.4	7.5	7.7	8.0	8.1
T31	6.1	6.4	6.9	7.1	7.3	7.6
T32	5.9	6.2	6.6	6.7	7.0	7.5
T33	5.4	5.7	6.1	6.6	6.6	6.9
T34	5.5	5.8	6.2	6.5	6.7	7.1
T35	6.2	6.4	6.9	7.0	7.2	7.6
T36	6.3	6.6	7.0	7.1	7.5	7.8
T37	6.7	7.0	7.4	7.5	7.6	7.9
T38	6.7	7.2	7.7	8.0	8.3	8.5
T39	7.3	7.7	8.3	8.3	8.7	9.0
T40	7.1	7.4	7.8	7.8	8.2	8.2
T41	6.8	7.1	7.7	7.6	7.9	8.2
T42	6.2	6.6	7.0	7.1	7.6	7.6

Note: See Figure 11 for tag point locations

7. PROJECT LIMITATIONS

There are a number of assumptions that have been made in this Study owing to a lack of available data and information. An outline of these limitations is presented in this Section, including opportunities for further Study to refine results.

7.1 Limitations

A significant limitation for this project is the prediction of future climatic conditions. Although this Study has included a review of the most relevant peer-reviewed scientific climate studies, there is an uncertainty with extrapolating data this far into the future. The current 2010 climate scenario, particularly the rainfall intensity, cyclone frequency and magnitude is based upon a limited data record. It is assumed that analysis of this record is representative of a stationary 2010 climate. These assumptions have been made to generate the baseline conditions for this Study.

Another limitation for this Study was the availability of survey data for analysis. A LiDAR survey for Karratha and Dampier was flown in October 2010. The extent of that survey was determined prior to the project team being appointed for this Study, and did not include the eastern section of the Nickol River tidal flats. Natural Surface Elevation 10 m contour data was used to model catchments and storage areas that extended to the east beyond the Study Area, however the accuracy of this data limited its usefulness. Therefore the extent of reporting of results for this Study is limited to LiDAR extent as data outside of this area is not sufficient to produce accurate modelling results.

The modelling in this Study, particularly the hydraulic modelling, has been performed at a coarse resolution. The size of the Study Area and model capabilities lead to the hydraulic model being established with a model grid size of 20m. This grid size is appropriate for regional modelling, as is the aim of this report. However more detailed modelling is required to determine the impacts of proposed developments, or assess the performance of existing drains within the townsite. Further processing of the LiDAR data will allow the generation of refined hydraulic models that will be useful at subsequent stages of planning.

A further limitation of the analysis results from the length of the cyclone records used. Even if it is assumed that the climate is stationary, there is statistical uncertainty as a result of the duration of the record. For a one in hundred analysis, it would be preferable to have at least 100 years of accurate records so as to limit any bias arising from the sampling error, particularly in relation to the frequency and intensity of cyclones. Any error associated with such bias will increase for longer return periods.

However as the results show in the Attachment IV Report, some change to overall frequency and intensity does not have a significant effect on water levels associated with longer return periods. This is because these longer return period events are associated with relatively rare, worst track cyclone impact.

The methodology presented in this report has been applied for a range of studies and applications. It is considered highly appropriate for developing a planning response to storm surge risk. However, as with the Hydraulic Modelling, it is being applied across a region, rather for a specific location it cannot by its nature account for highly localized effects such as the extent of wave set-up. This aspect of storm surge risk is largely accounted for in consideration of set-back beyond nominal inundation areas and is considered separate to this storm surge report.

The Coastal Movement Study has been undertaken using a collation of individual empirical models of landform evolution in response to sea level rise, with an overall consideration of net balance of sediment. This represents an approach that has not been extensively tested, and does not have a direct parallel in available studies worldwide, although it is consistent with the geomorphic approach recommended by the UK Environment Agency for the characterisation and prediction of long-term coastal change (French & Burningham 2009; Whitehouse et al 2009).

It should be recognised that the geomorphic models used to assess coastal movement are preliminary and empirical in nature, as the extensive field and research studies required to describe the relationships between environmental drivers and geomorphic response, in a Western Australian context, have not been fully resolved. Although significant research and data sets have been accumulated, much of the relevant information remains fragmented. Review of the available methods for projection of shoreline response to changing environmental conditions is underway as part of the Western Australian Marine Science Initiative (WAMSI) Project 6.2, which aims to assess the potential impacts of climate change on the Western Australian coast. An important part of the project is the development of geomorphic models that are specifically suitable for the Western Australian coast.

The geomorphic analysis has been conducted using several significant assumptions and interpretations, including:

- It is assumed that surface materials are representative to the depths that will be affected by geomorphic change caused by sea level rise. Hence the projected processes will not be significantly interrupted by the underlying geological structure;
- There is a high reliance upon an estimated supply of marine sediment, which is itself likely to respond to sea level change;

The risk of dune breaching has been derived from a simple estimate of dune storage volume;

- The projected expansion of tidal channel networks has been mapped as relatively uniform in either direction. In reality, such expansion normally occurs along narrow pathways and is controlled by drainage lines and underlying geological structure.

There is also a lack of historical flood data available for the calibration of the model. During this Study, Cyclone Bianca and Cyclone Carlos hit Karratha and resulting debris was used to calibrate the respective models. As these events were minor (<5yr ARI), the accuracy of larger ARI events is limited.

A final limitation of this Study is the assumption that rivers and creeks will maintain their geomorphology under the changing climate scenarios. Rivers and creeks are dynamic systems that migrate laterally through erosion processes. These processes can be accelerated by changing climate, including increased rainfall intensity and more frequent, higher magnitude cyclones. A change in morphology may alter the flooding regime, particularly on a local scale.

7.2 Accuracy

There is a level of uncertainty associated with the estimation of flood levels. These relate to the survey data, storm surge modelling and hydraulic modelling. These are addressed below.

Survey Accuracy

Advice provided with the survey data by AAM indicates that the vertical accuracy for the data is ± 0.10 m. This accuracy will impact on both the storm surge and hydraulic modelling.

Storm Surge Accuracy

The storm surge component (Attachment IV – Appendix B: Model Validation and Accuracy) identified potential uncertainties associated with the cyclone database, selection of wind field and the accuracy of the model itself.

Numerical computations were used generate overall error values and provide an estimate of the 90% confidence level. The confidence estimate for the 100yr ARI event is 0.5 m.

Hydraulic Modelling Accuracy

The sensitivity of modelled flood levels to hydraulic parameters has been analysed to provide an estimate of model accuracy.

The sensitivity of flood levels to runoff rate has been considered by analysis of flows 25% greater than, and 25% lower than, the 100yr ARI flow hydrographs for the input catchments.

Sensitivity of flood levels to Mannings roughness coefficient has also been considered by analysis of coefficients 33% greater than, and 33% lower than, the assumed values of the coefficients.

The sensitivity analysis shows that over most of the Study Area, flood levels are insensitive to the variable parameters. The greatest sensitivity occurs within the river channels, where flood levels are generally within ± 0.2 m, with higher values in the Nickol River upstream of North West Coastal Highway and some areas of the Nickol River tributaries downstream of North West Coastal Highway.

Statistics of flood level differences indicates that greater than 0.2 m variation only occurs in 1% to 3% of the Study Area. The statistics also show that 90% of the Study Area has less than ± 0.1 m variation in 100yr ARI flood level in response to changes in parameters.

7.3 Future Refinement

There are two aspects that will assist in refinement of the results in this Study, further processing and modelling of the available data and collection of additional data. Both of these opportunities were beyond the scope of this Study but will provide additional assisting to land use planning.

Further processing of the LiDAR data and additional hydraulic modelling has been discussed throughout this report. The coarse modelling is suited to regional land use planning however more detail modelling is required to determine the impacts of a particular development or accurately delineate risk areas on a local scale. This additional hydraulic modelling is being undertaken by LandCorp for several sites within the Karratha Study Area.

While regional wave set-up assessment was included in this Study, additional coastal modelling is required at the local scale also to determine the impacts of wave set-up which should be considered in delineating coastal setbacks.

The collection of additional data will assist in refining the results of this Study. The data may be used to either assess the predictions from the various models or monitoring the rate of change that is occurring at certain points across the Study Area.

General data collected by the Bureau of Meteorology will be useful to evaluate the future climate projections of rainfall intensity and cyclone frequency and magnitude. Flood level information should also surveyed for all major cyclone events (>5yr) and compared to modelled results. This will provide an analysis of the accuracy of the modelled flood levels.

It is also recommended that an ongoing monitoring program is established for the Karratha Airport as it the most significant piece of infrastructure that is threatened by shoreline movement. Protective measures may be required based on this monitoring.

Two possible investigations that could help to refine the projected coastal changes are:

- Geotechnical investigation to evaluate the level of protection afforded by the dunes, to confirm anecdotal evidence that the dunes are comprised mainly of rock.
- Interpretation of geomorphology, topography and historic aerial imagery to evaluate the most likely pathways for tidal creek expansion.

It is advisable that a review of the assumptions made in this document is undertaken around 2020. Further climate data, including future projections, will be available as should be considered.

8. CONCLUSIONS

The Karratha Coastal Vulnerability Study has been undertaken for LandCorp to determine the areas that are prone to inundation to assist with land use planning. The Study looked at three time periods – current (2010), and then 50 years (2060) and 100 years (2110) from present. The Study involved five components:

I. Climate Change Drivers and Projections (Coastal Zone Management)
II. Hydrological Assessment (JDA Consultant Hydrologists)
III. Coastal Movement Study (Damara WA)
IV. Storm Surge and Coastal Inundation (GEMS)
V. Hydraulic Modelling (JDA Consultant Hydrologists)

These components have been integrated to provide a comprehensive assessment of the flooding and shoreline stability in the Karratha Study Area.

The Climate Change component was used to identify projected changes in climate for the 2060 and 2110 scenarios. The impact of these changes would then be assessed by the other study components.

The Coastal Movement component utilises the storm surge and coastal conditions to assess movement of the coastline, and how this will change with the change in climate. This component feeds into the Storm Surge component.

The Storm Surge and Hydraulic Modelling components model flooding behaviour as result of cyclonic activity and terrestrial rain runoff respectively, with the Hydraulic Modelling being informed by the Hydrological Assessment for catchments outside of the Study Area.

The following conclusions have been made:

Climate Change

- The projected climate conditions for 2060 included a 0.3m rise in sea level, 10% increase in intensity and frequency of cyclones and a 0 to 20% increase in rainfall intensity for events great than 20yr ARI.
- The projected climate conditions for 2110 included a 0.9m rise in sea level, 10% increase in intensity and frequency of cyclones and a 10 to 30% increase in rainfall intensity for events great than 20yr ARI.

Coastal Movement

- Shoreline projections indicated that tidal creeks west of the Karratha townsite will continue to expand, with acceleration of the process as a result of sea level change. Sea level change will also result in increased sediment transport and destabilisation of the fringing mangroves. With the destabilisation of the mangroves and increased sediment transport, there is insufficient material storage within the dune adjacent to the airport, resulting in a risk that the dune will be breached by overtopping during a storm surge event.
- The Karratha townsite is landward of a high, largely continuous coastal dune that provides some protection to inundation. With sea level rise, the tidal flat fronting the dune system will progressively experience inundation, with formation of a tidal creek network and then formation of a coastal lagoon behind the coastal dune. As sea level increases, erosion of the coastal dune will occur, decreasing the level of protection provided by the dune.

- The eastern Karratha area (east of the gold course) has a narrow fringe of mangroves, fronting a thin sandy foreshore and backed by a rocky hinterland. The change in sea level will result in the loss of the mangroves however the rocky structure provides a significant constraint to potential shoreline movement, and this stable configuration results in minimal coastline changes through this area.
- The Nickol River Delta east of the townsite will be subjected to increased inundation under rising sea level conditions.
- Wave run-up has been estimated to be between 0.1 and 0.3 m adjacent to Karratha Townsite, occurring within the floodplain areas under existing conditions, based on application of site specific factors using standard empirical methods. Wave run-up levels are likely to increase if development of the floodplain areas are filled and incorporate steep batter slopes.

Flood Mapping 2010

- Flood mapping was produced by combining the 100yr ARI storm surge modelling results with the 100yr ARI terrestrial runoff hydraulic modelling.
- The flood modelling shows that almost all existing development in Karratha is protected from the 100yr ARI flood event. The only areas which will be affected are properties along Balmoral Rd between Gawthorne Drive and Warambie Rd, which are subject to some inundation as a result of storm surge.
- Within the Karratha townsite, flood flows are generally kept within the drainage channels and on roads.
- All of the creek crossings on North West Coastal Highway are subject to inundation. Many of these crossings are floodways, and so some inundation is expected after any significant rainfall event.
- The four NWCH crossings with bridge structures (Turnoff Creek, Lulu Creek, Hilux Creek and Nickol River) convey flow in the 2yr and 10yr events without overtopping of the roadway, however in the 100yr ARI and greater events, these structures are breached, with greater than 400 m of roadway inundation occurring at each creek crossing.
- The NWCH crossings which have culverts at creek lines as well as floodways have a low level of service, with some overtopping even in the 2yr ARI event.
- The Dampier Rd crossing of 7 Mile Creek can convey the 2yr and 10yr ARI flow with no overtopping. In the 100yr ARI event, some overtopping of the western approach occurs to a shallow depth (<0.2 m) for a short length (<100 m). In the 200yr ARI, greater overtopping of the bridge and approaches occurs.
- The Dampier Rd crossing of Madigan Creek shows overtopping of the floodway to the immediate west of the creek line. The mapping also shows some flow westward along Dampier Rd to 7 Mile Creek.
- The eastern tributaries of 7 Mile Creek show a wide extent of flooding (up to 1 km in places) however most of this flooding is less than 0.25 m depth.
- The developments on the eastern and western banks of 7 Mile Creek upstream of Dampier Rd are both above the 100yr ARI flood level.
- The Karratha LIA area is protected from flooding for the 100yr ARI event, although Coolawanyah Rd is inundated for several hundred metres at the creek crossing.
- West of Karratha Rd, the Nickol River tributary has a flow width of up to 500 m and depths of up to 1 m. Significant areas of the upper catchment for this tributary are subject to inundation, although flood depth is generally less than 0.25 m.

- Between Turnoff Creek and Nickol River, downstream of NWCH, a large percentage of the area has a degree of inundation, with numerous creeks crossing the area.

Flood Mapping 2060

- Over the next 50 years, it is estimated that rainfall intensities may increase by up to 20%, that sea level will rise by 0.3 m and that cyclone intensity and frequency will increase by 10%. As this will increase the volume of water impacting on the Study Area, it is not unexpected that flood levels will rise.
- Flood modelling indicates that flood levels will rise by up to 0.5 m, with an average of 0.2 m rise across all tag points. However there is only a small increase in areas affected by flooding, with these mainly along the coast.
- The increased storm surge levels result in a small increase in the townsite subjected to inundation. An area of land between Searipple Rd and the golf course that was previously dry in the 100yr ARI is now inundated.
- Within the riverine catchments, the increase in flood levels is generally less than 0.2 m, with increases of 0.3 m in the larger catchments at downstream locations.
- Increased flood levels result in a greater degree of inundation at floodways and other channel crossings. The Dampier Rd crossing of 7 Mile Creek now has overtopping of a long section of bridge and approaches due to an upstream increase of 0.3 m in 100yr ARI level.

Flood Mapping 2110

- Over the next 100 years, it is estimated that rainfall intensities may increase by up to 30%, that sea level will rise by 0.9 m and that cyclone intensity and frequency will increase by 10%. This further increase in the volume of water will have a greater impact than the 2060 climate scenario.
- Flood modelling indicates that 100yr ARI flood levels will rise by up to 1.9 m compared to 2010 in some locations, with an average of 0.5 m rise across all tag points. Again, coastal locations show the greatest increases in levels.
- Within the townsite, more properties adjacent to Balmoral Rd will be affected by storm surge, with properties along Searipple Rd also affected.
- Developments at the western end of Karratha will not be affected by flooding from 7 Mile or Madigan Creeks.
- The Karratha LIA is also not affected by flooding from the adjacent creek networks.
- The western bank of 7 Mile Creek is subject to increased inundation, particularly downstream of Dampier Rd, where a further width of approximately 1 km is inundated compared to the 2010 scenario.
- Within the riverine catchments, the increase in flood levels from 2010 is generally less than 0.4 m, with increases of 0.5 m in the larger catchments at downstream locations.
- Increased flood levels result in a greater degree of inundation at floodways and other channel crossings. The Dampier Rd crossing of 7 Mile Creek has increased overtopping of a long section of bridge and approaches due to an upstream increase of 0.4 m in 100yr ARI level compared to 2010.

It should be noted that Attachments I to V also have their own conclusions specific to each component of the Study.

9. RECOMMENDATIONS

- The projected shoreline changes to 2110 should be considered in the context of existing infrastructure and future land use planning. This includes protection of coastal dunes as they form the major natural protection for the Karratha Townsite;
- Coastal setbacks proposed in this report should be adopted;
- More detailed modelling should be performed for future land development to determine the wave run-up impact which may increase the setback required or require other management options;
- A monitoring program should be established at Karratha airport of shoreline stability and erosion risk. Monitoring should take the form of surveys measuring the crest height of the dune and a minimum of three cross-sections at identified low or narrow sections. The relative risk of breaching should be evaluated relative to the FEMA (2003) criteria for dune stability. Monitoring should be conducted with a maximum interval of 10 years, and within six months following any tropical cyclone where the total recorded water level exceeds 3.5m AHD;
- A geotechnical investigation should be commenced to evaluate the level of protection afforded by the coastal dunes;
- Historic aerial imagery should be interpreted with respect to geomorphology and topography to evaluate the most likely pathways for tidal creek expansion;
- The projected shoreline changes to 2110 should be considered in the context of existing infrastructure and future land use planning;
- Future waterway crossing, including upgrading of existing infrastructure, should be designed to allow appropriate flow conveyance for the 2010 climate scenario;
- Stormwater management should take into account the inundation risk areas shown in the report;
- More detailed modelling is recommended to determine the impacts of a particular development or accurately delineate risk areas on a local scale;
- This report should be reviewed around 2020 taking into account additional climate data and future projections at that time.

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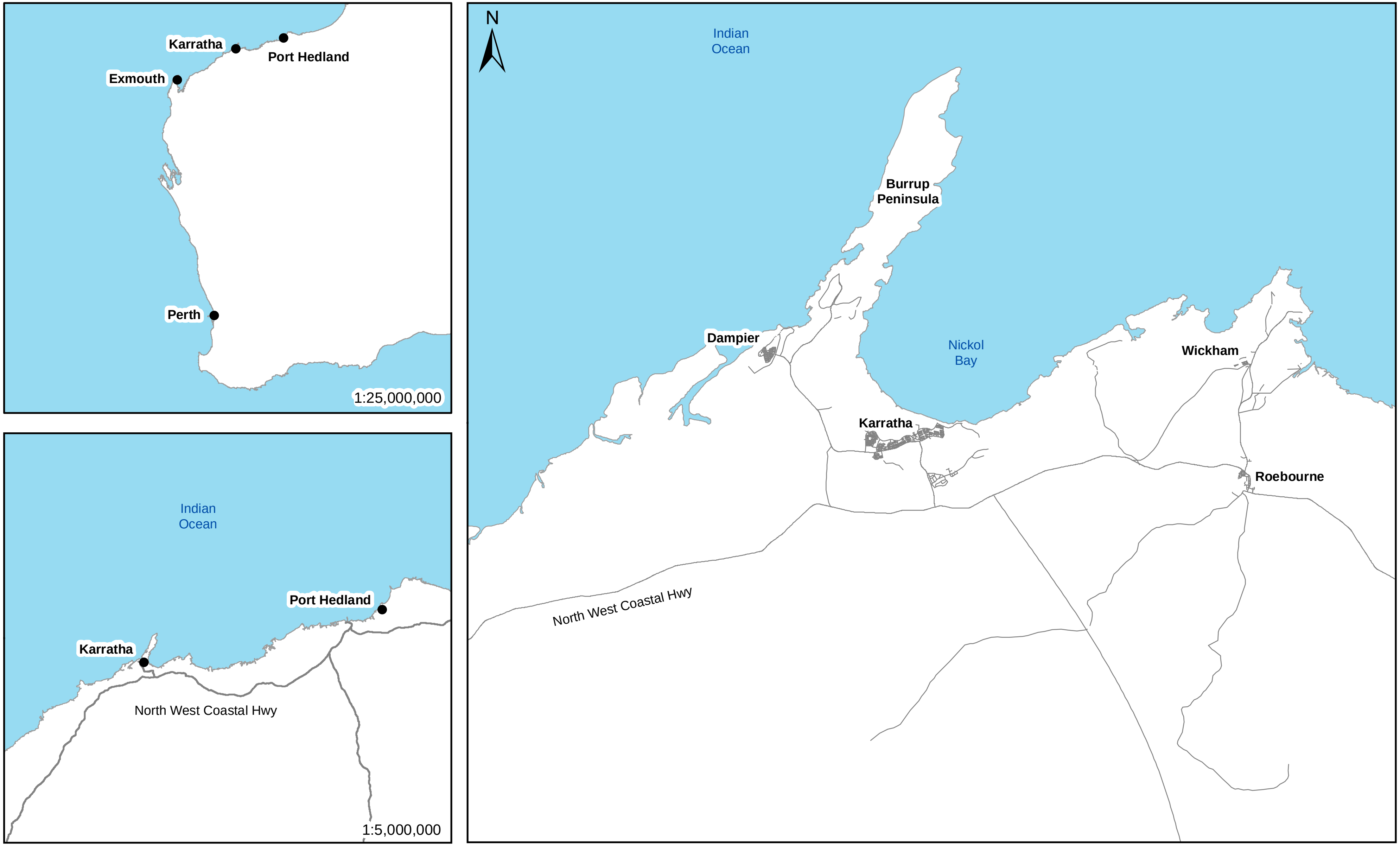
FIGURES



Data Source: Main Roads 2010

JDA Consultant Hydrologists

Job No. J4812

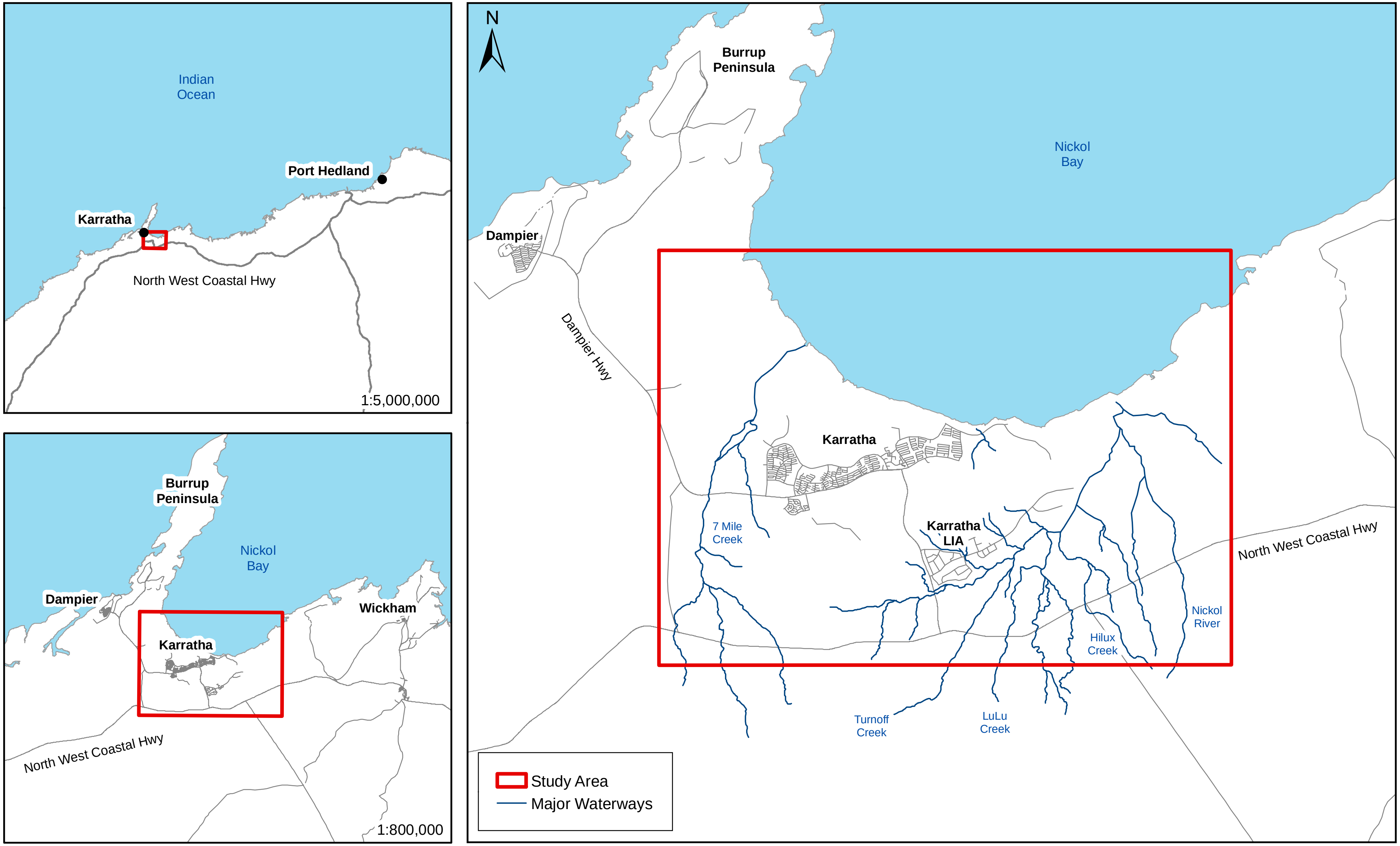
Scale:1:500,000

0 5 10 15 20 Kilometers

LandCorp

Karratha Coastal Vulnerability Study: Main Report

Figure 1: Location Plan



Data Source: Main Roads 2010

JDA Consultant Hydrologists

Job No. J4812
Scale:1:200,000
0 2.5 5 7.5 10 Kilometers

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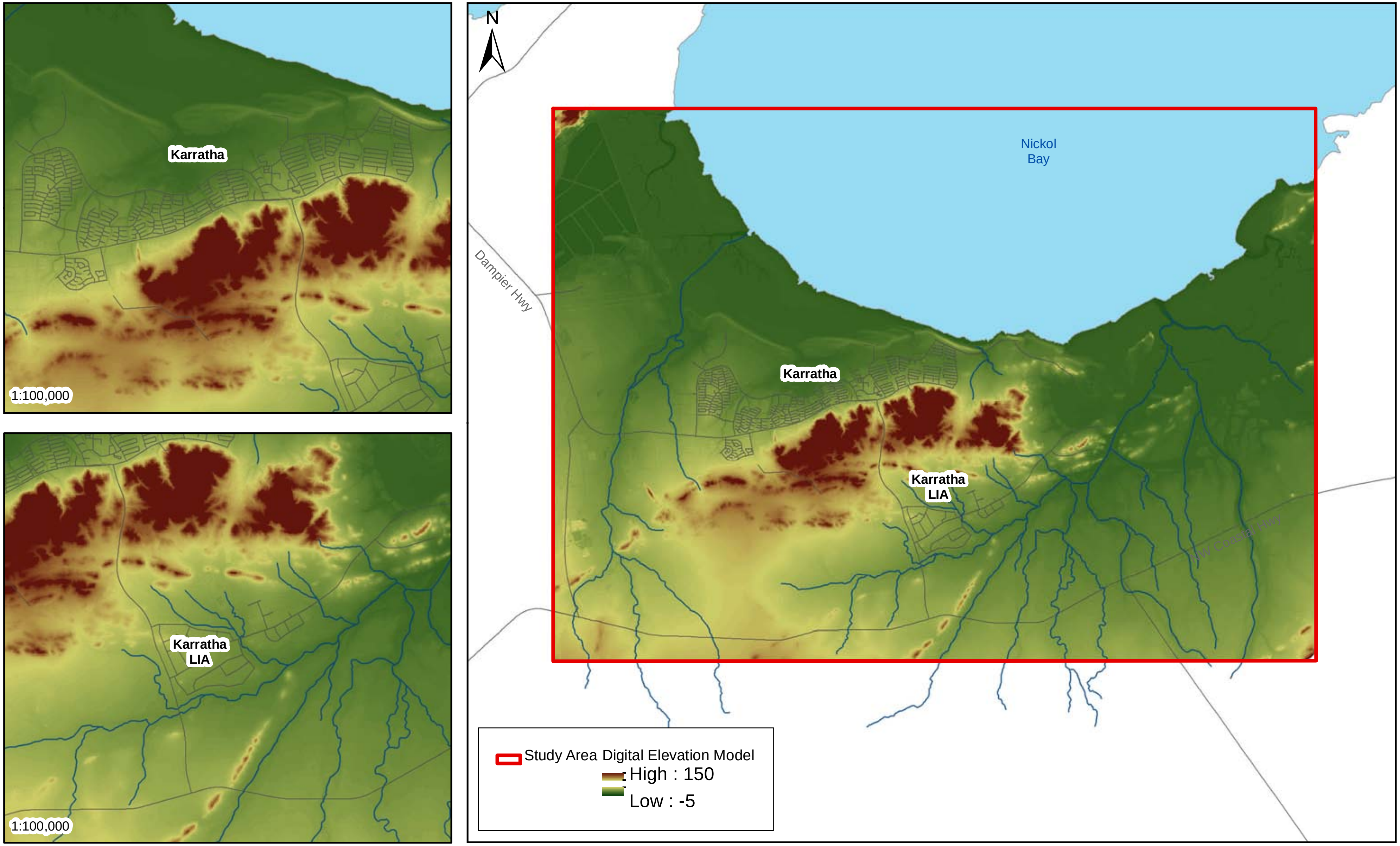
Karratha Coastal Vulnerability Study: Main Report
Figure 2: Karratha Study Area



Data Source: NearMap 2011

Job No. J4812

Scale:1:150,000

0 2.5 5 7.5 10 Kilometers

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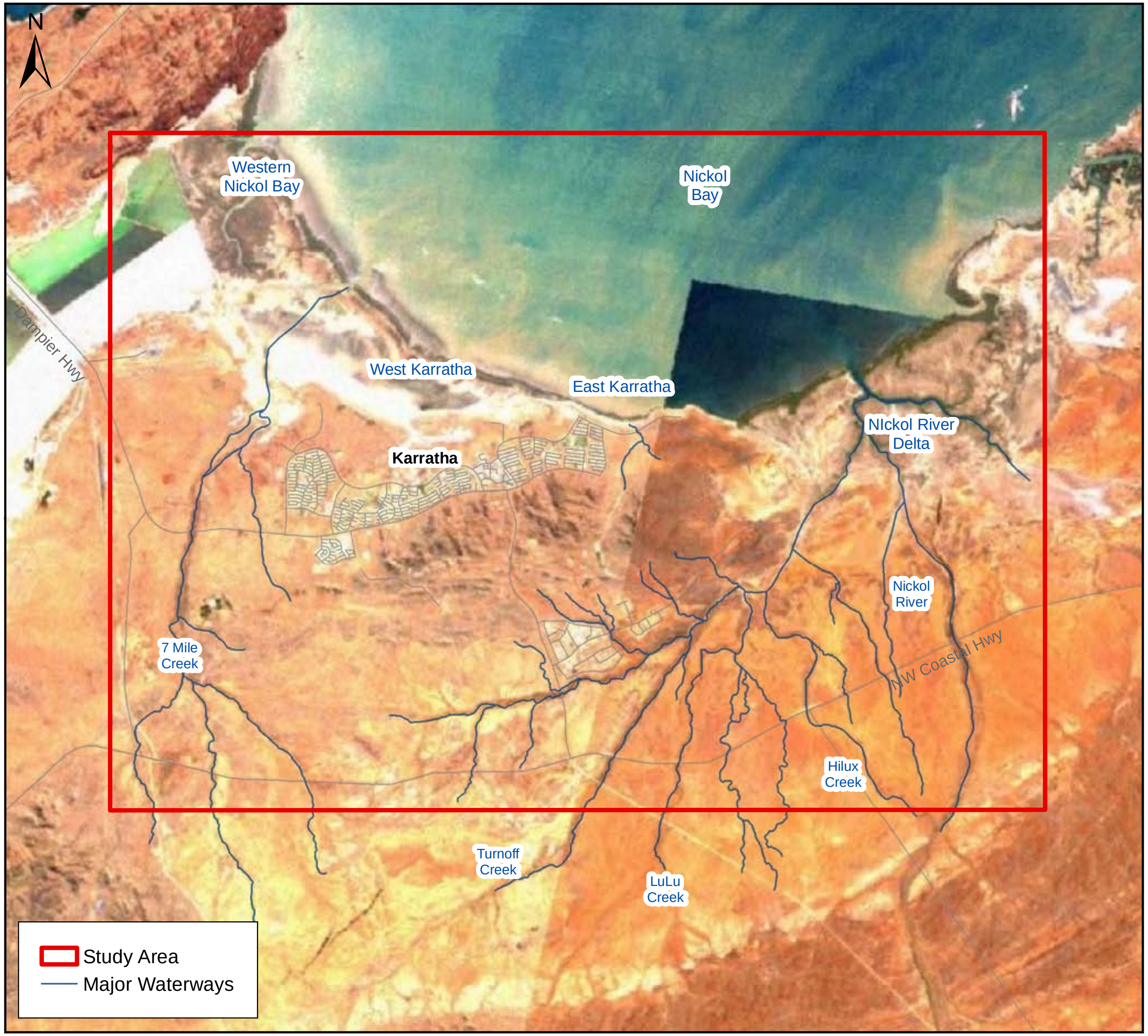
Karratha Coastal Vulnerability Study: Main Report

Figure 3: Topography

Vegetation near Nickol Creek

Vegetation near Madigan Rd (Karratha Hills in the Background)



Data Source: NearMap 2011

Job No. J4812

Scale:1:150,000

0 2.5 5 7.5 10 Kilometers

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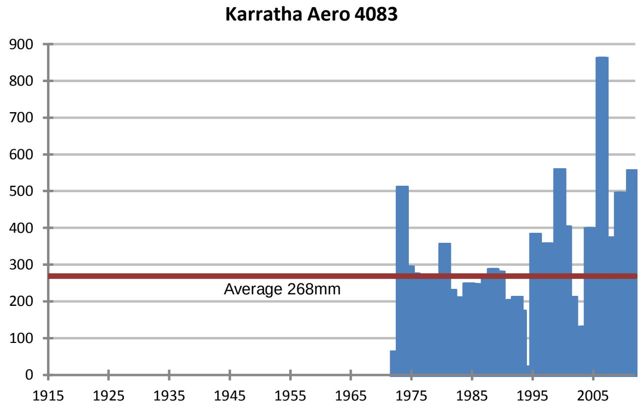
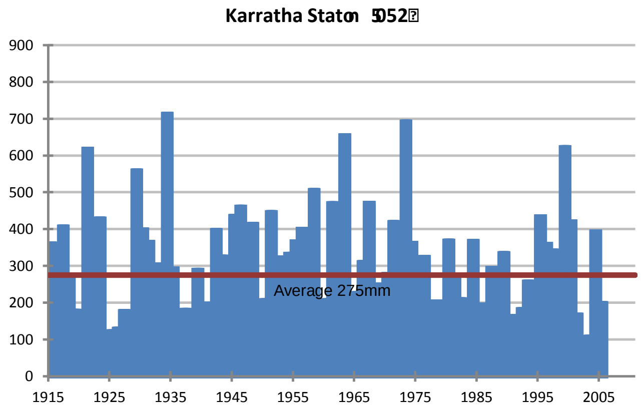
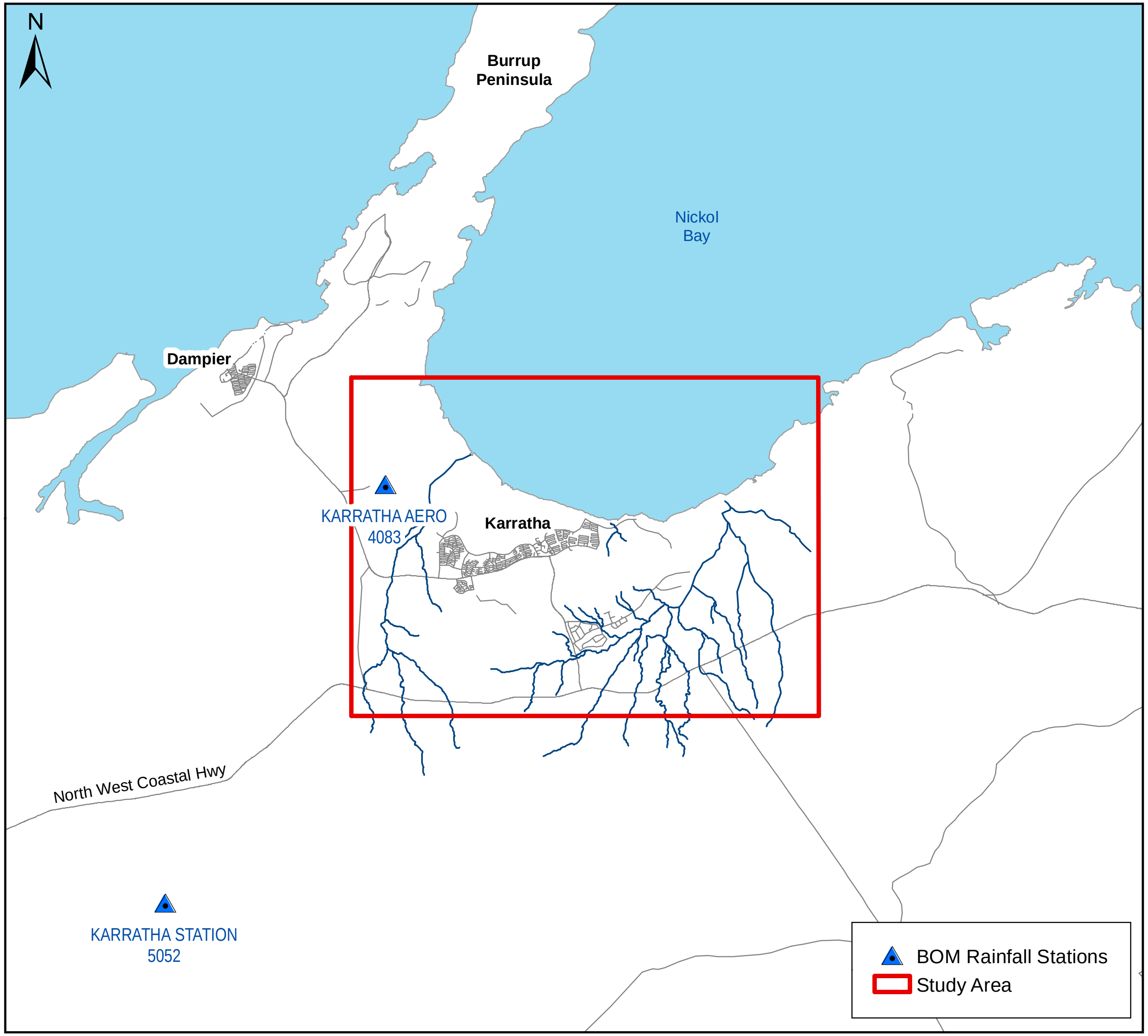
Karratha Coastal Vulnerability Study: Main Report

Figure 4: Aerial Photography







Data Source: Bureau of Meteorology 2011

Job No. J4812

Scale:1:300,000

0 5 10 15 20 Kilometers

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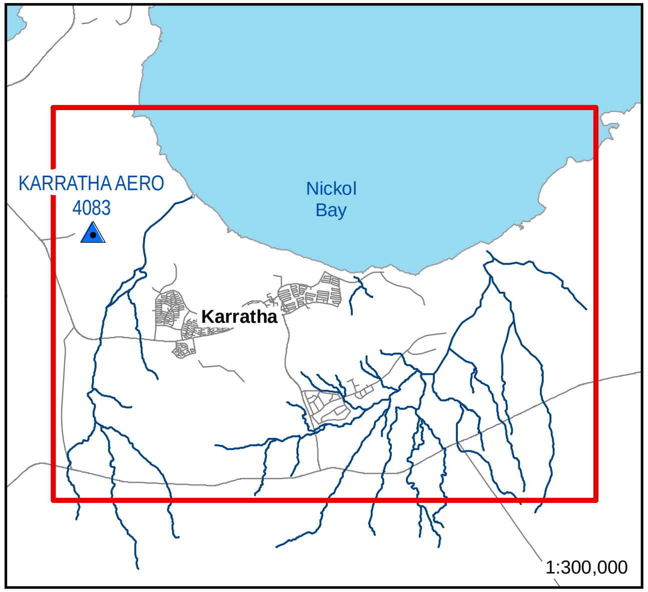
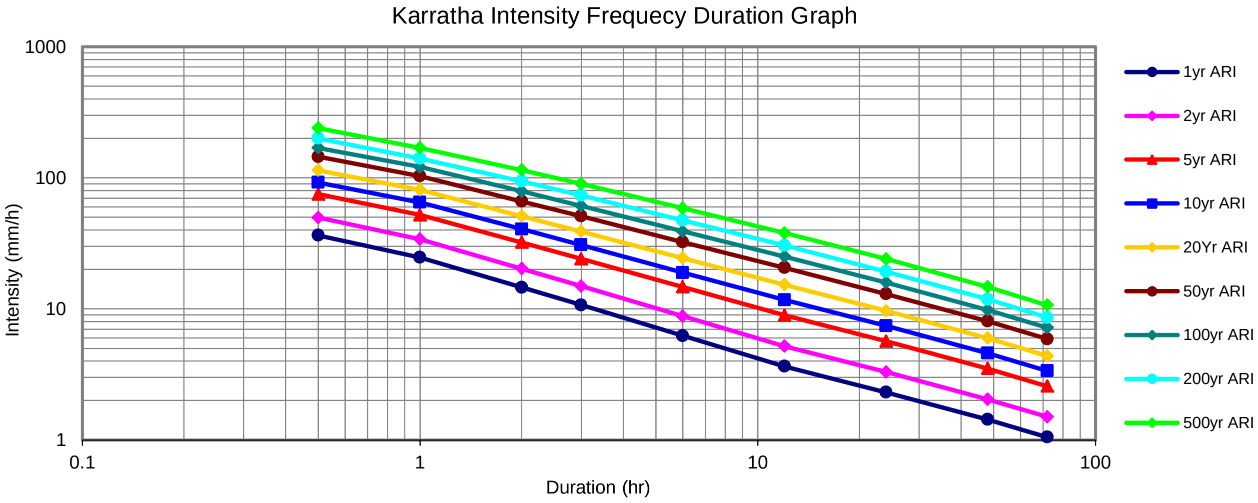
Figure 5: Annual Rainfall Data






Cyclone Bianca (2-5yr ARI): Flooding over the NW Coastal Hwy

Data Source: Shire of Roebourne 2011

Karratha Intensity Frequecy Duration Table

Duration	1 Year	2 years	5 years	10 years	20 years	50 years	100 years
5Mins	78.6	106	157	190	231	289	336
6Mins	73.2	99.1	146	177	216	271	314
10Mins	59.8	81.2	121	147	181	227	264
20Mins	44.1	60.2	91	112	138	175	204
30Mins	35.9	49.1	74.9	92.4	114	146	171
1Hr	23.7	32.7	50.7	63.2	78.8	101	119
2Hrs	14.6	20.3	32.2	40.6	51.3	66.5	79.2
3Hrs	10.7	15	24.2	30.8	39.2	51.3	61.3
6Hrs	6.26	8.83	14.7	19	24.4	32.4	39.2
12Hrs	3.73	5.31	9.01	11.8	15.2	20.4	24.8
24Hrs	2.32	3.3	5.62	7.34	9.53	12.8	15.6
48Hrs	1.45	2.06	3.46	4.49	5.8	7.73	9.37
72Hrs	1.05	1.49	2.5	3.24	4.17	5.57	6.73

Data Source: Bureau of Meteorology 2011

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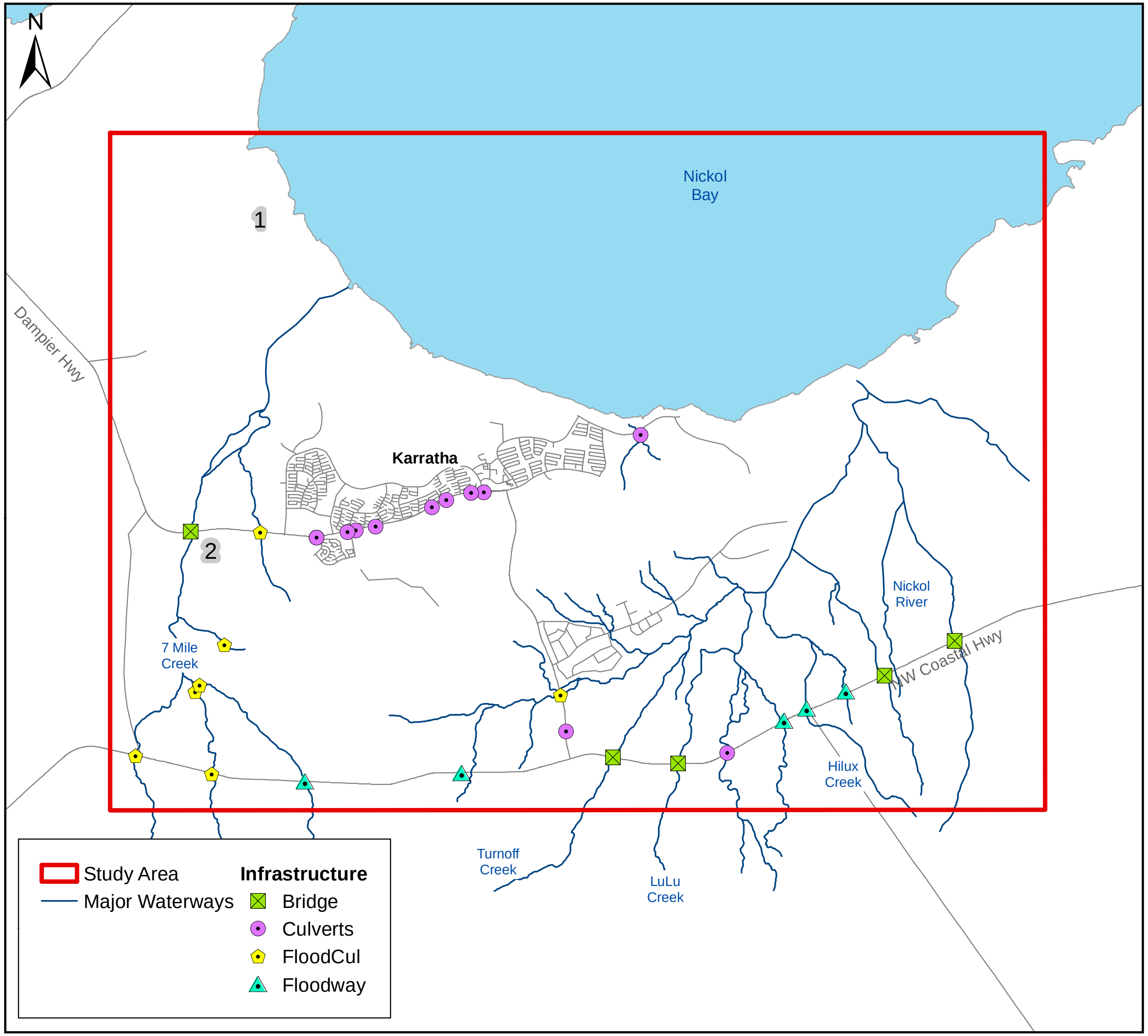
Karratha Coastal Vulnerability Study: Main Report
Figure 6: Karratha IFD



Data Source: JDA Site Visit Feb 2011

JDA Consultant Hydrologists

Job No. J4812
Scale:1:150,000
0 2.5 5 7.5 10 Kilometers

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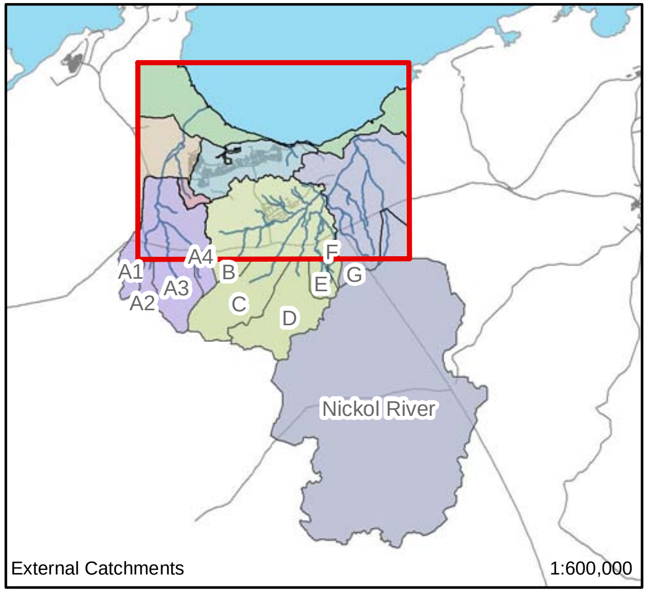
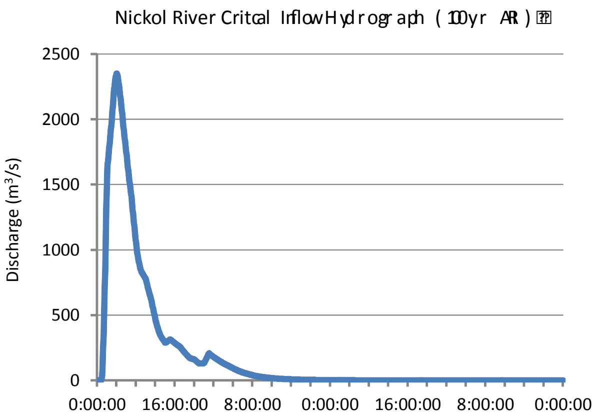
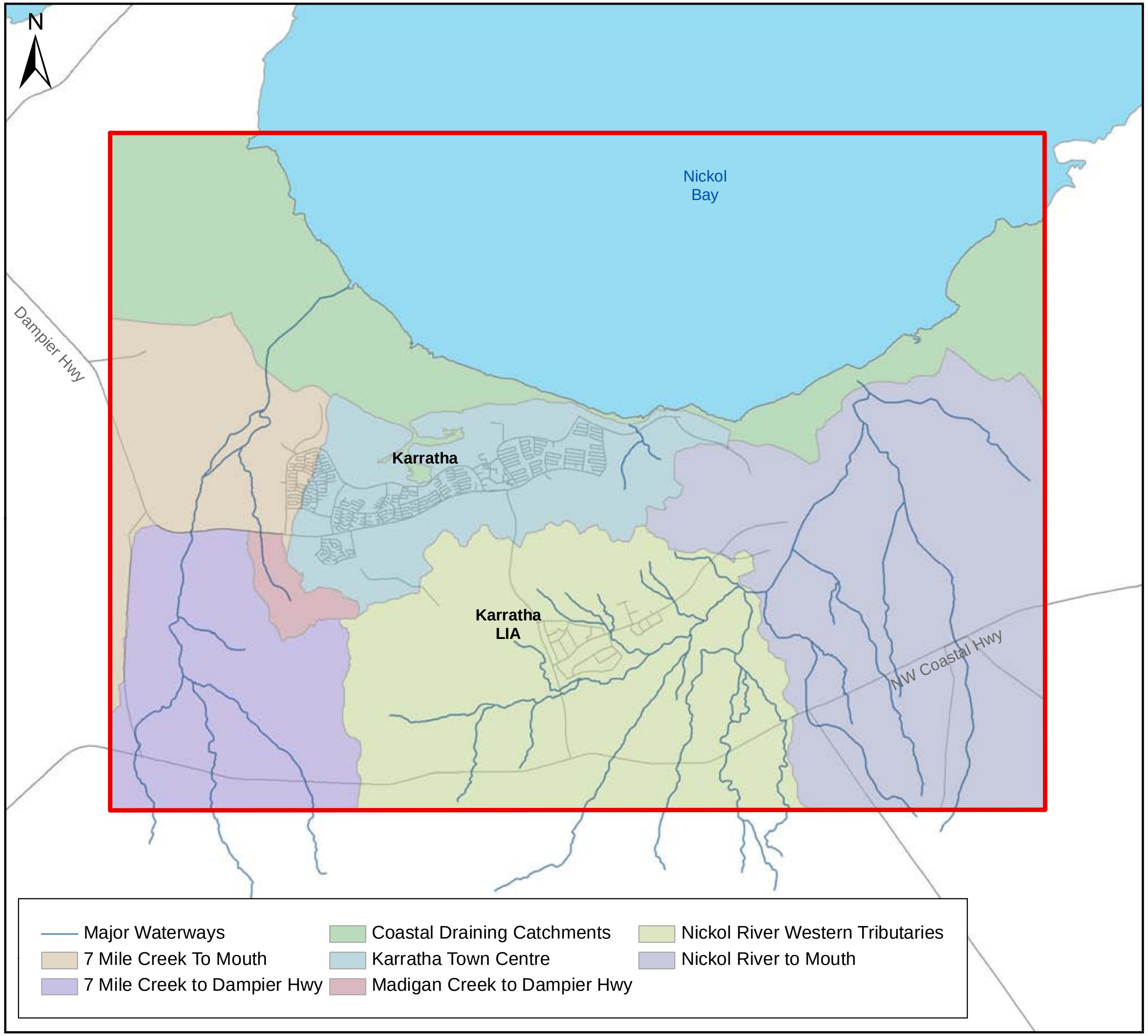
Figure 7: Waterways and Drainage Infrastructure







Data Source: JDA Hydrological Modelling 2011

Job No. J4812

Scale:1:150,000

0 2.5 5 7.5 10 Kilometers

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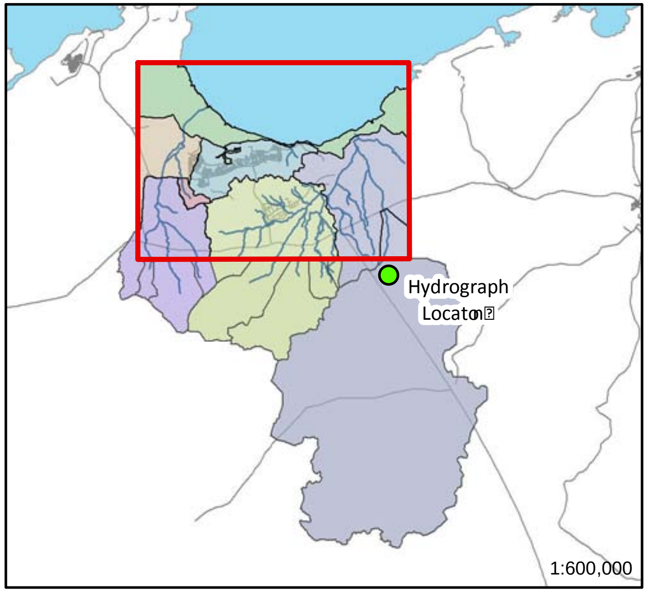
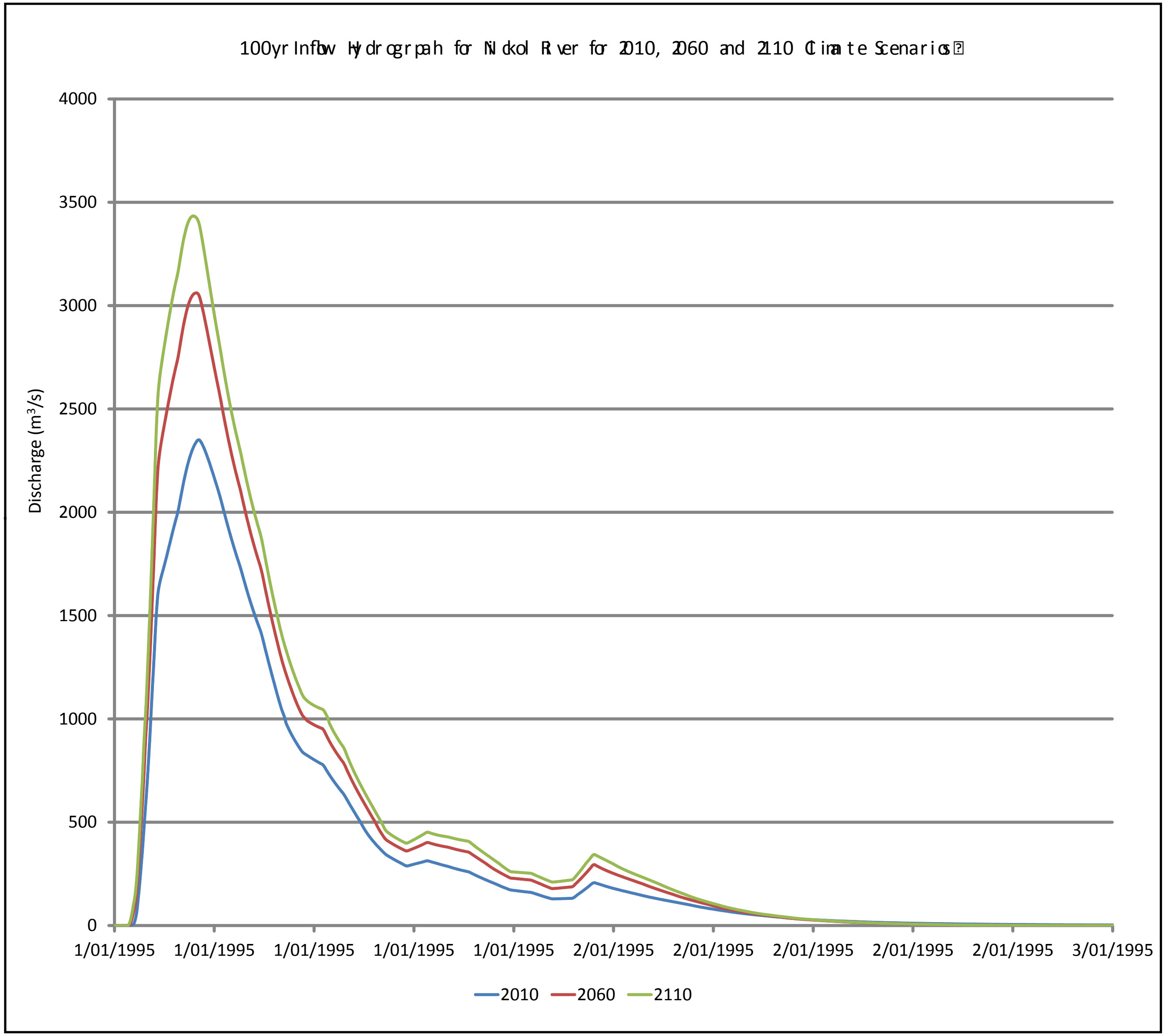
Figure 8: Hydrology Catchments





Karratha IFD and Predicted IFD (100yr ARI)

Duration	100yr ARI		
	2010	2060	2110
5 mins	336	403.2	436.8
6 Mins	314	376.8	408.2
10 Mins	264	316.8	343.2
20 Mins	204	244.8	265.2
30Mins	171	205.2	222.3
1 Hrs	119	142.8	154.7
2 Hrs	79.2	95.04	102.96
3 Hrs	61.3	73.56	79.69
6 Hrs	39.2	47.04	50.96
12 Hrs	24.8	29.76	32.24
24 Hrs	15.6	18.72	20.28
48 Hrs	9.37	11.244	12.181
72 Hrs	6.73	8.076	8.749

Data Source: JDA Hydrological Modelling 2011

Job No. J4812

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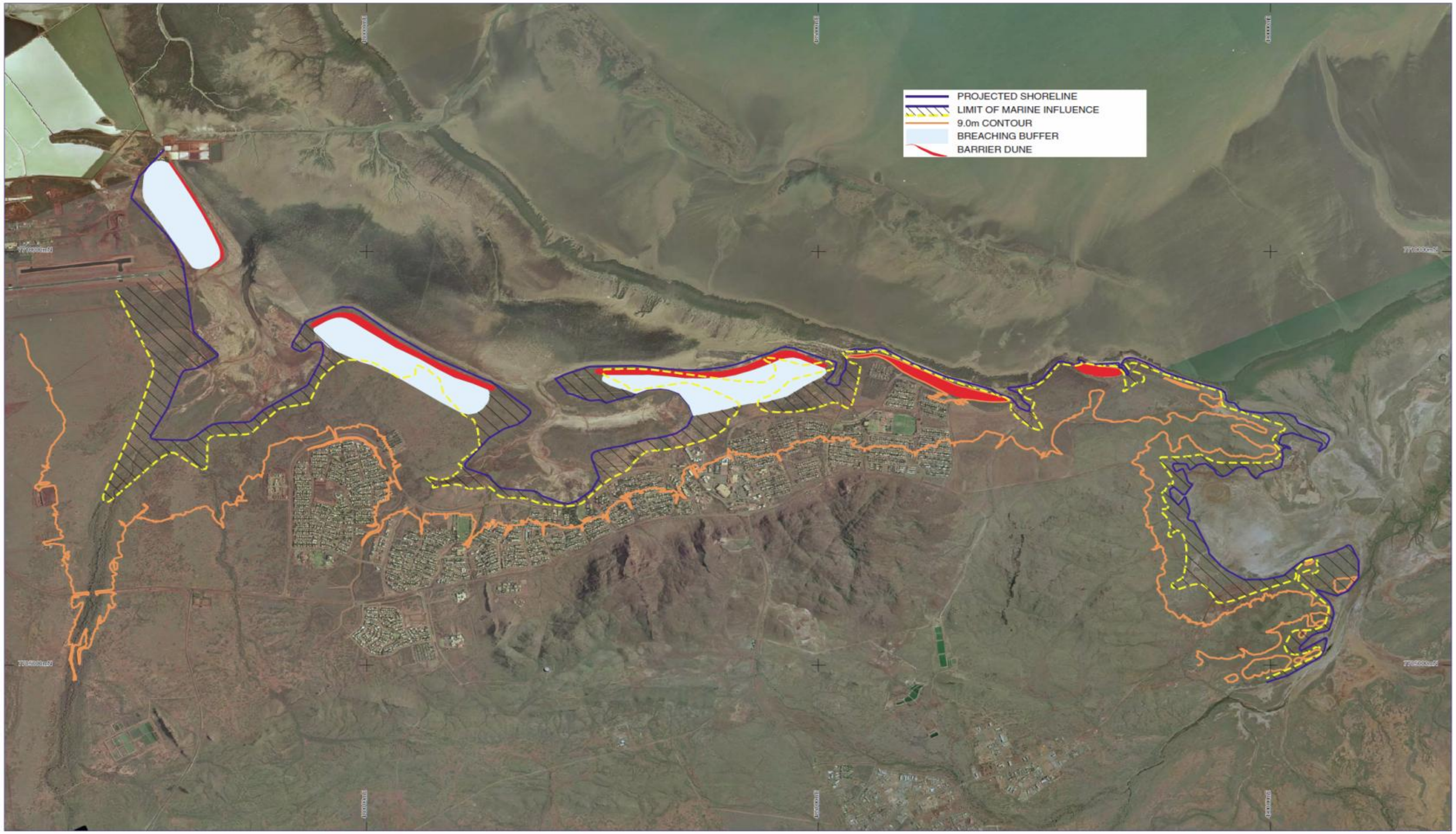
Karratha Coastal Vulnerability Study: Main Report
Figure 9: Hydrographs and Climate Change



Data Source: Damara WA 2011

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Job No. J4812

Scale 1 : 50,000

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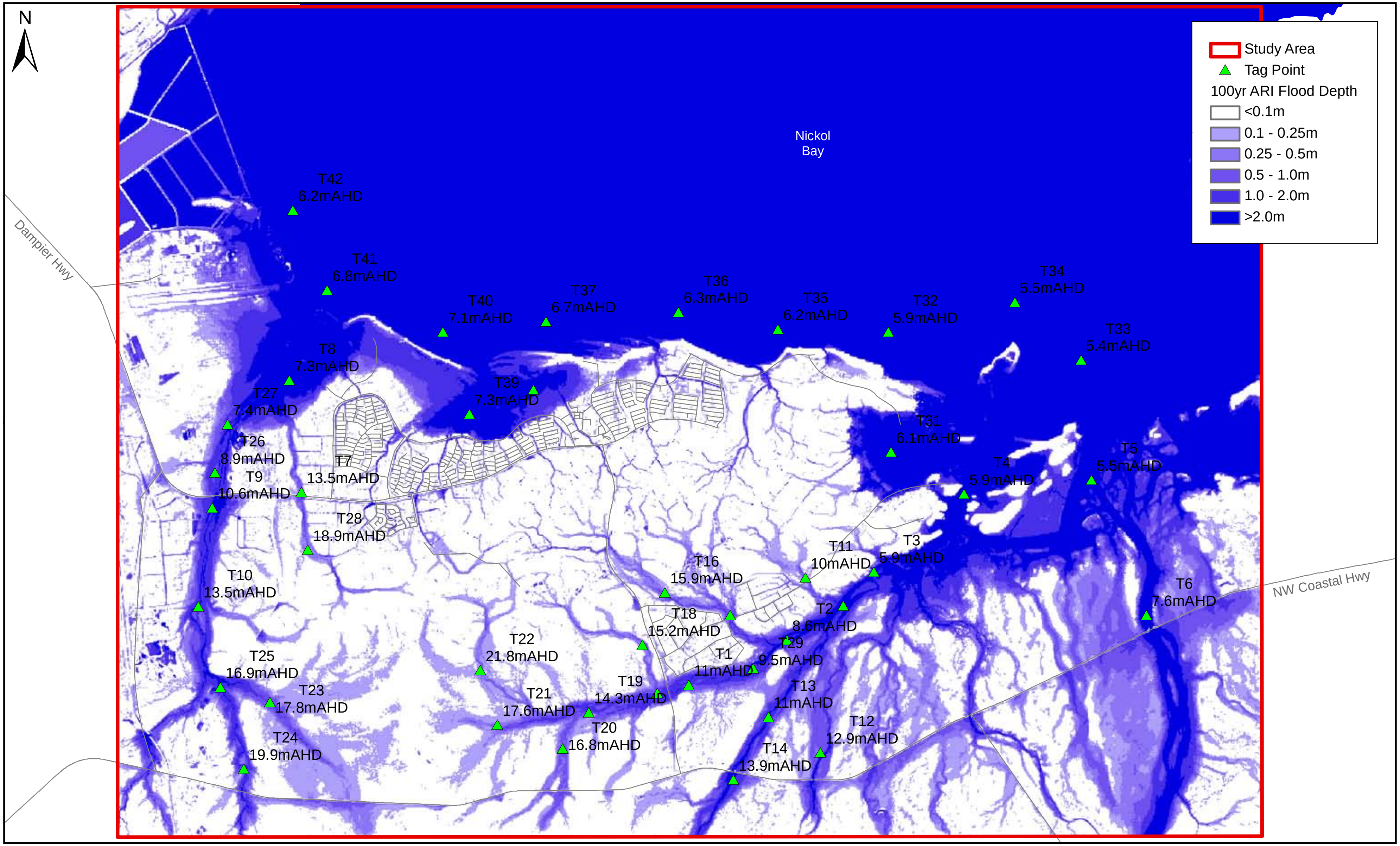
Figure 10: Projected Shoreline Change



Data Source: GEMS Modelling & JDA Hydraulic Modelling 2011

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Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

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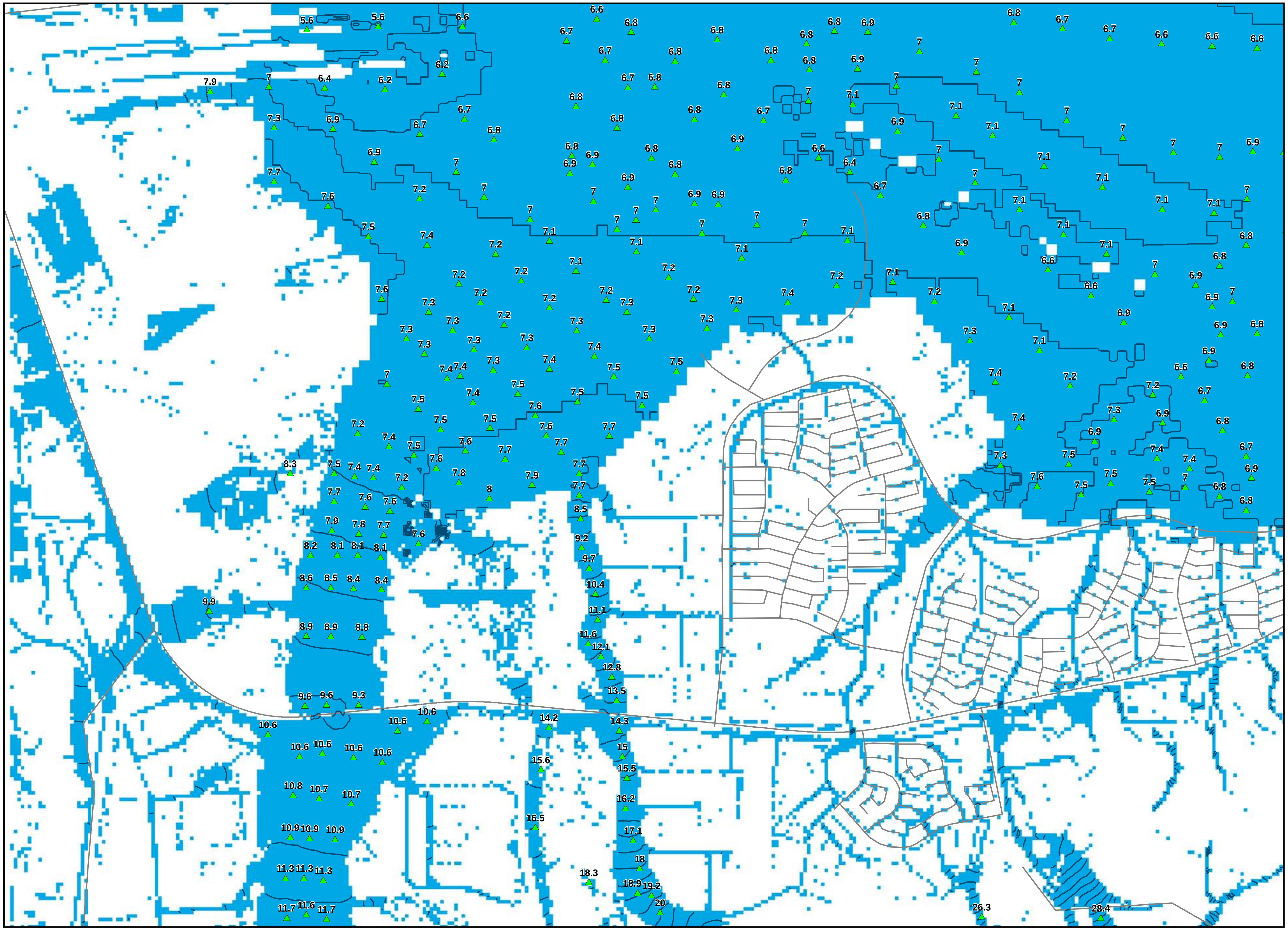
Figure 11: 100yr ARI Flood Depth - 2010 Climate Scenario



N

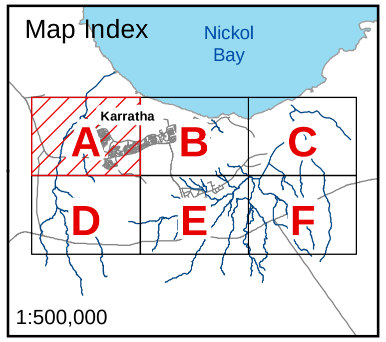
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

100yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

LandCorp
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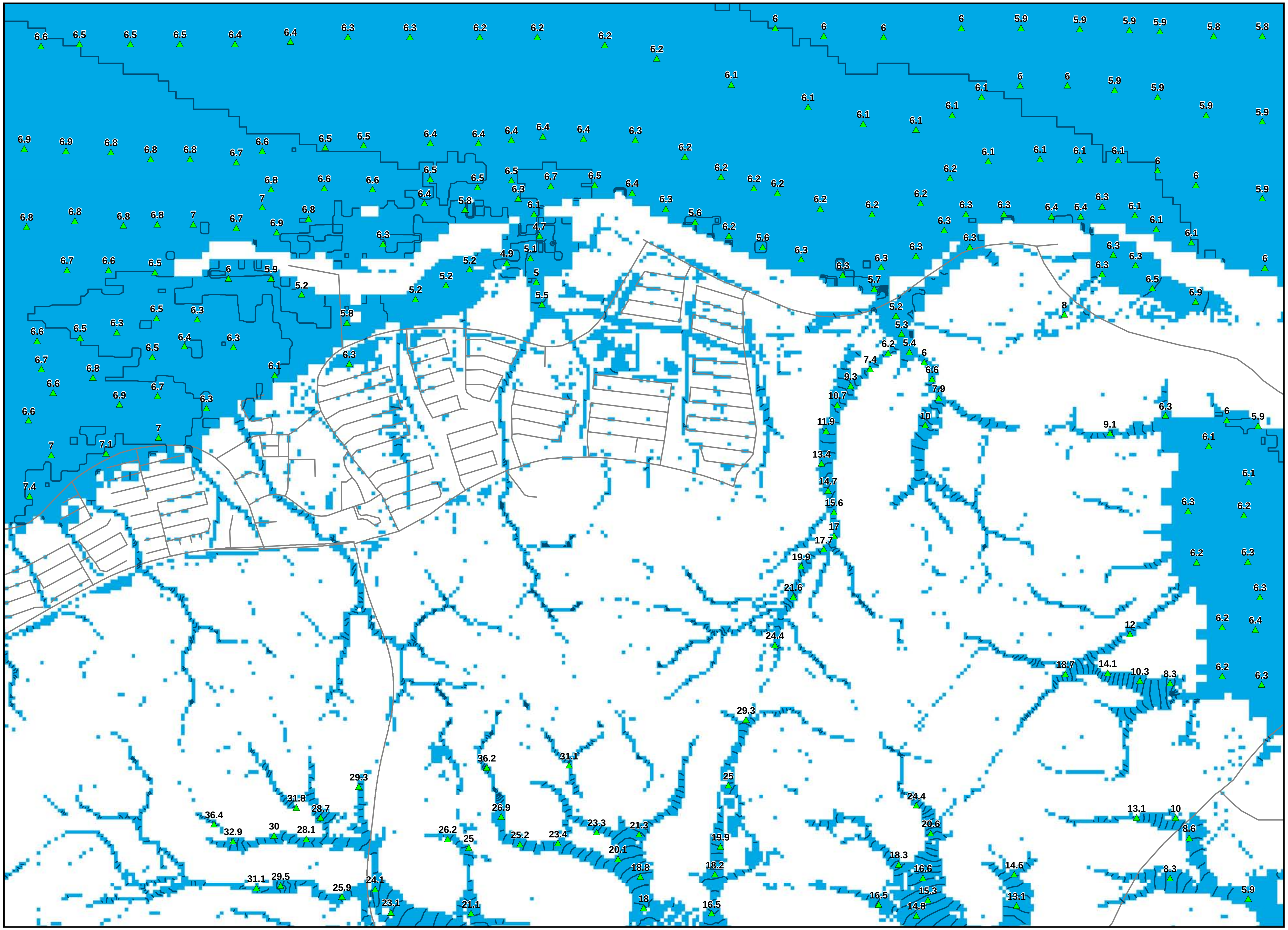
Figure 12A: 100yr ARI Flood Elevation - 2010 Climate Scenario - Sheet A



N

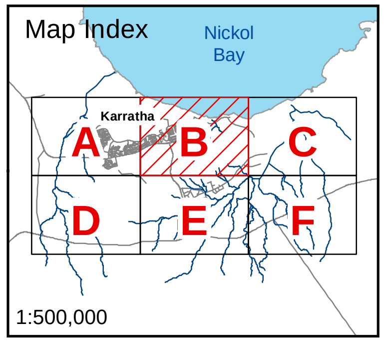
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

100yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

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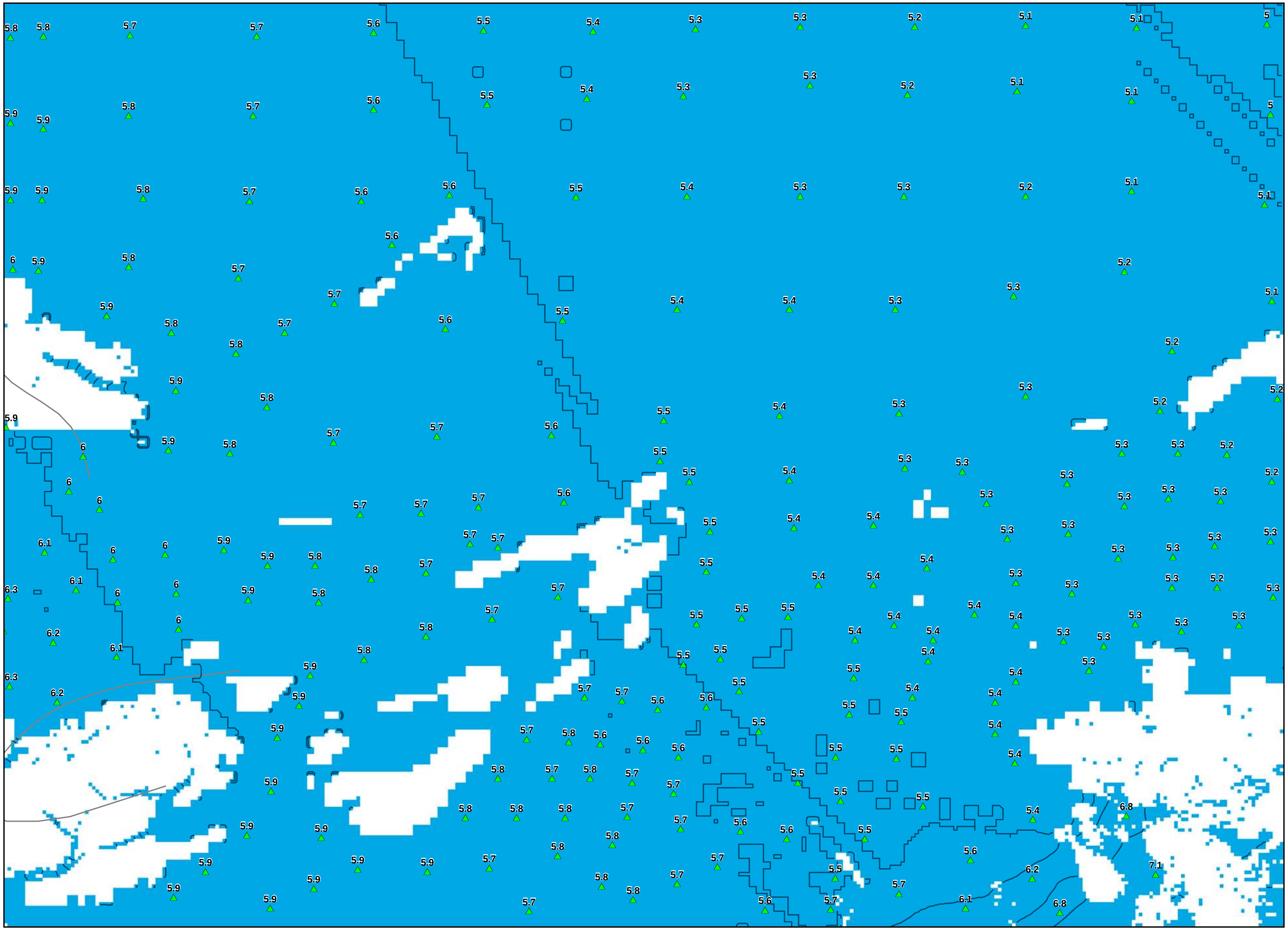
Figure 12B: 100yr ARI Flood Elevation - 2010 Climate Scenario - Sheet B

N



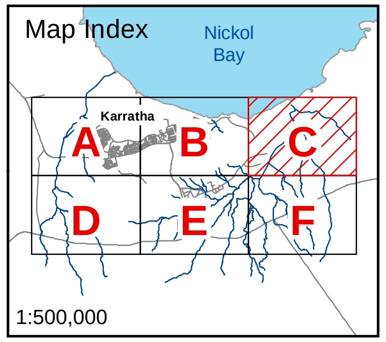
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

100yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

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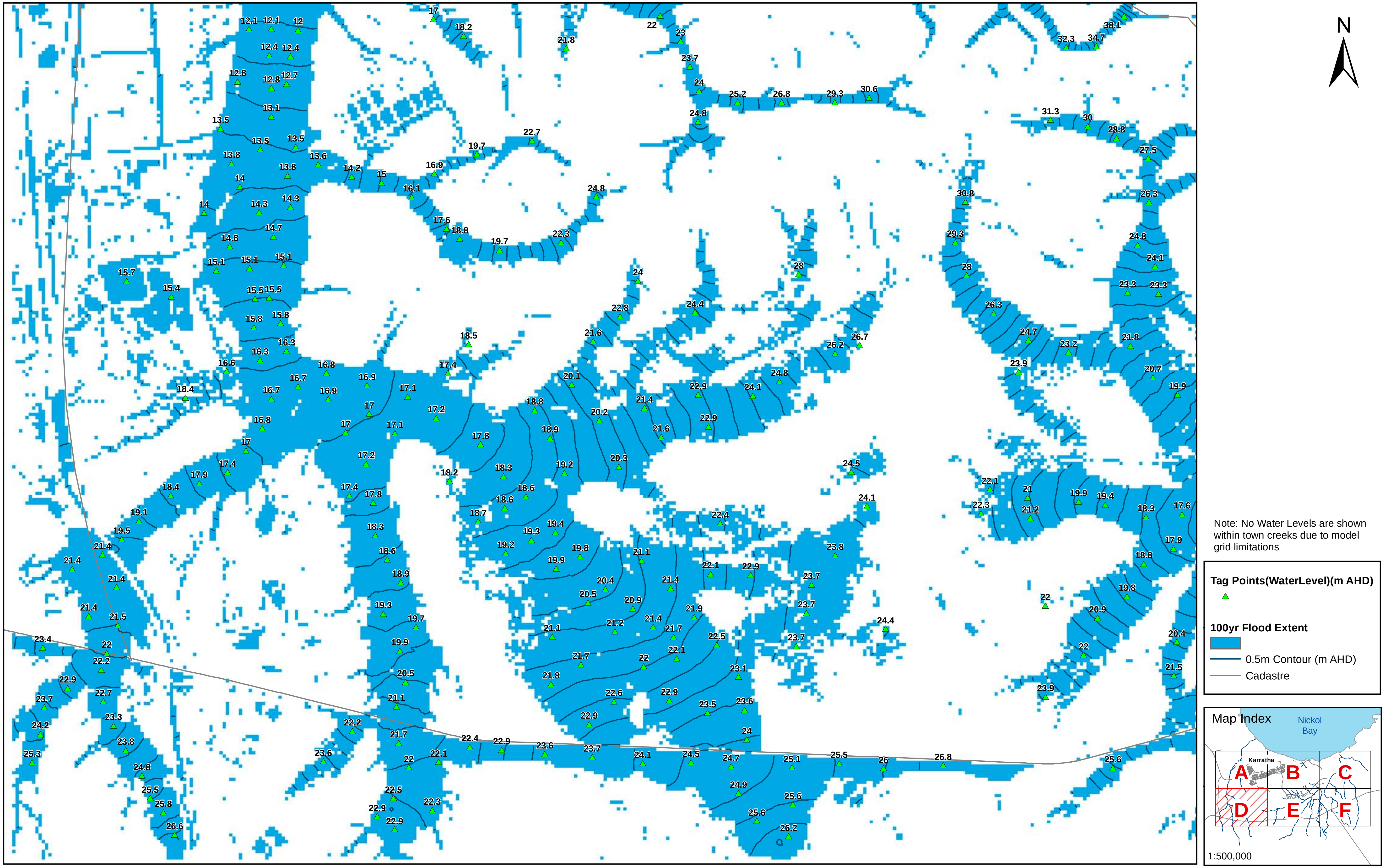
Figure 12C: 100yr ARI Flood Elevation - 2010 Climate Scenario - Sheet C



JDA

Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

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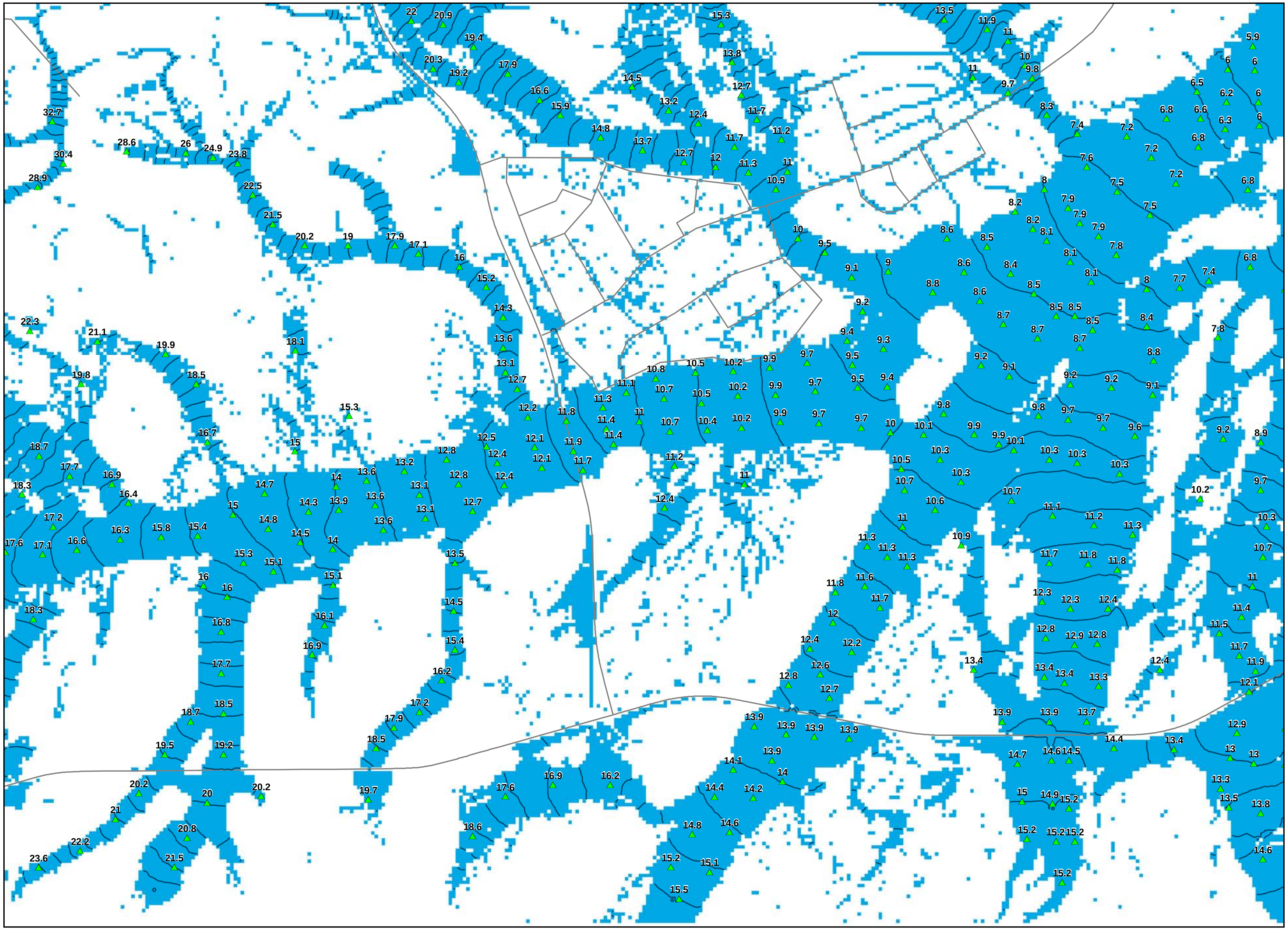
Figure 12D: 100yr ARI Flood Elevation - 2010 Climate Scenario - Sheet D



N

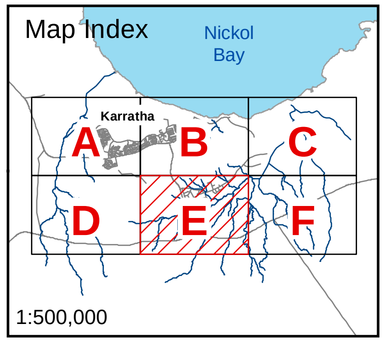
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

100yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812

Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

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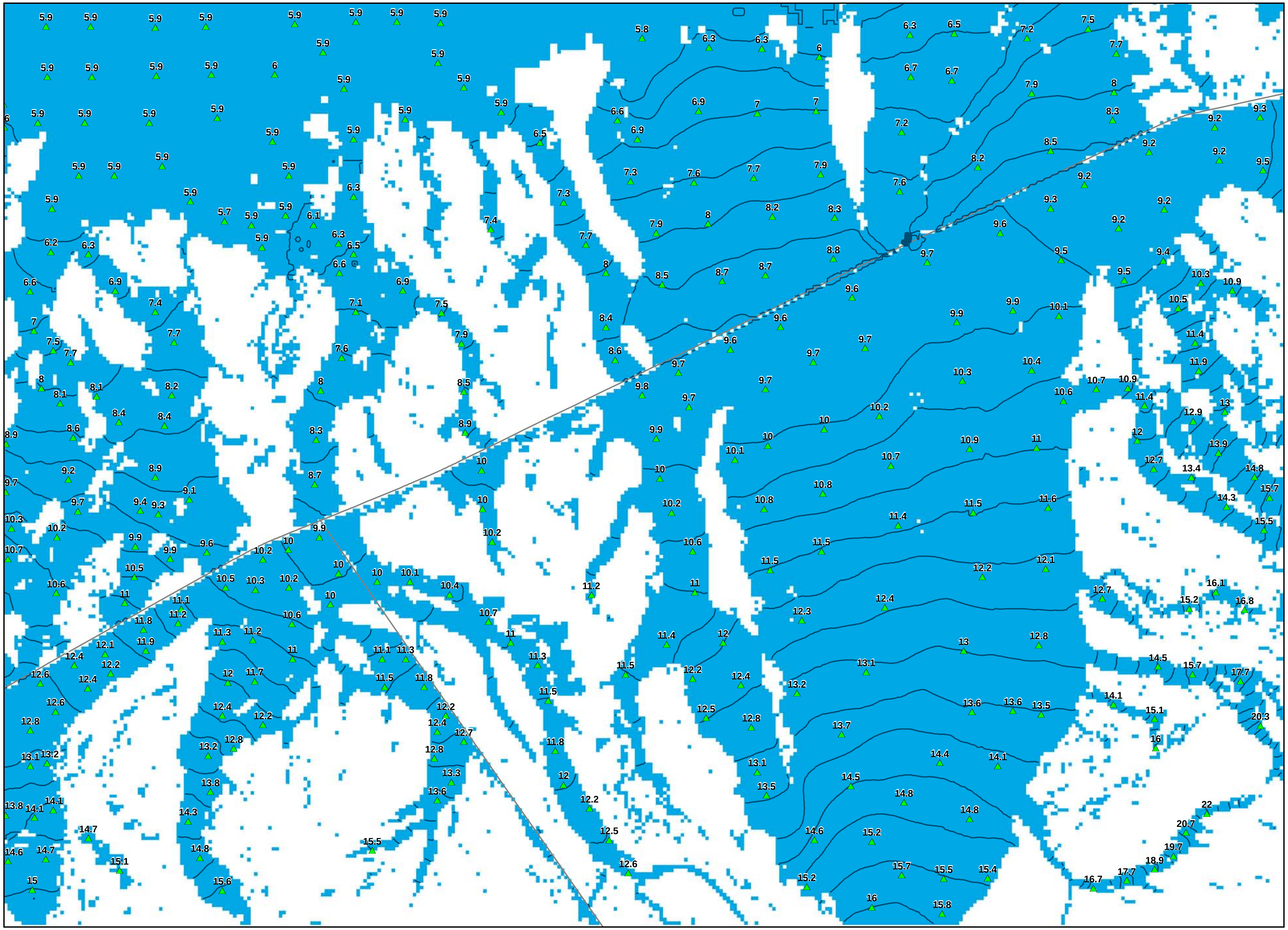
Figure 12E: 100yr ARI Flood Elevation - 2010 Climate Scenario - Sheet E



Note: No Water Levels are shown within town creeks due to model grid limitations

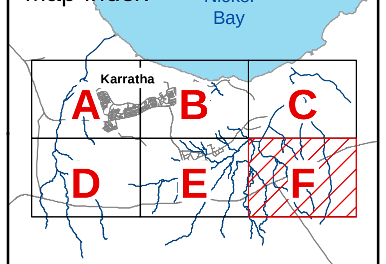
Tag Points(WaterLevel)(m AHD)

100yr Flood Extent

0.5m Contour (m AHD)

Cadastre

Map Index



1:500,000

Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

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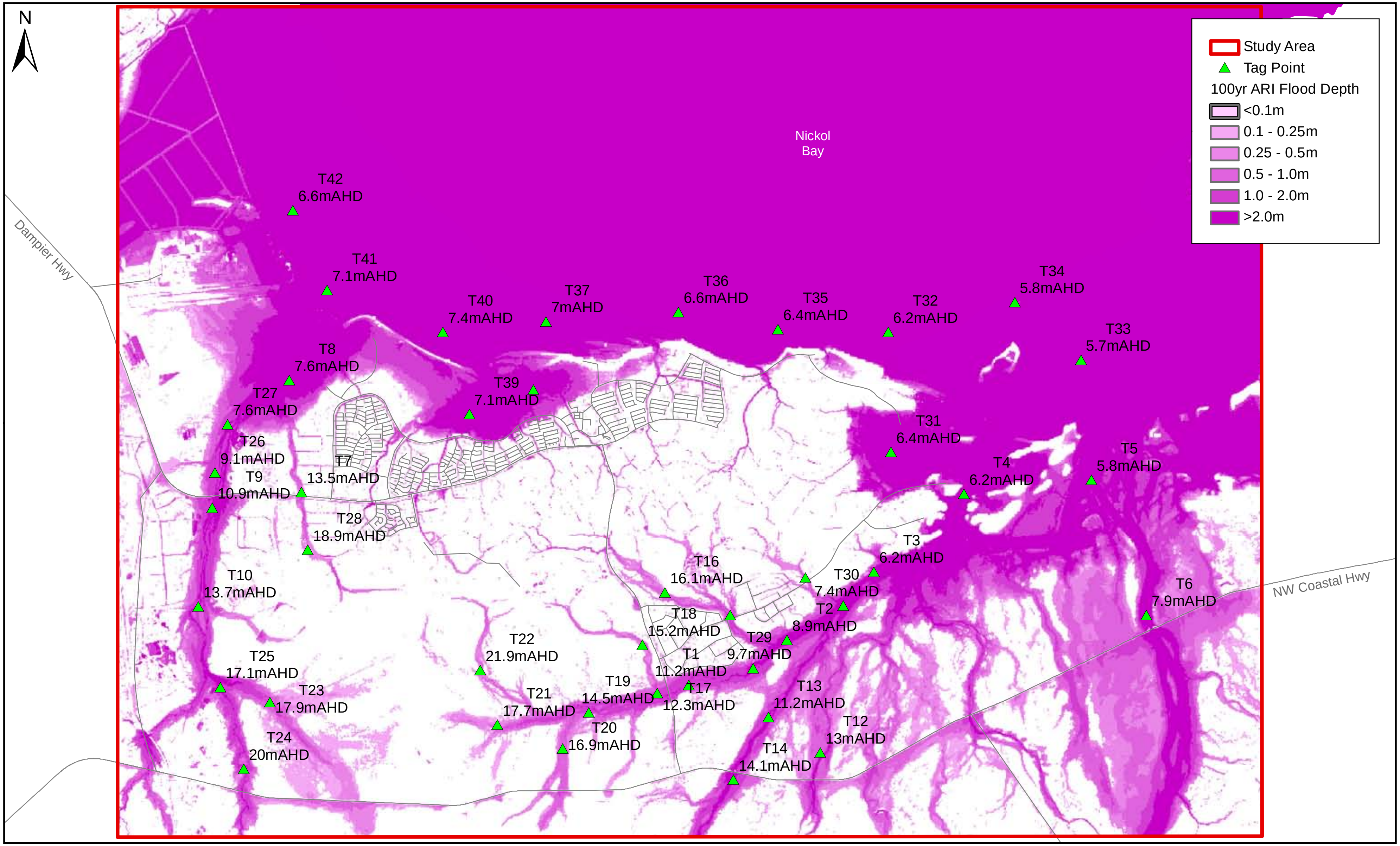
Karratha Coastal Vulnerability Study :Main Report

Figure 12F: 100yr ARI Flood Elevation - 2010 Climate Scenario - Sheet F



Data Source: GEMS Modelling & JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

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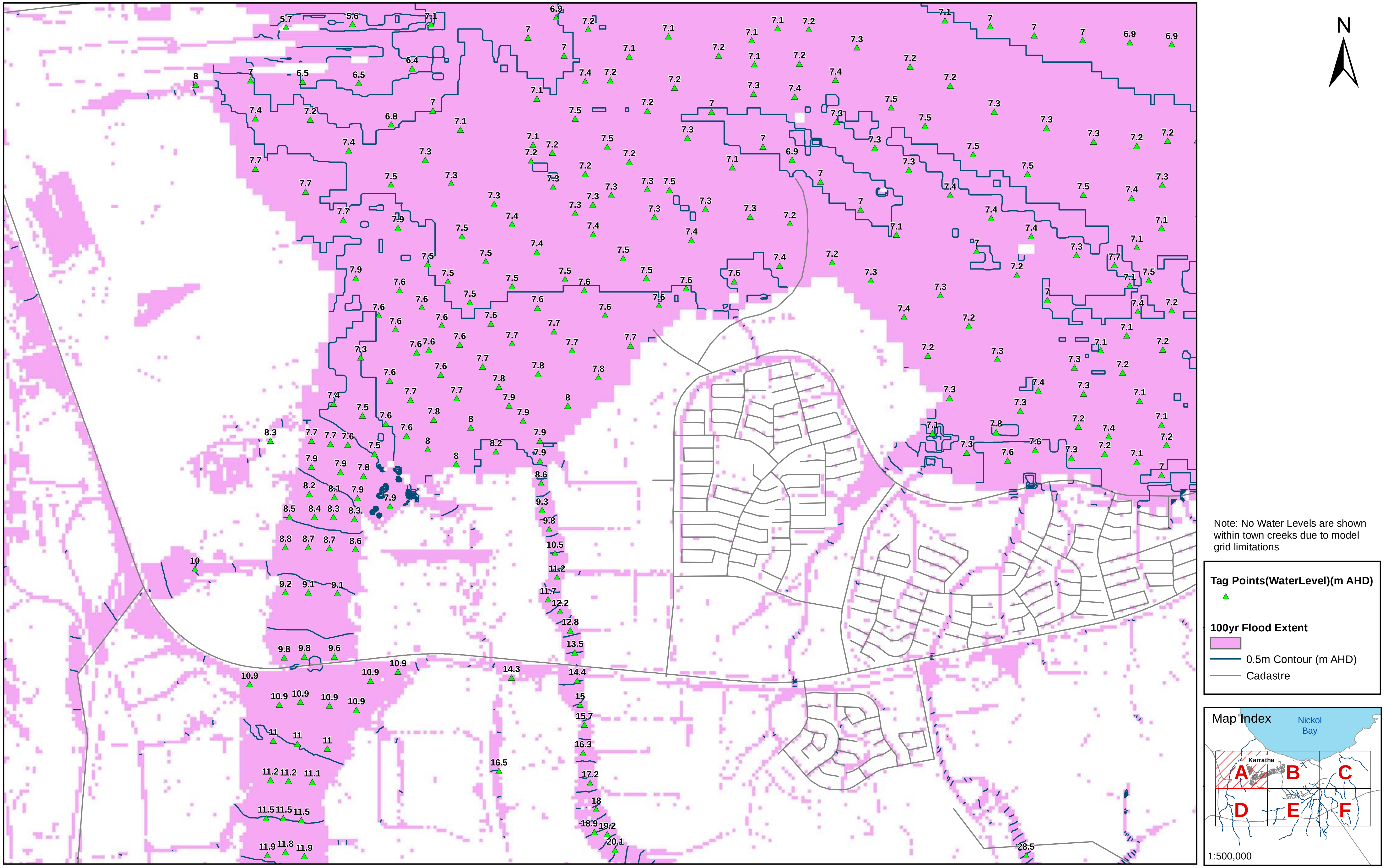
Karratha Coastal Vulnerability Study: Main Report

Figure 13: 100yr ARI Flood Depth - 2060 Climate Scenario



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

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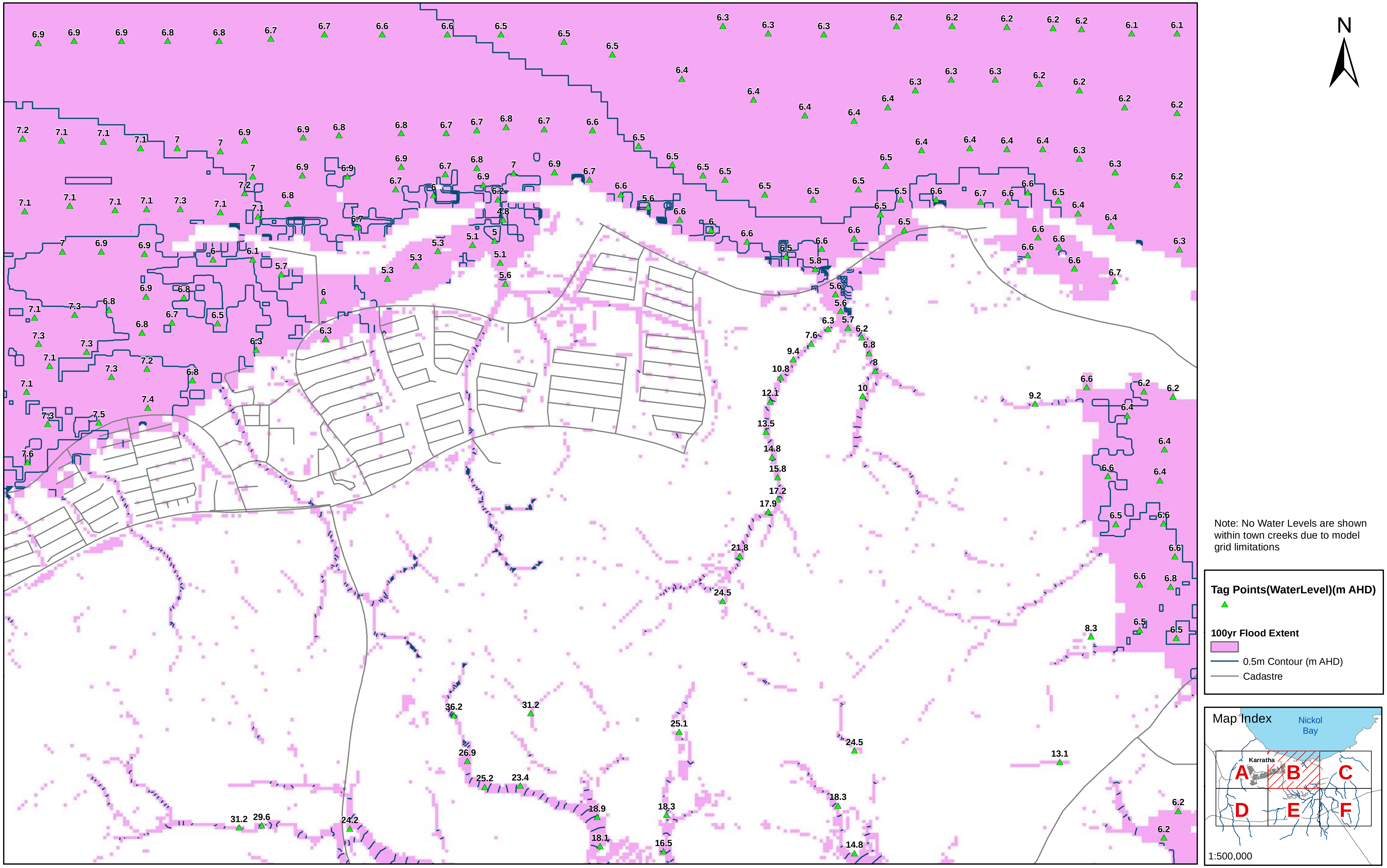
Figure 14A: 100yr ARI Flood Elevation - 2060 Climate Scenario - Sheet A



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

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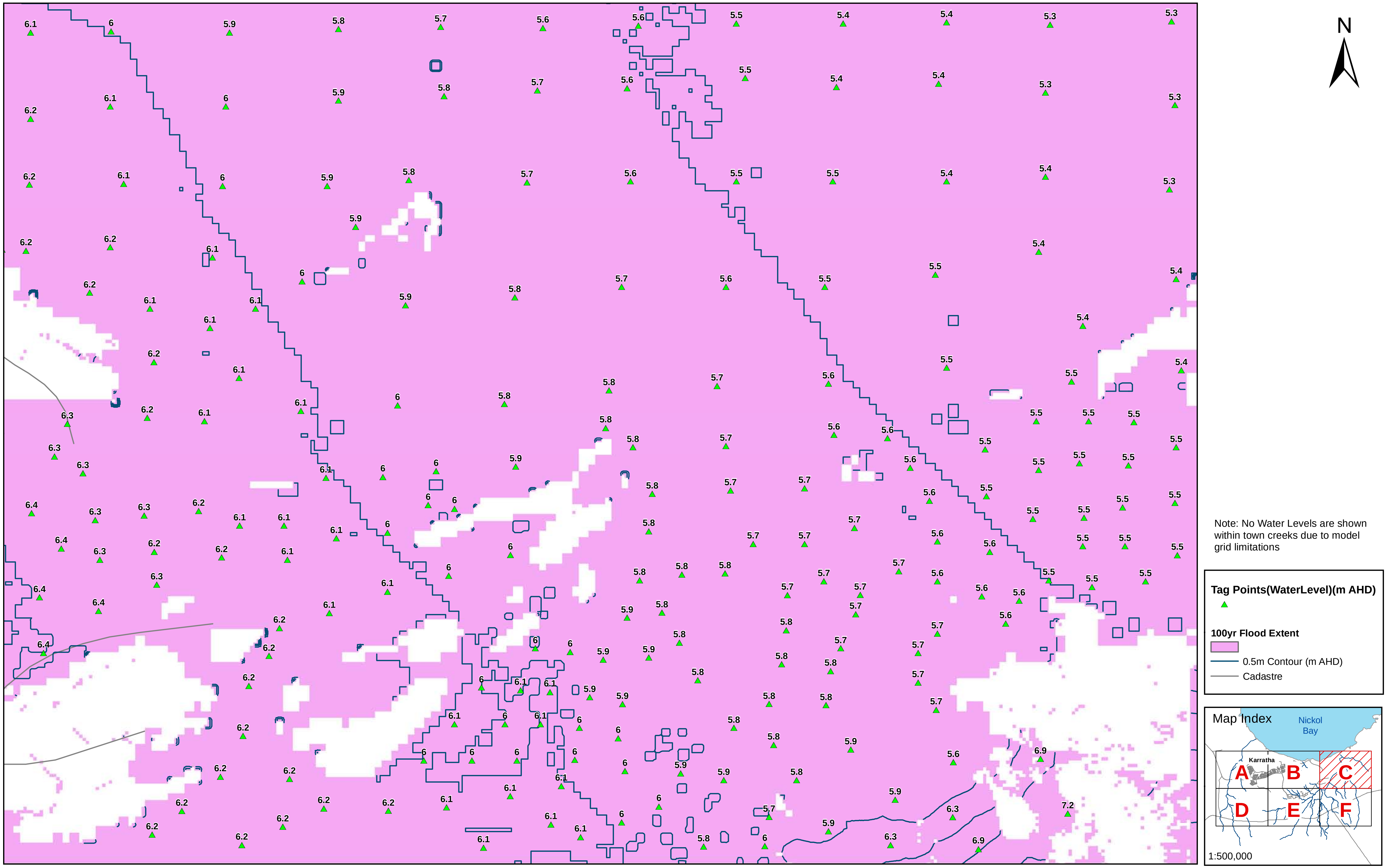
Figure 14B: 100yr ARI Flood Elevation - 2060 Climate Scenario - Sheet B



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

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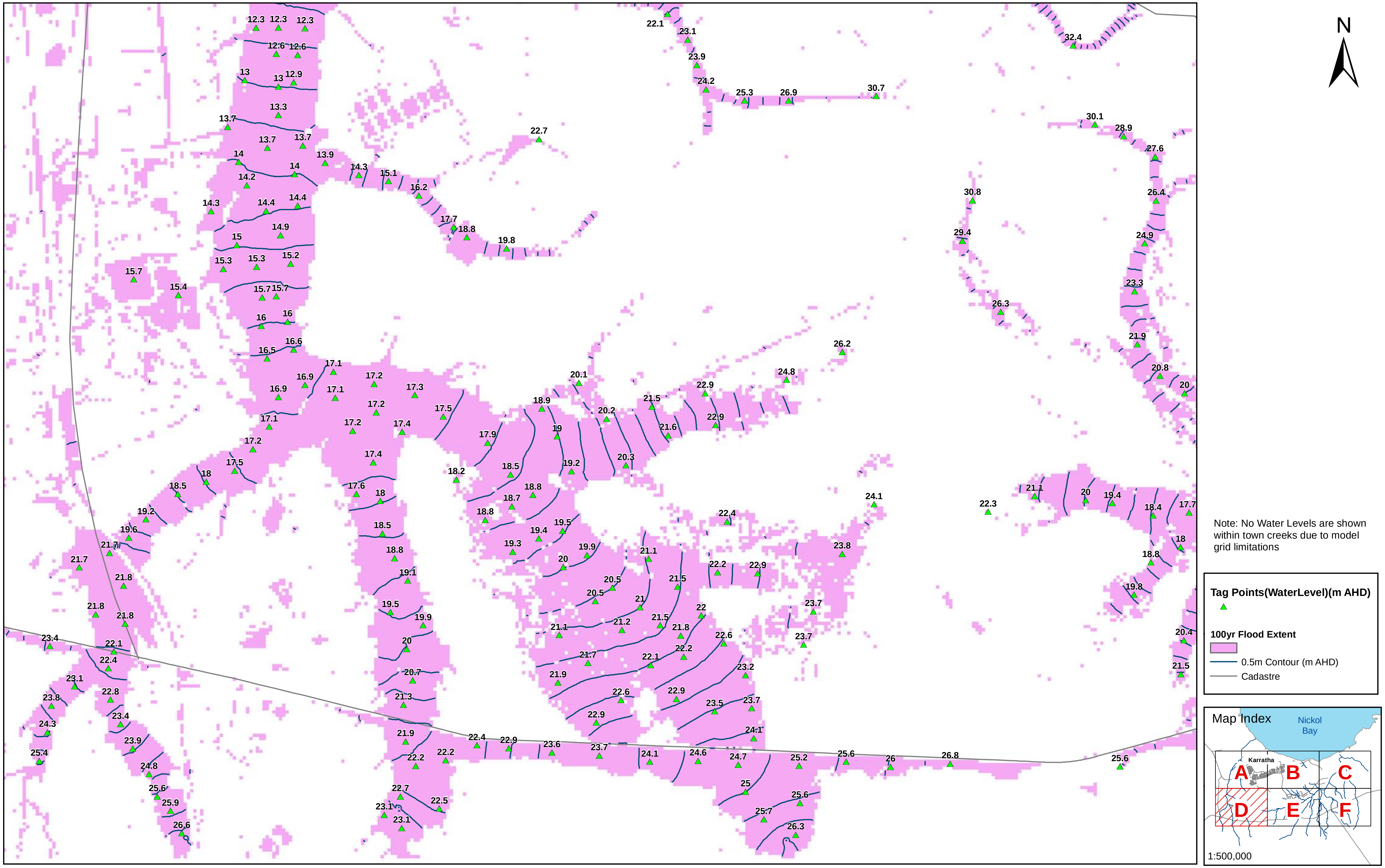
Figure 14C: 100yr ARI Flood Elevation - 2060 Climate Scenario - Sheet C



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

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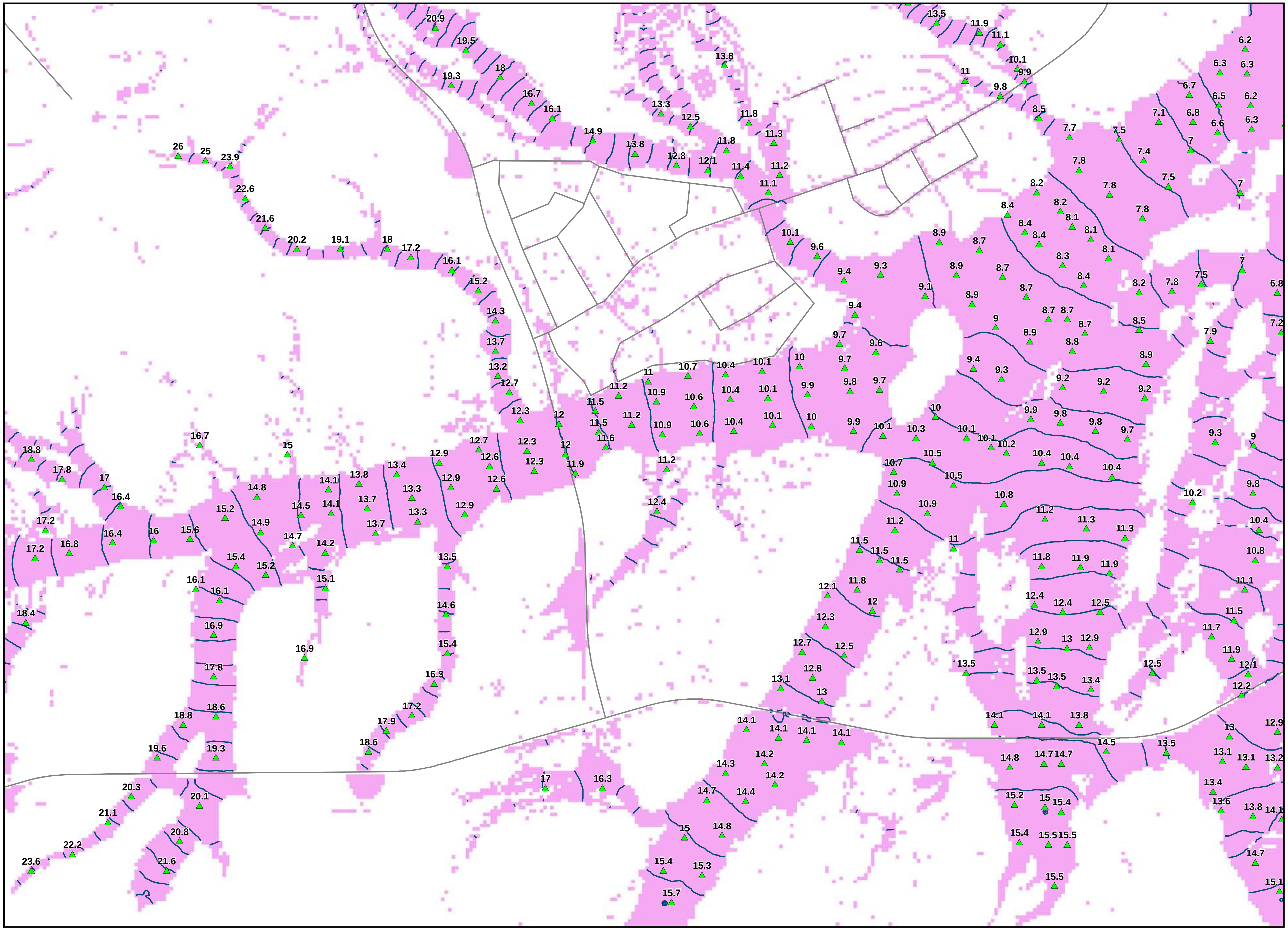
Figure 14D: 100yr ARI Flood Elevation - 2060 Climate Scenario - Sheet D



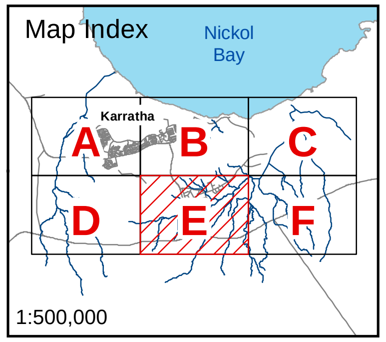
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

100yr Flood Extent

0.5m Contour (m AHD)

Cadastre



JDA

Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

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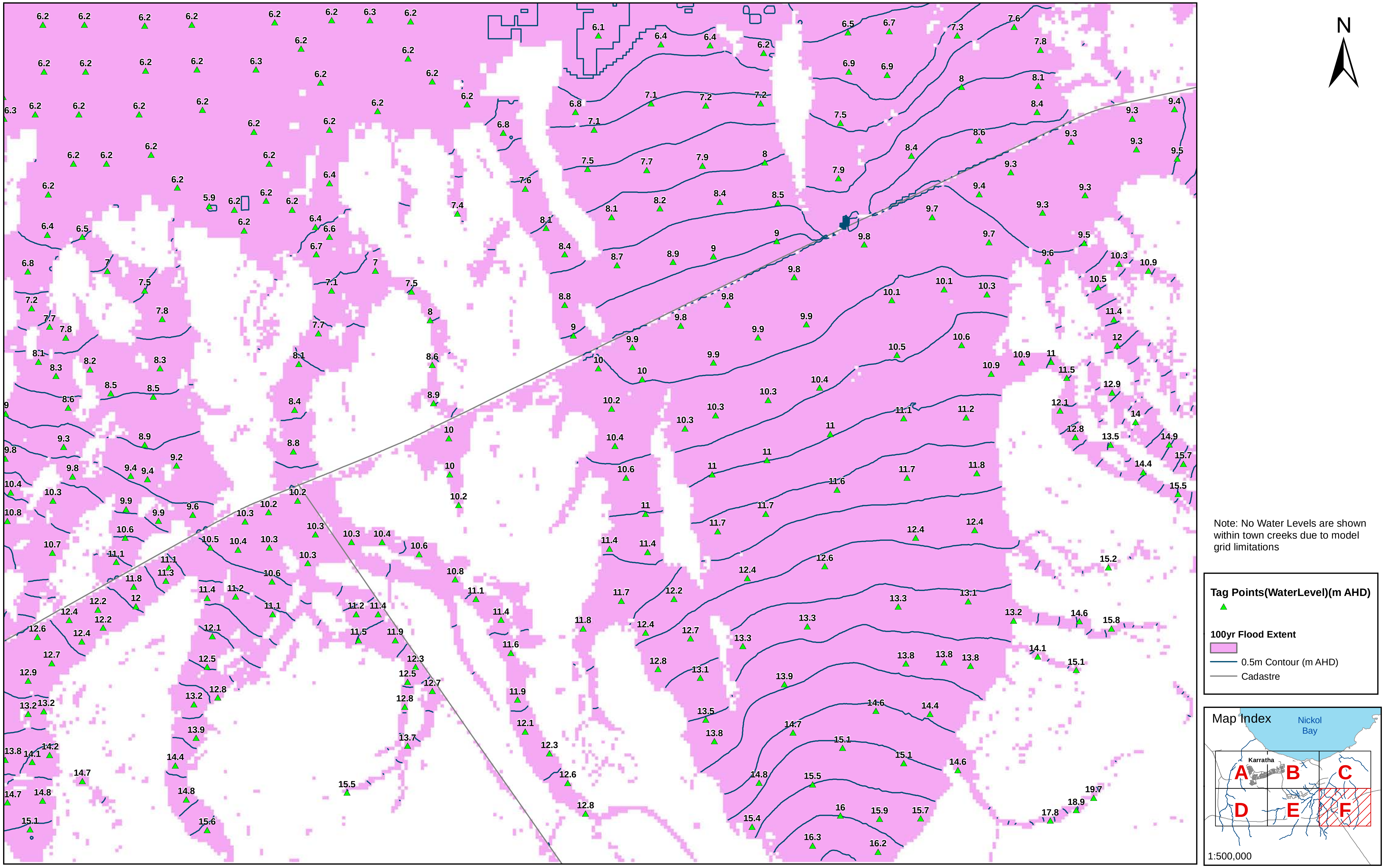
Karratha Coastal Vulnerability Study :Main Report
Figure 14E: 100yr ARI Flood Elevation - 2060 Climate Scenario - Sheet E



Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

LandCorp
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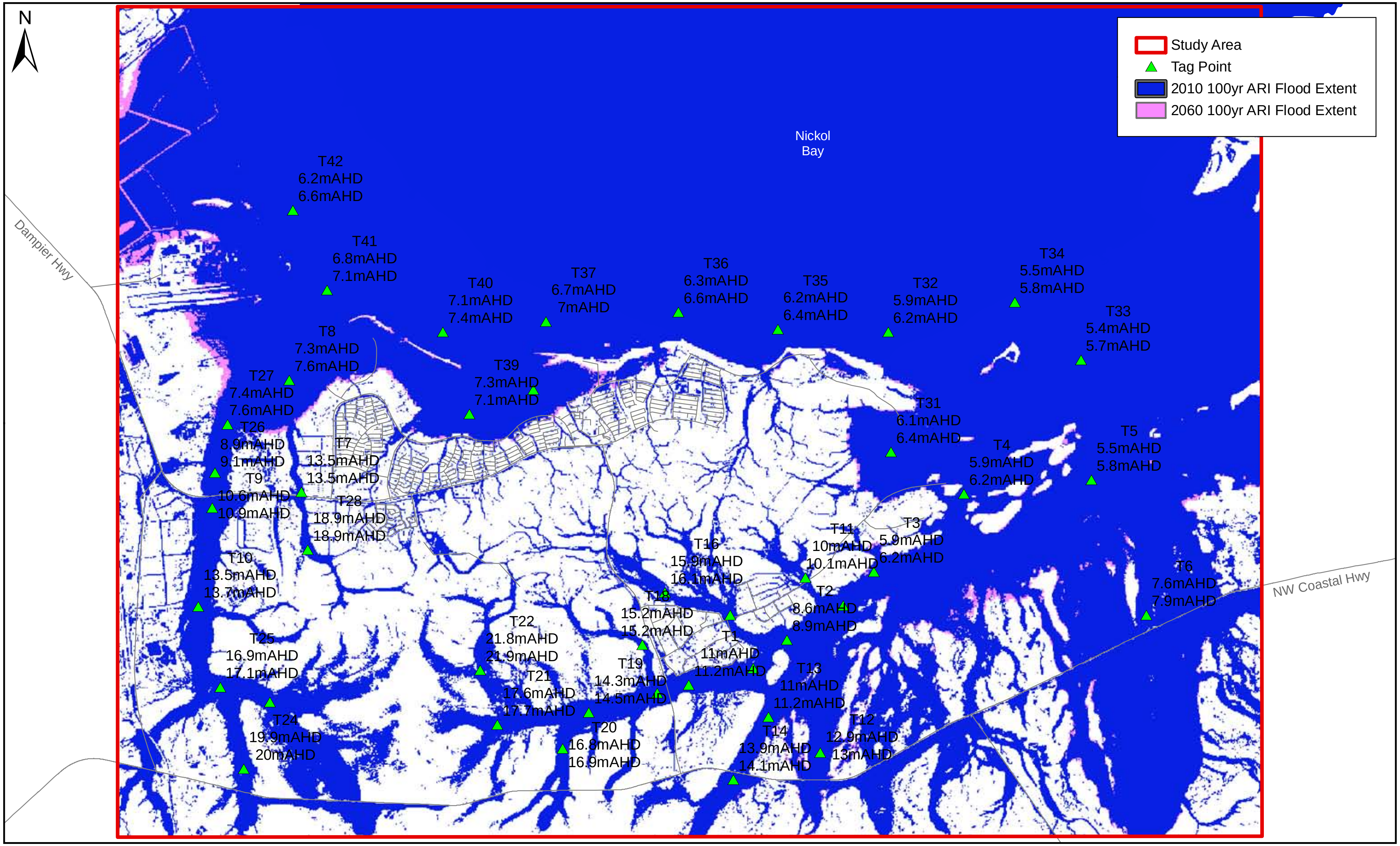
Figure 14F: 100yr ARI Flood Elevation - 2060 Climate Scenario - Sheet F



Data Source: GEMS Modelling and JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

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Karratha Coastal Vulnerability Study: Main Report

Figure 15 : Comparison of 100yr (2010) and 100yr (2060) Flood Extent

Data Source: GEMS Modelling and JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

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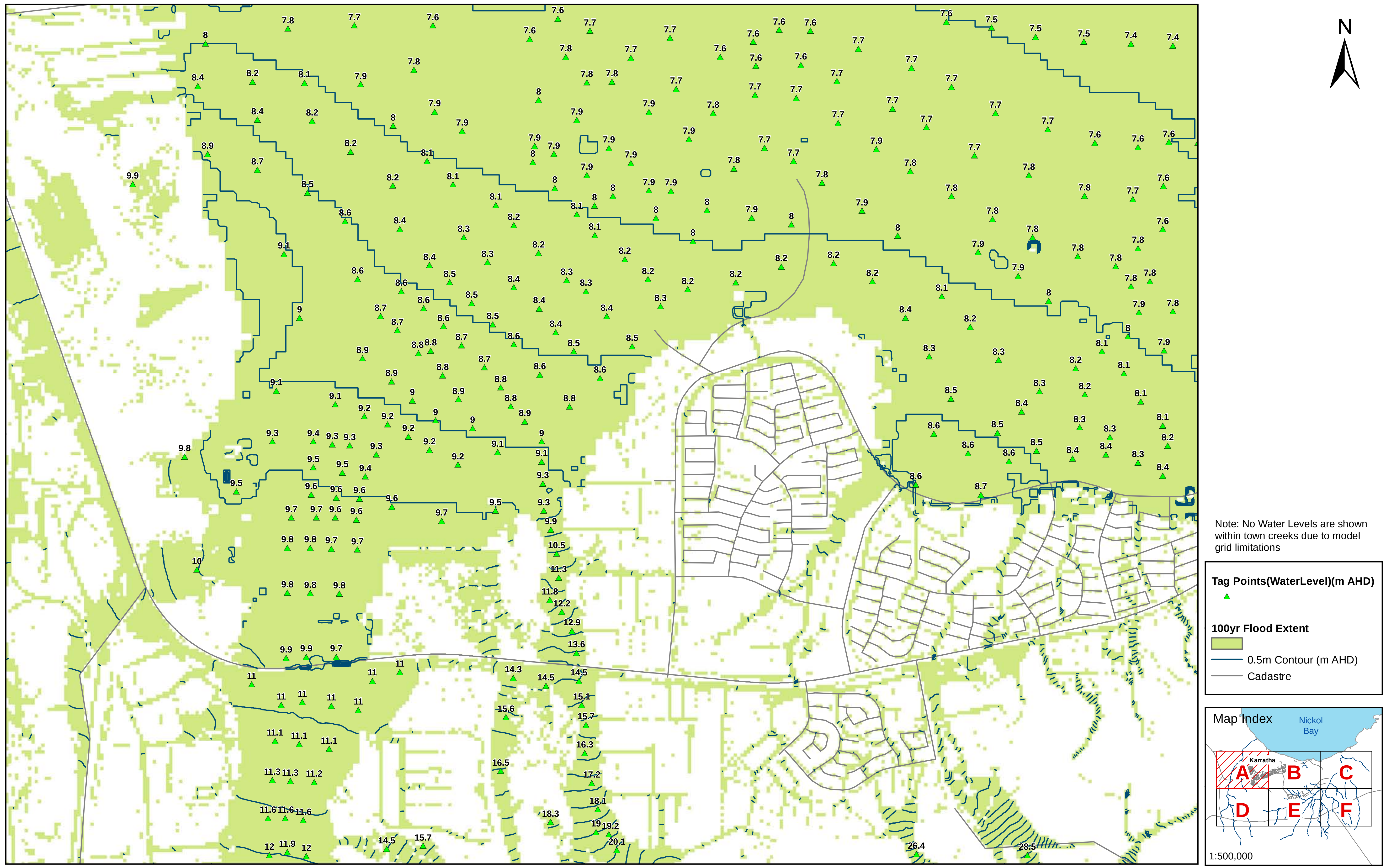
Figure 16: 100yr ARI Flood Depth - 2110 Climate Scenario



JDA

Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

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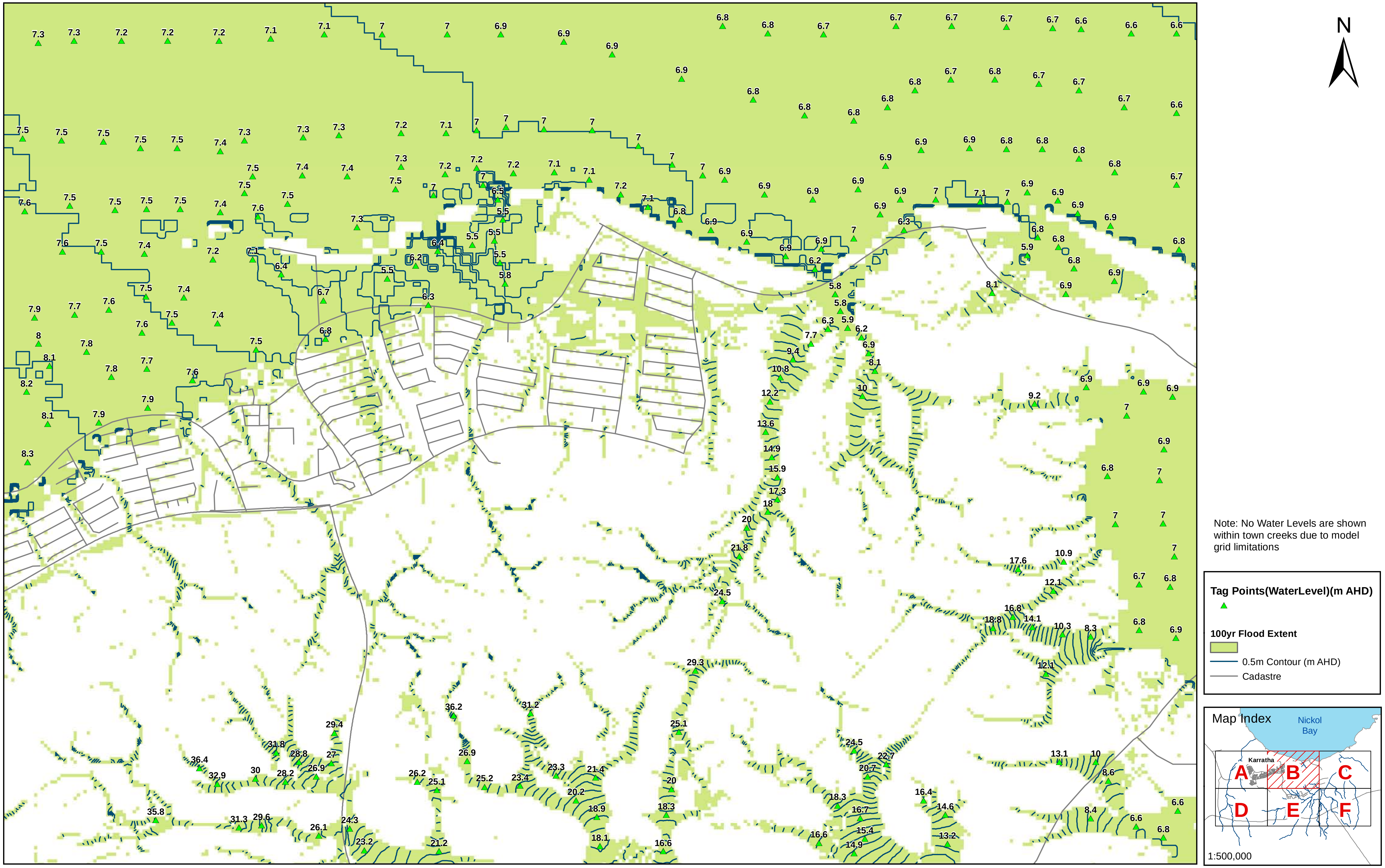
Karratha Coastal Vulnerability Study :Main Report
Figure 17A: 100yr ARI Flood Elevation - 2110 Climate Scenario - Sheet A



Job No. J4812

Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

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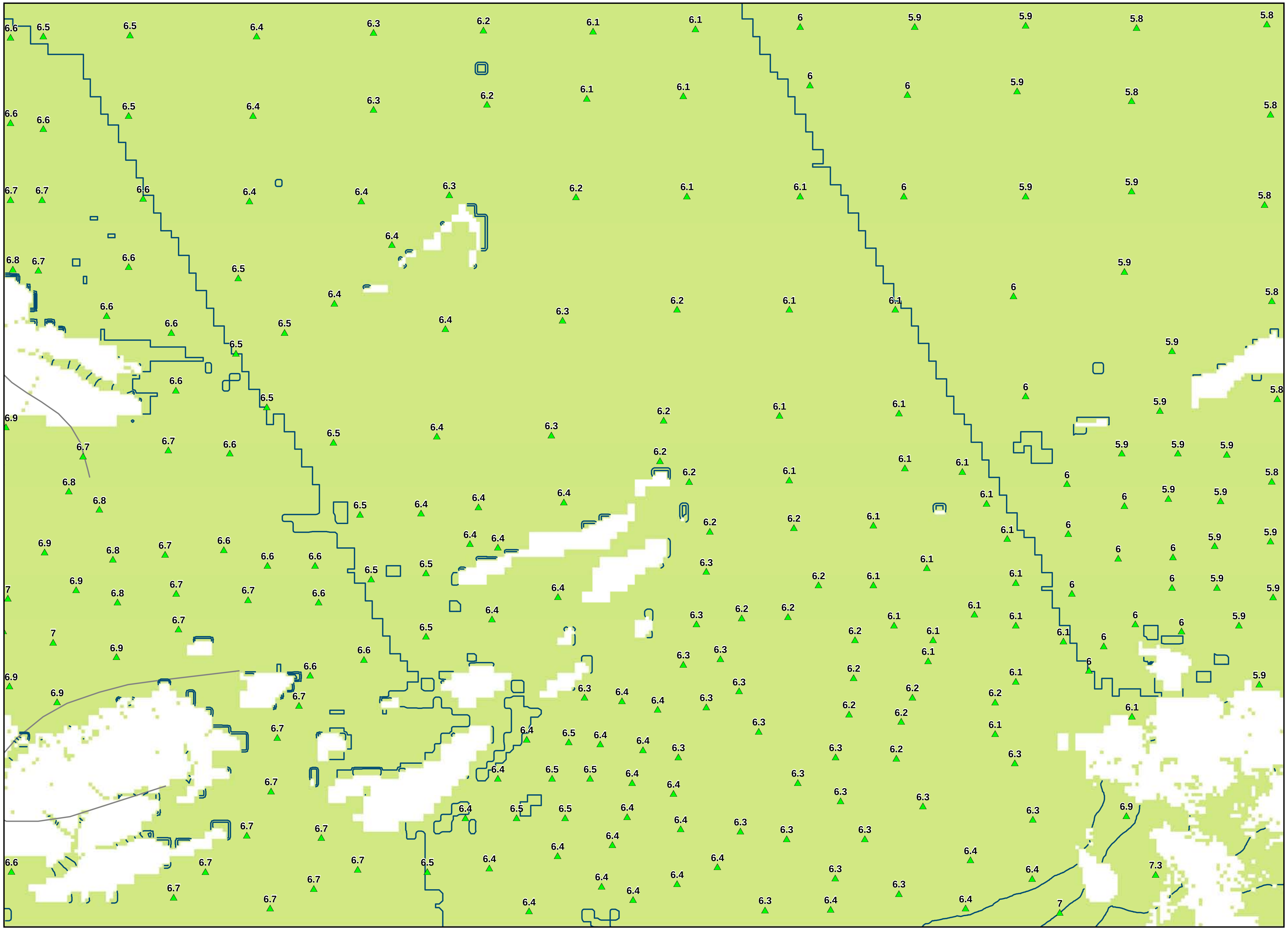
Figure 17B: 100yr ARI Flood Elevation - 2110 Climate Scenario - Sheet B



N

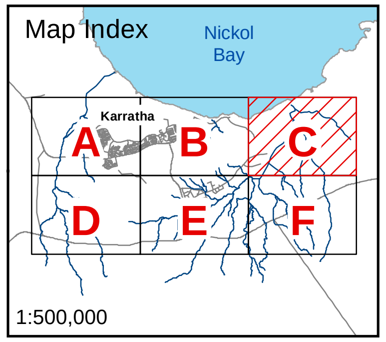
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

100yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

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Figure 17C: 100yr ARI Flood Elevation - 2110 Climate Scenario - Sheet C

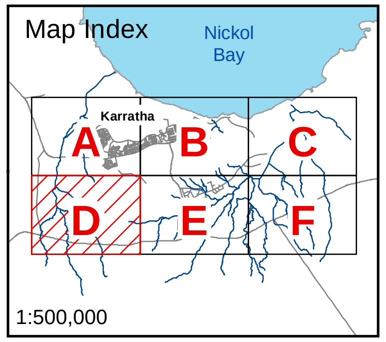
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

100yr Flood Extent

0.5m Contour (m AHD)

Cadastre



JDA

Job No. J4812

Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

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Figure 17D: 100yr ARI Flood Elevation - 2110 Climate Scenario - Sheet D

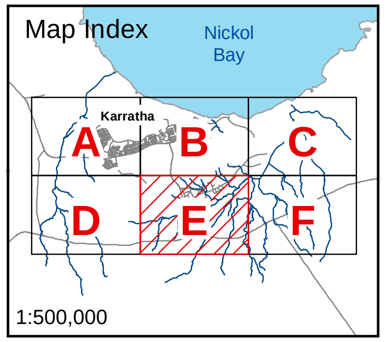
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

100yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812

Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

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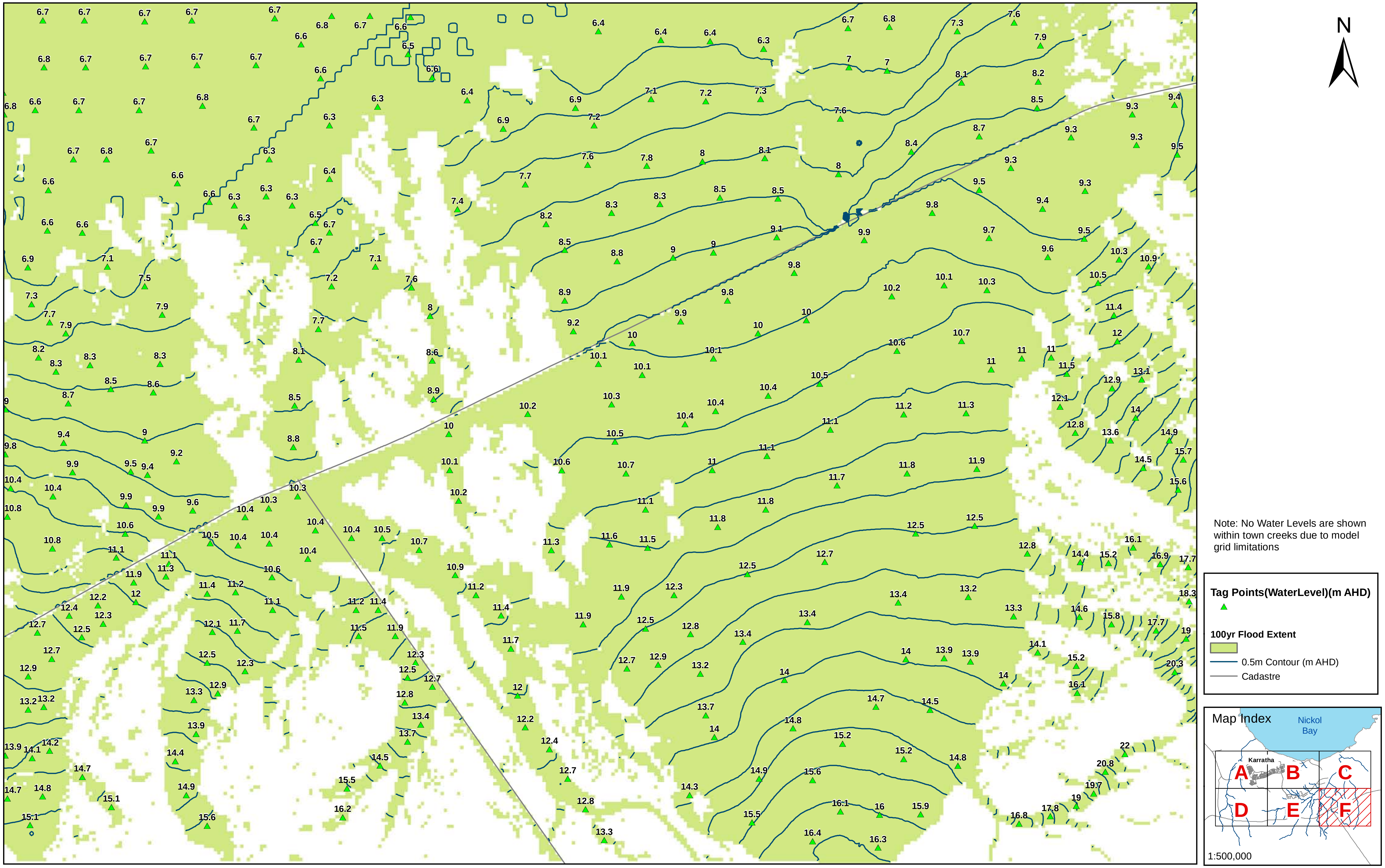
Figure 17E: 100yr ARI Flood Elevation - 2110 Climate Scenario - Sheet E



Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

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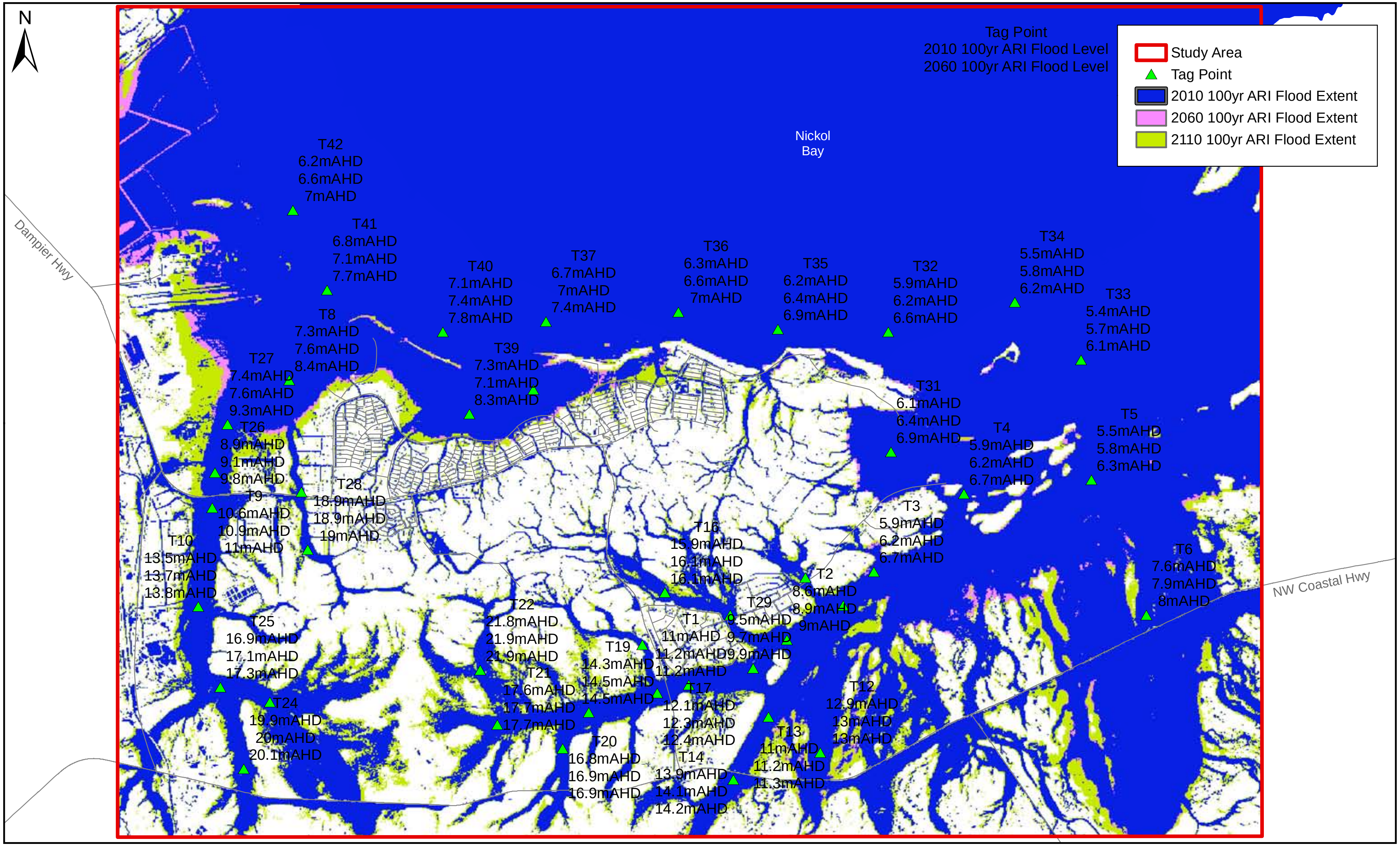
Karratha Coastal Vulnerability Study :Main Report

Figure 17F: 100yr ARI Flood Elevation - 2110 Climate Scenario - Sheet F



Data Source: GEMS Modelling and JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

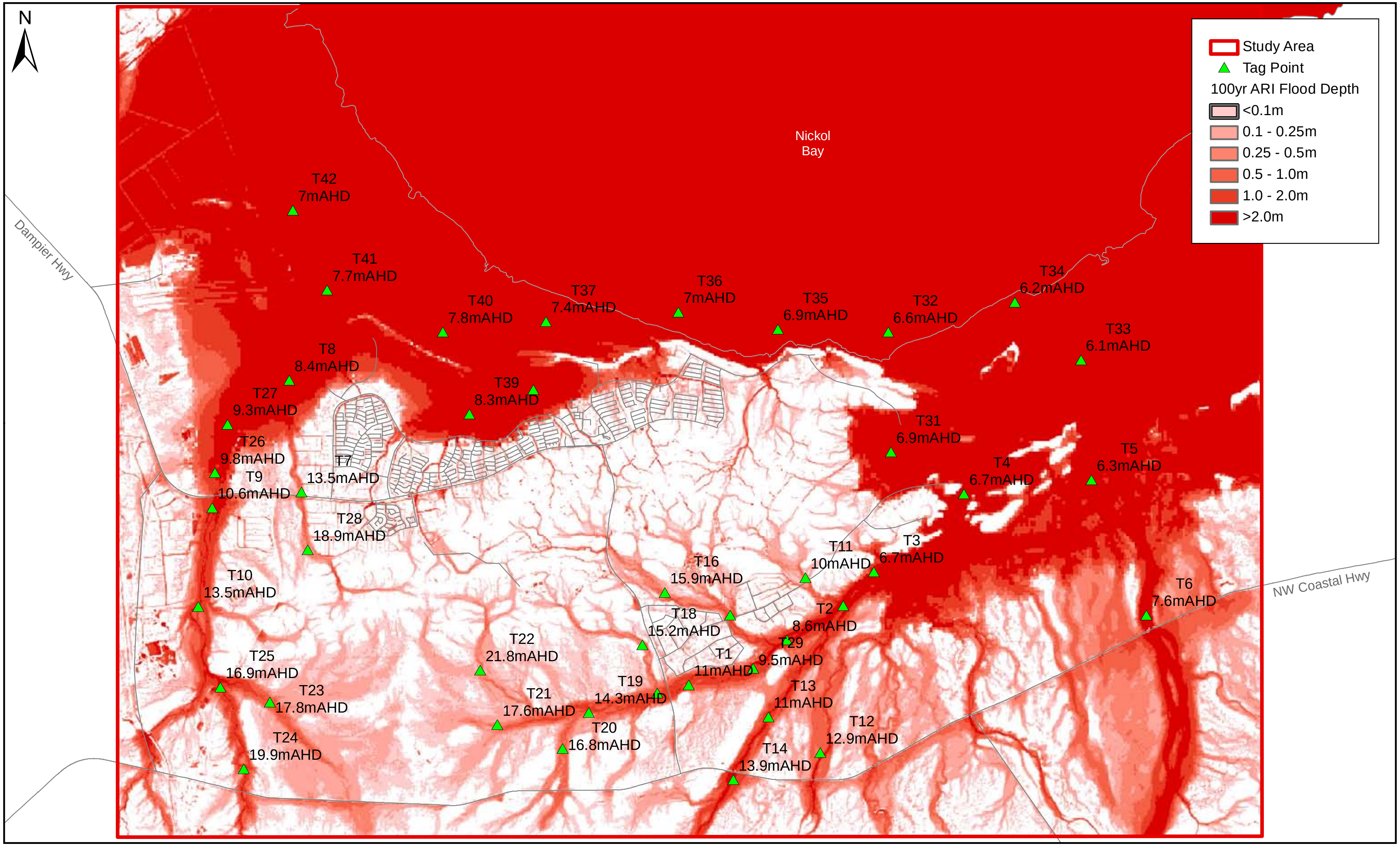
Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

LandCorp

Karratha Coastal Vulnerability Study: Main Report

Figure 18 : Comparison of 100yr (2010), 100yr (2060) and 100yr (2110) Flood Extent



Data Source: GEMS Modelling & JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

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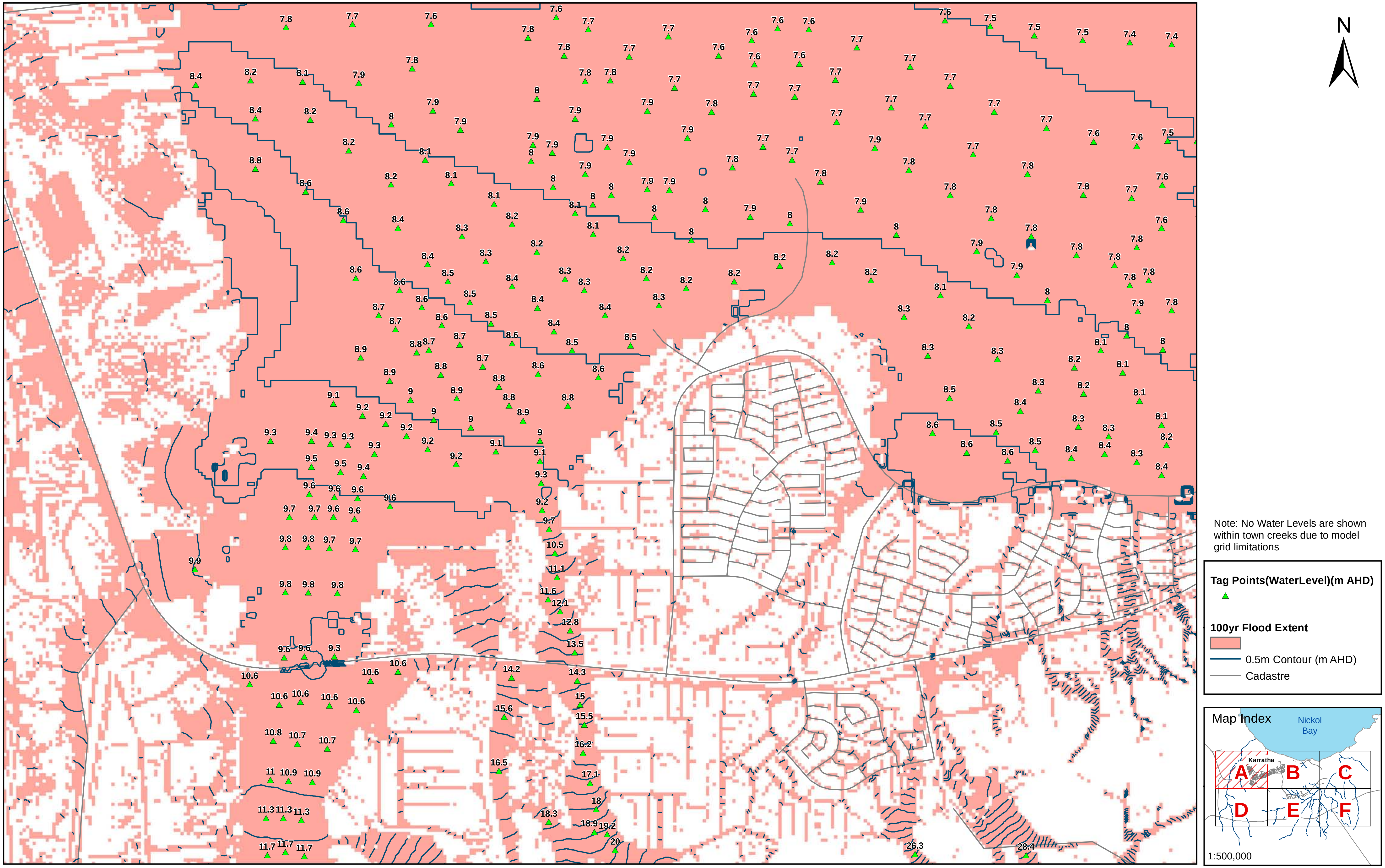
Karratha Coastal Vulnerability Study: Main Report

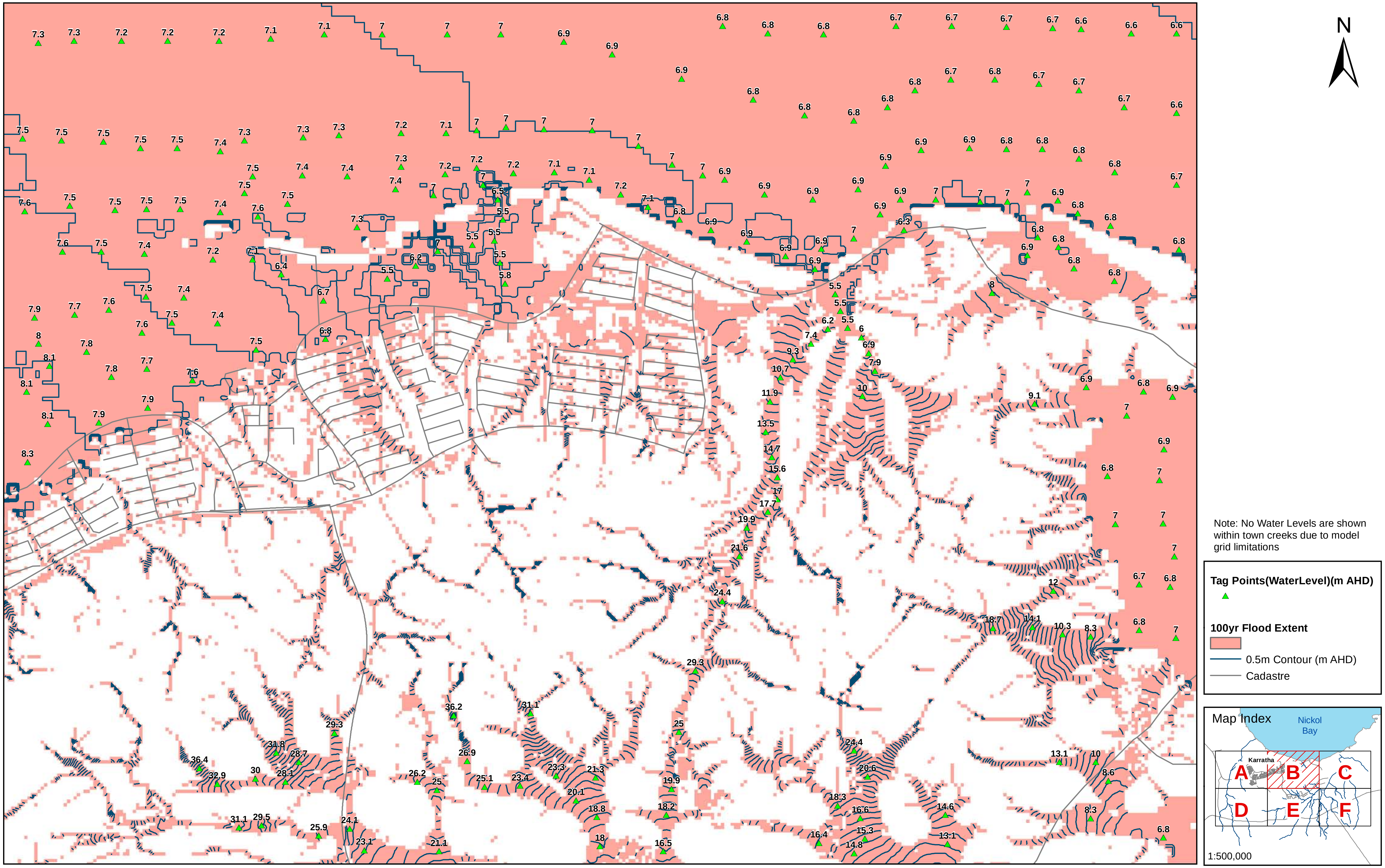
Figure 19 : 100yr ARI Flood Depth - 2010 Climate & 2110 SurgeStorm Scenario



JDA

Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure 20A: 100yr ARI Flood Elevation - 2010 Climate & 2110 SurgeStorm Scenario - Sheet A



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

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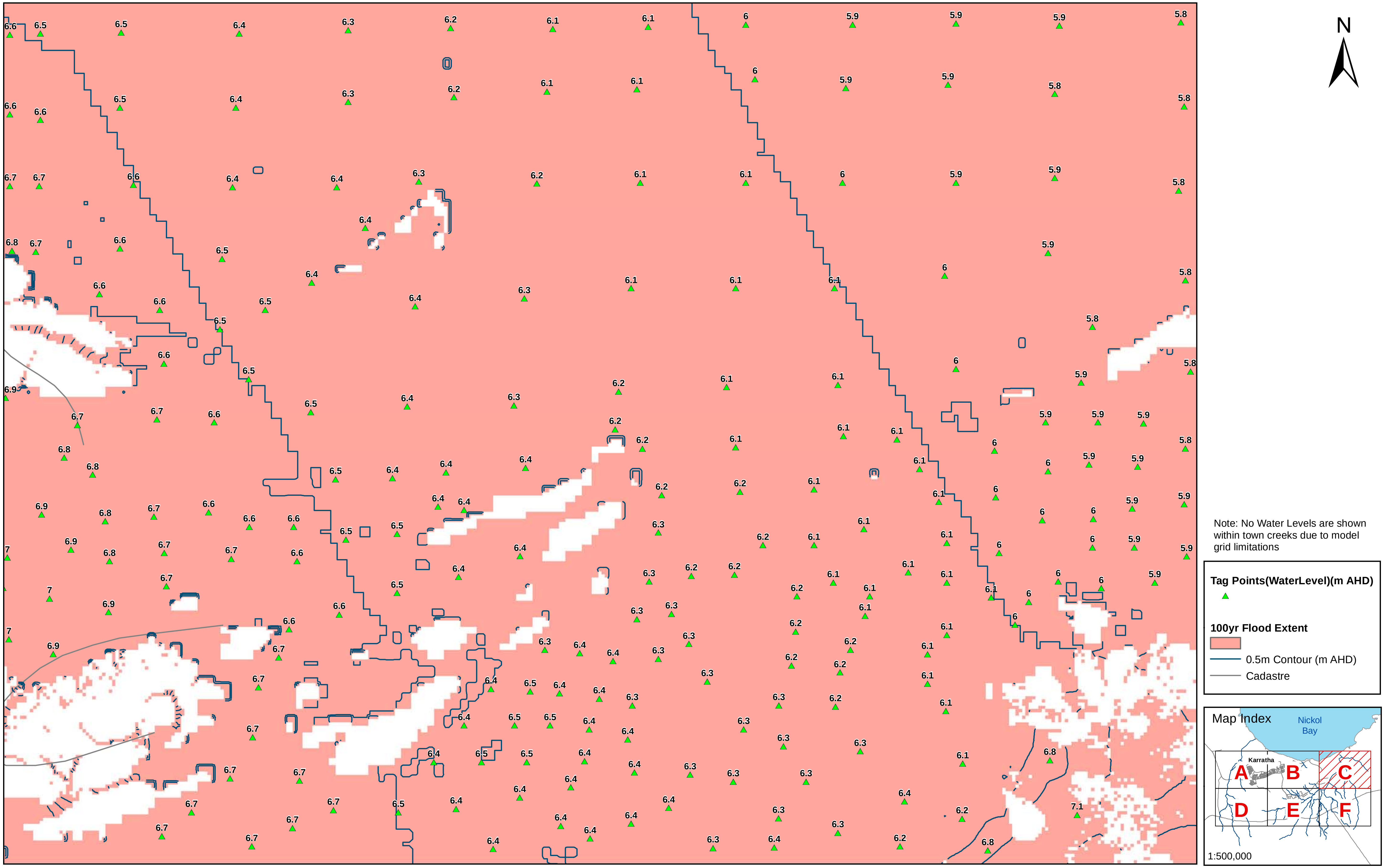
Figure 20B: 100yr ARI Flood Elevation - 2010 Climate & 2110 SurgeStorm Scenario - Sheet B



Job No. J4812
Scale:1:22,000
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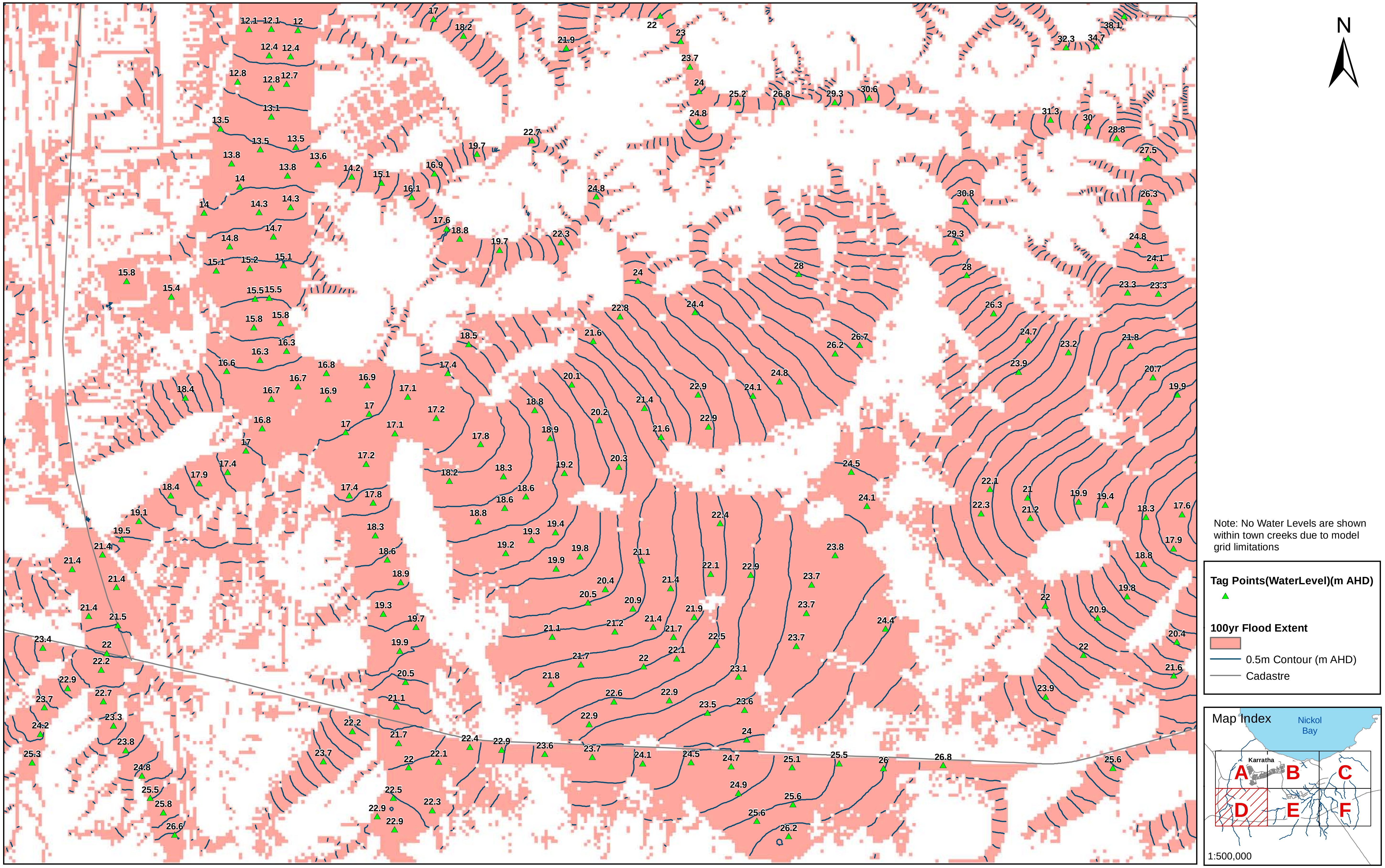
LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure 20C: 100yr ARI Flood Elevation - 2010 Climate & 2110 SurgeStorm Scenario - Sheet C



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

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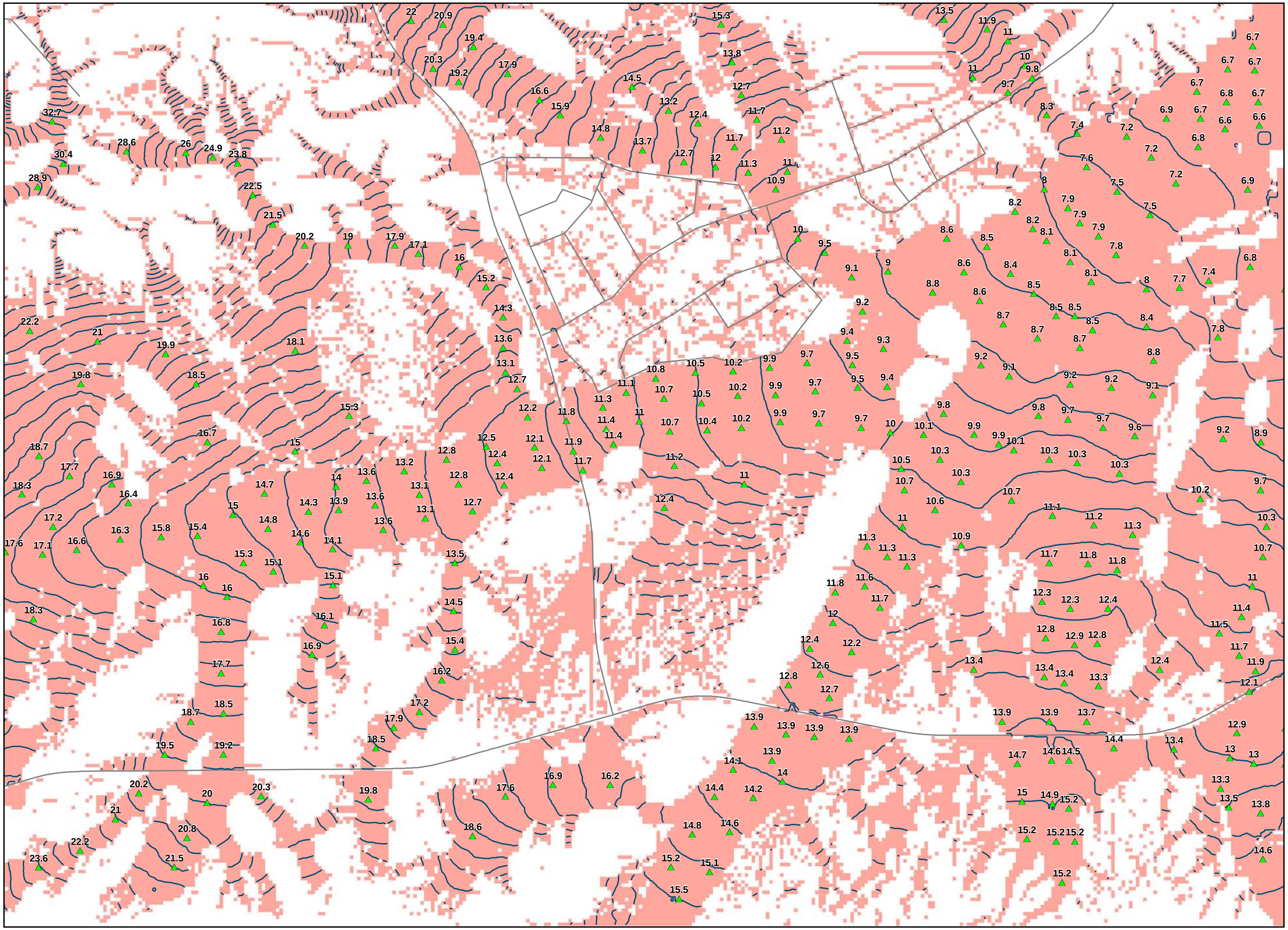
Figure 20D: 100yr ARI Flood Elevation - 2010 Climate & 2110 SurgeStorm Scenario - Sheet D



N

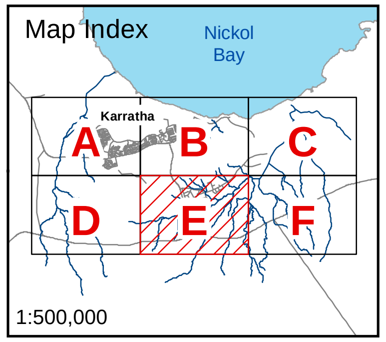
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

100yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
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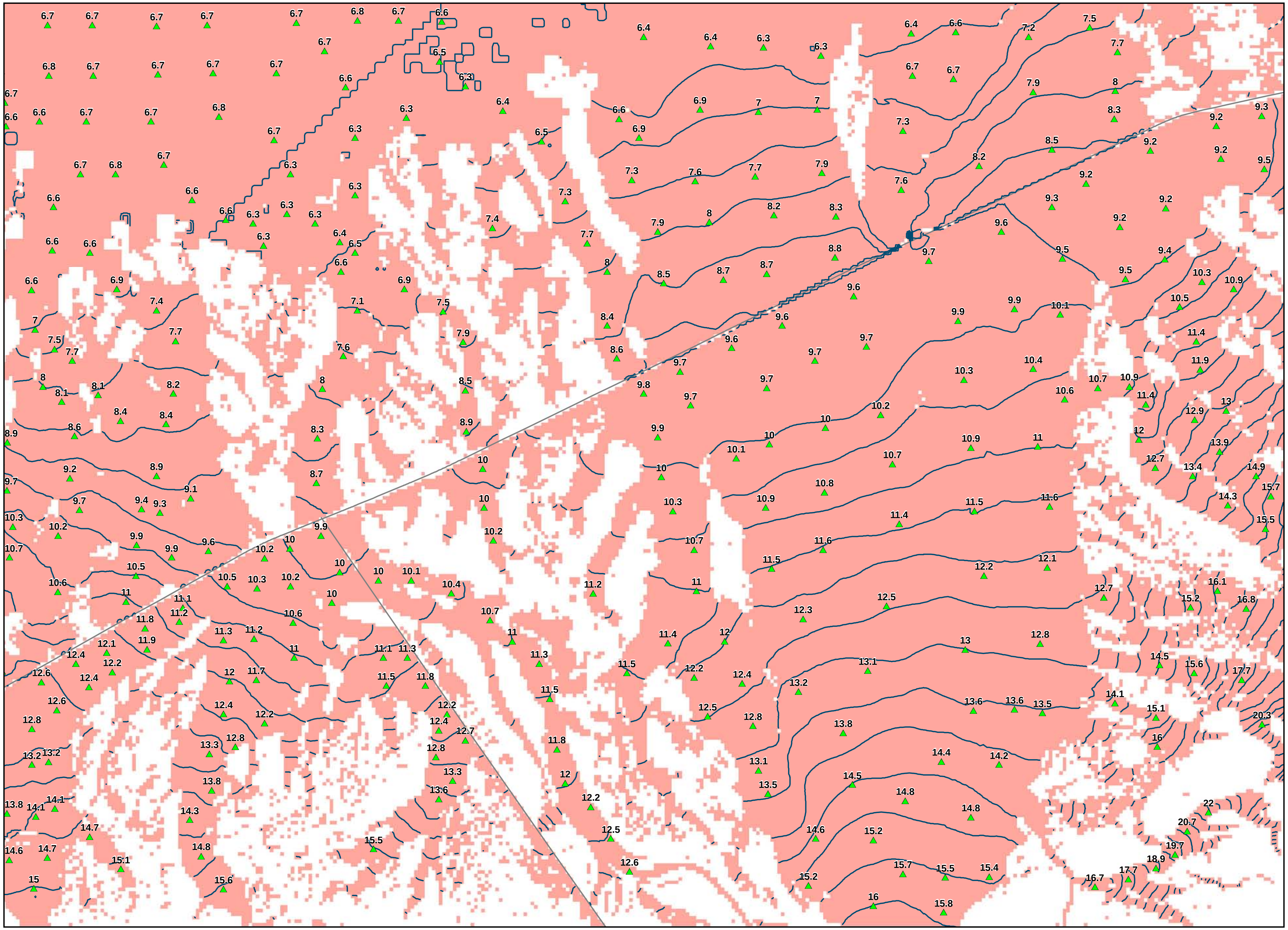
Figure 20E: 100yr ARI Flood Elevation - 2010 Climate & 2110 SurgeStorm Scenario - Sheet E



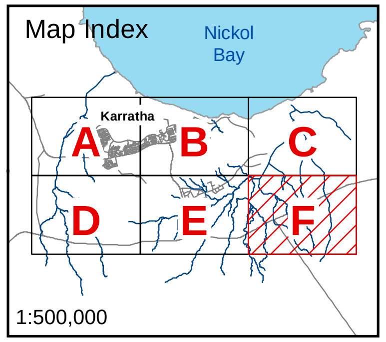
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

100yr Flood Extent

0.5m Contour (m AHD)

Cadastre



JDA

Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

LandCorp
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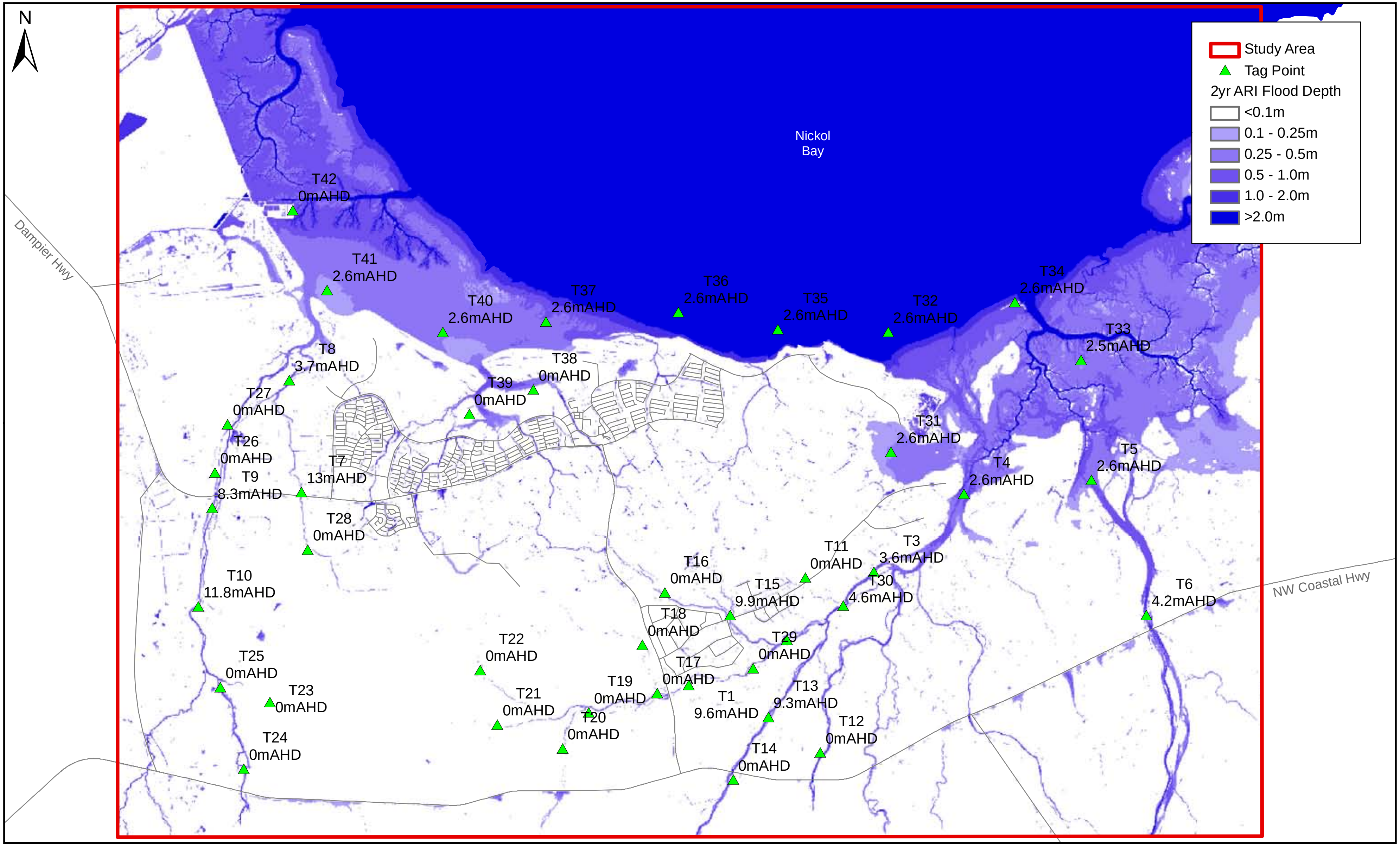
Figure 20F: 100yr ARI Flood Elevation - 2010 Climate & 2110 SurgeStorm Scenario - Sheet F

APPENDIX A

2yr ARI Flood Extent, Depth, Level and Flow Velocity for the 2010, 2060 & 2110 Climate Scenarios



Data Source: GEMS Modelling & JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

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Figure A1: 2yr ARI Flood Depth - 2010 Climate Scenario

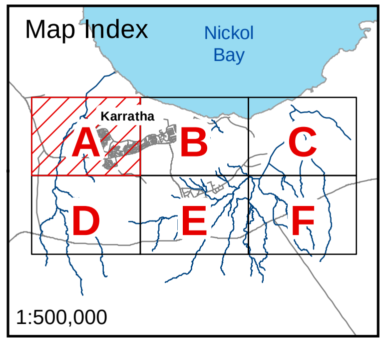
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

2yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812

Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

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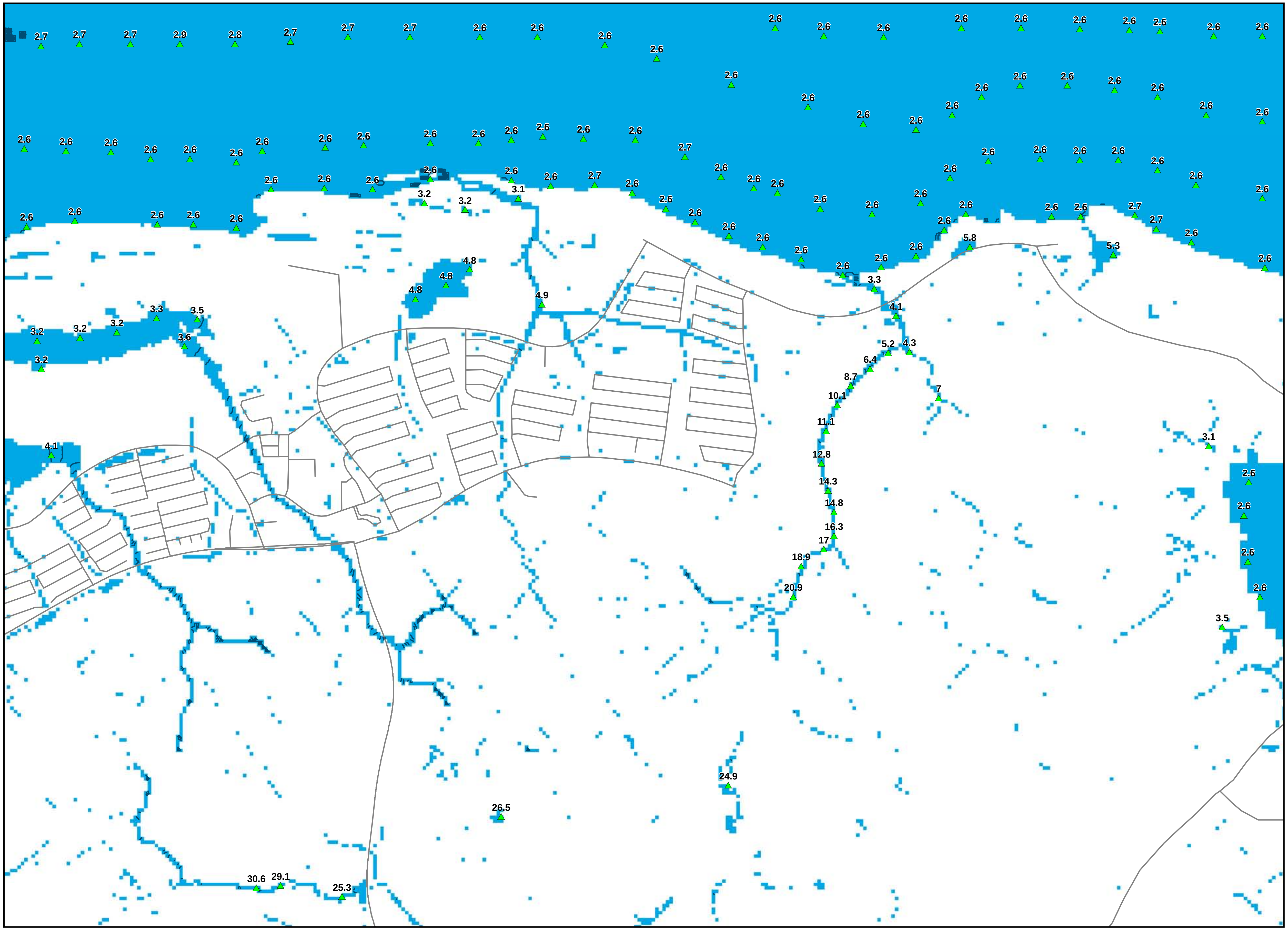
Figure A2A: 2yr ARI Flood Elevation - 2010 Climate Scenario - Sheet A



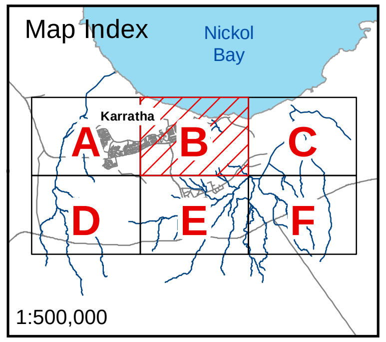
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

2yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
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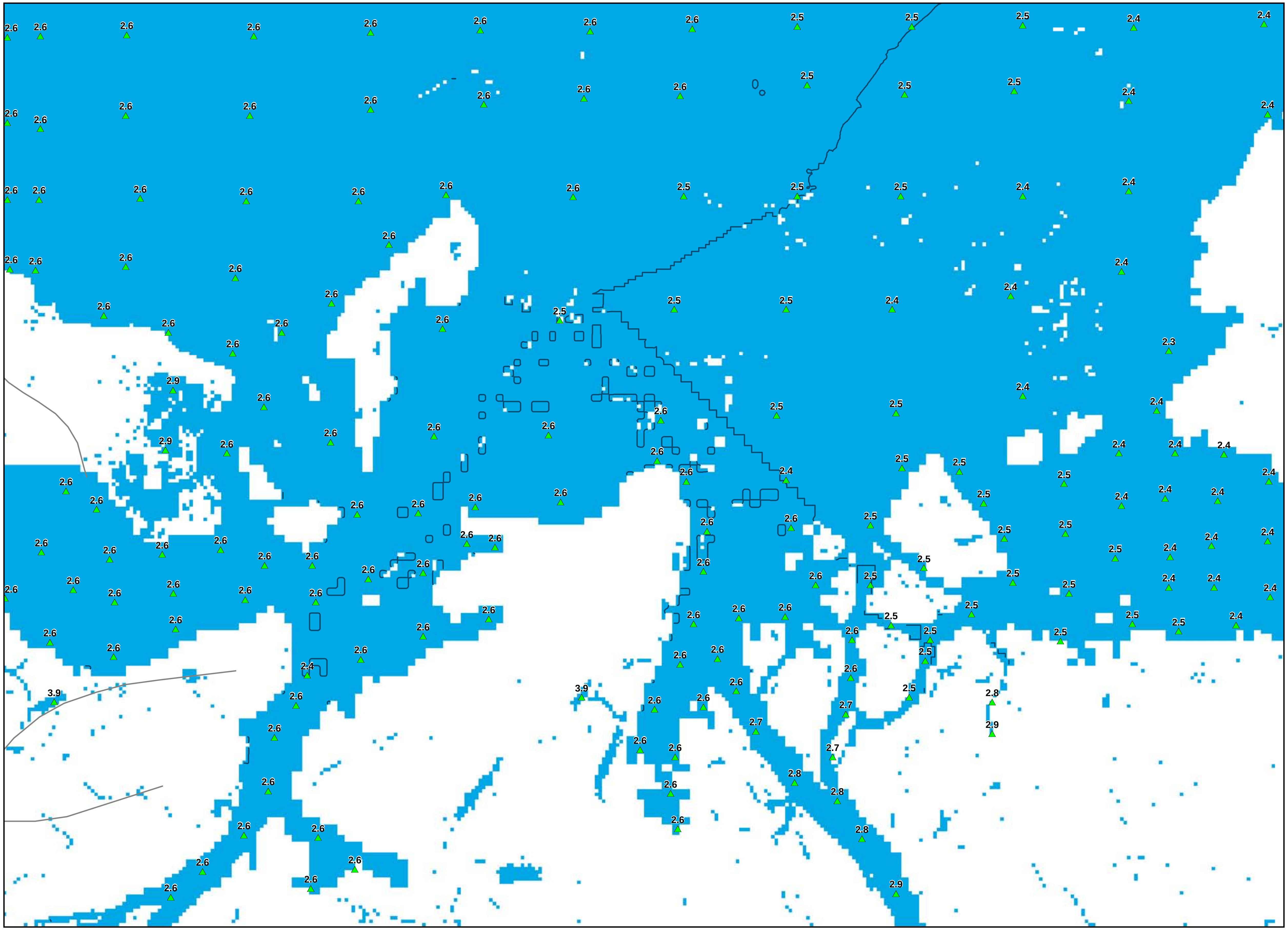
Figure A2B: 2yr ARI Flood Elevation - 2010 Climate Scenario - Sheet B



N

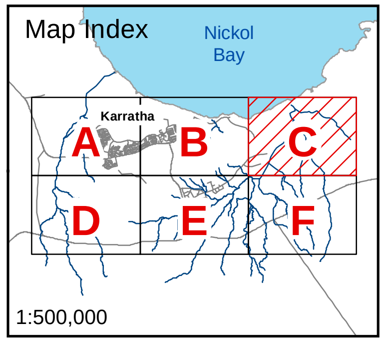
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

2yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

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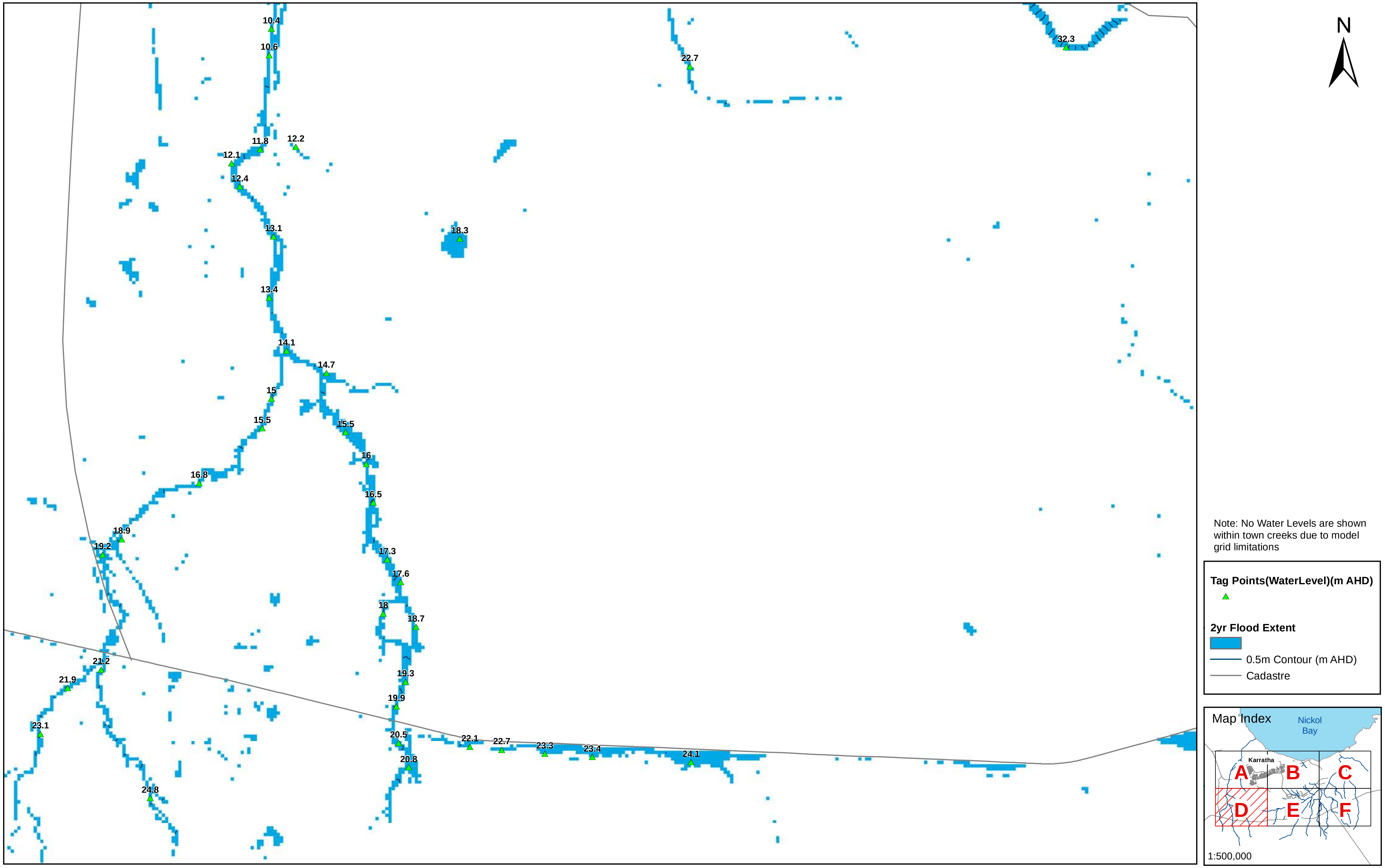
Karratha Coastal Vulnerability Study :Main Report

Figure A2C: 2yr ARI Flood Elevation - 2010 Climate Scenario - Sheet C

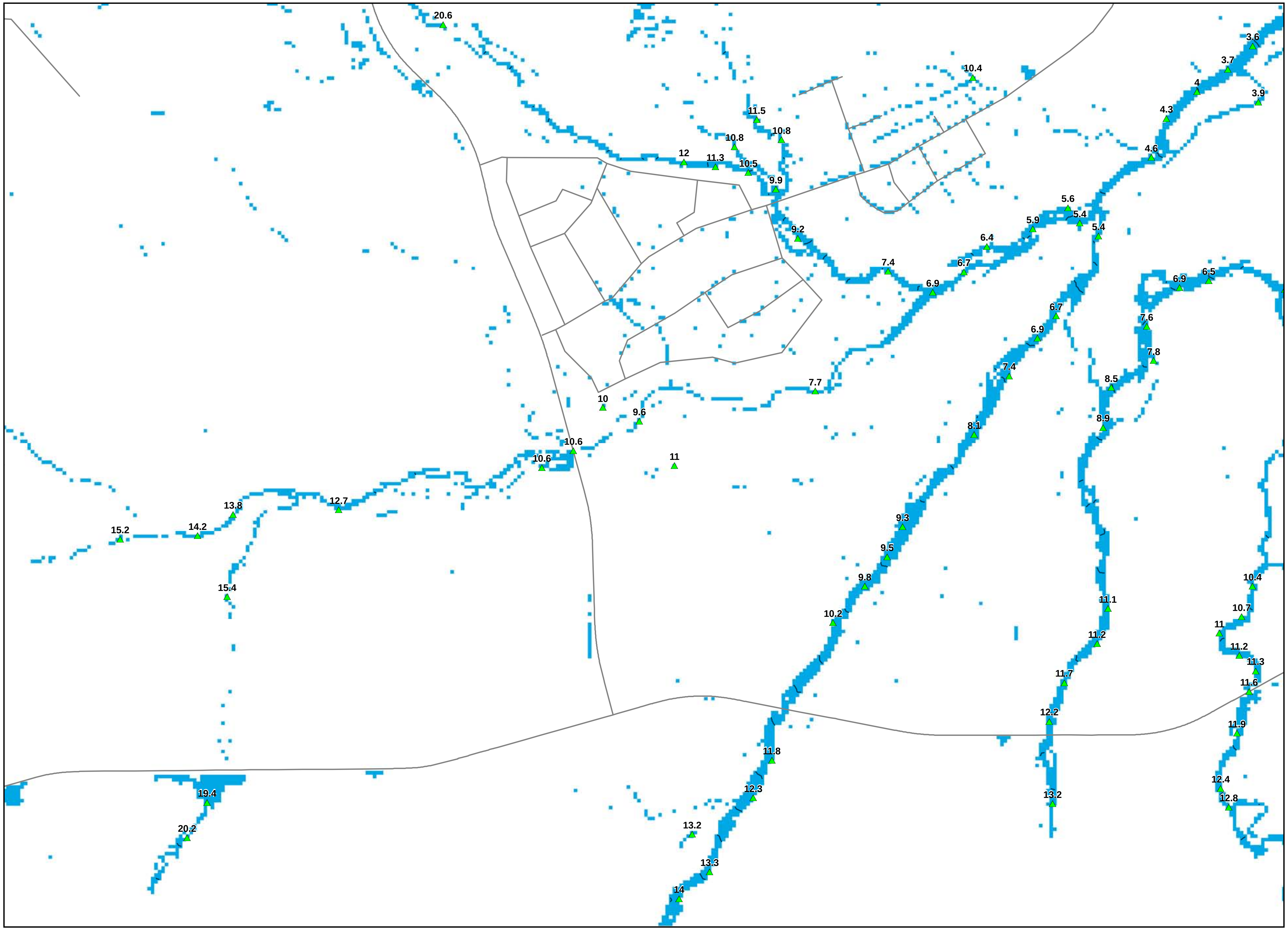


Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report

Figure A2D: 2yr ARI Flood Elevation - 2010 Climate Scenario - Sheet D



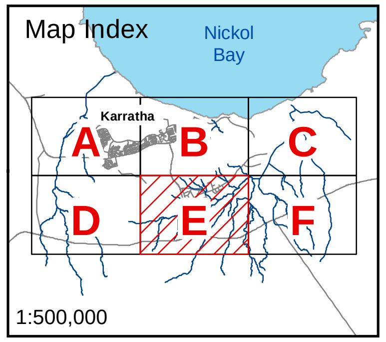
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

2yr Flood Extent

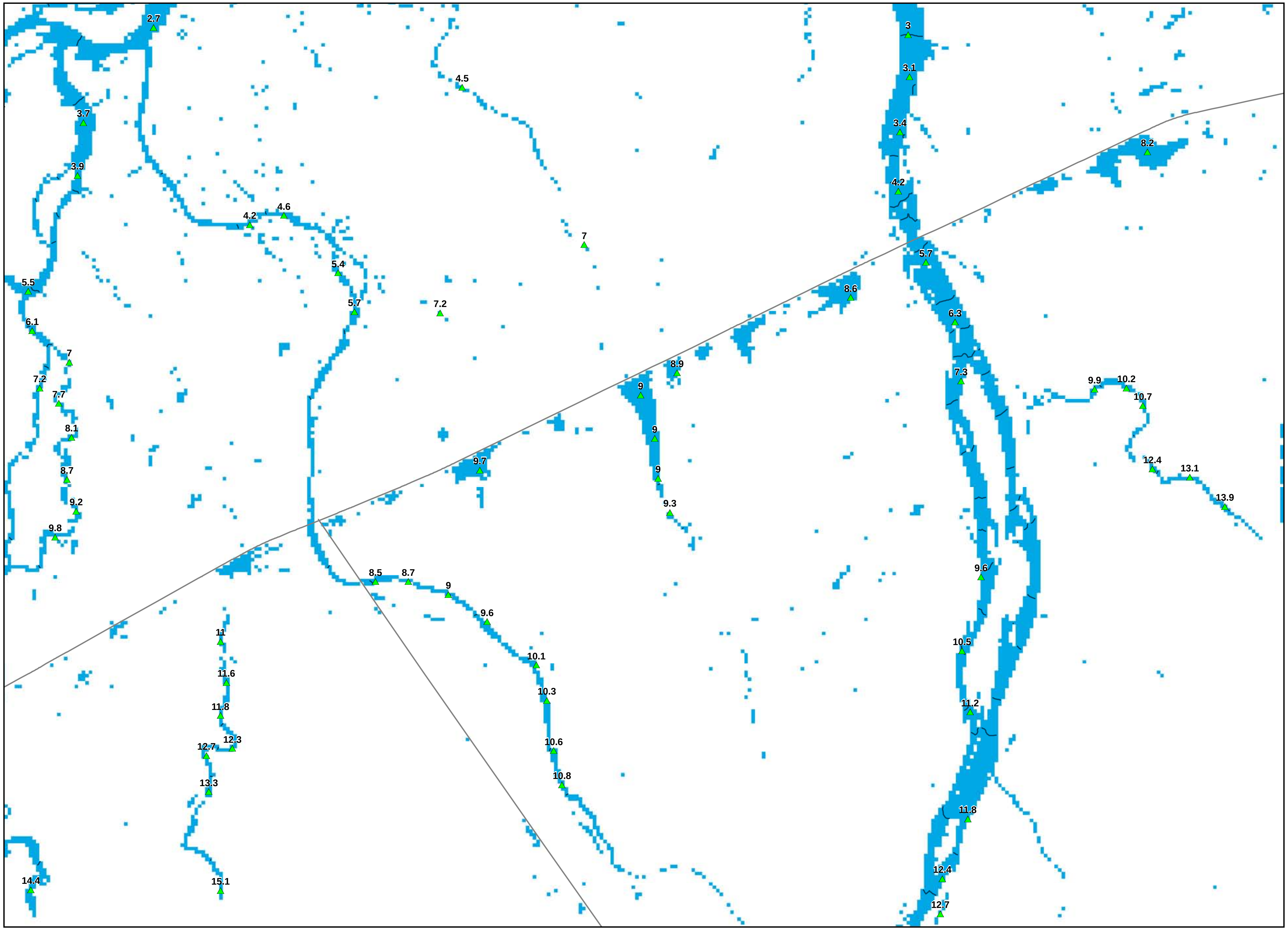
0.5m Contour (m AHD)

Cadastre



Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure A2E: 2yr ARI Flood Elevation - 2010 Climate Scenario - Sheet E



N

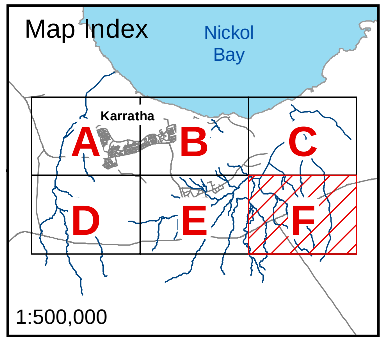
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

2yr Flood Extent

0.5m Contour (m AHD)

Cadastre



1:500,000

Job No. J4812

Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

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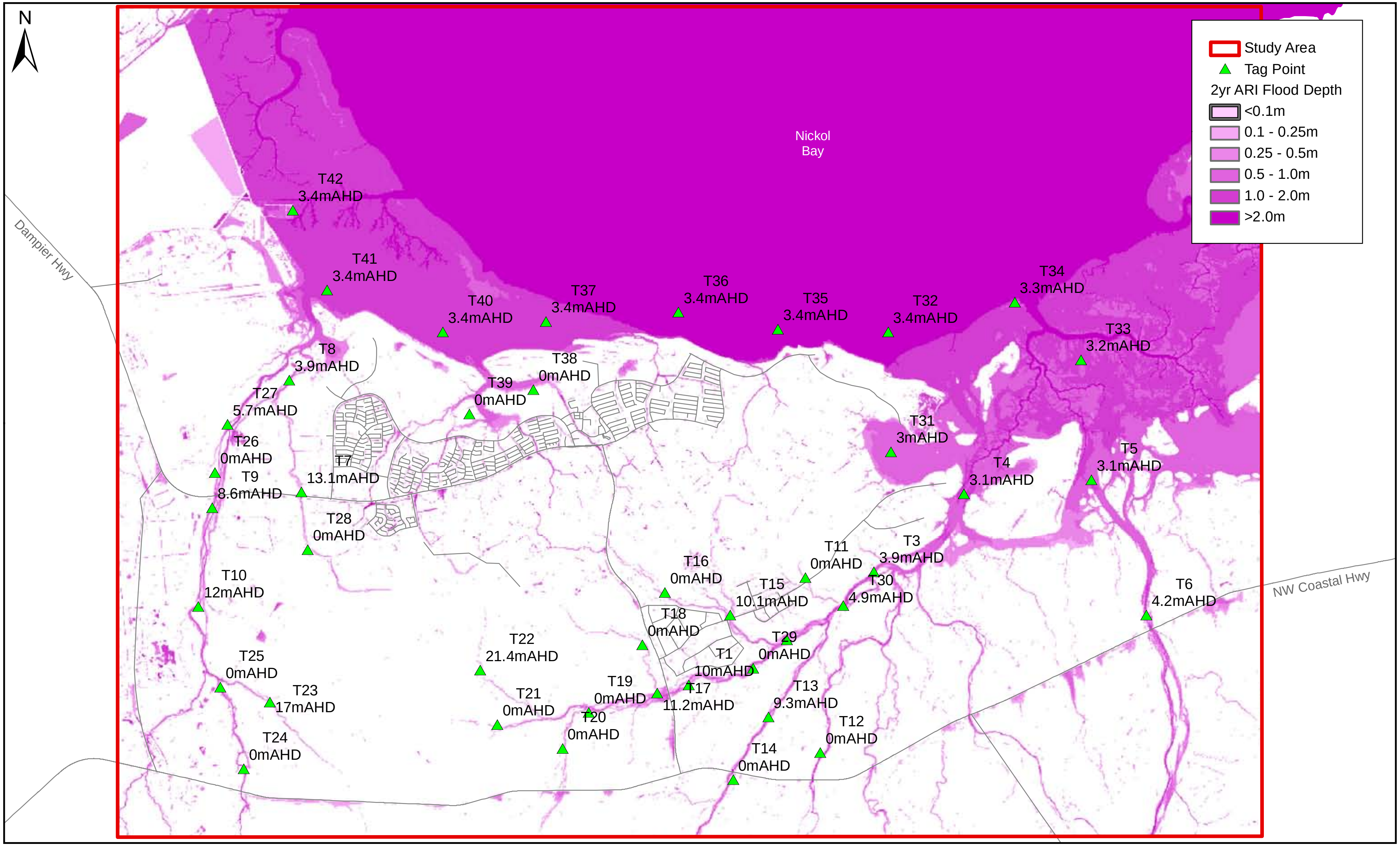
Figure A2F: 2yr ARI Flood Elevation - 2010 Climate Scenario - Sheet F



Data Source: GEMS Modelling & JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

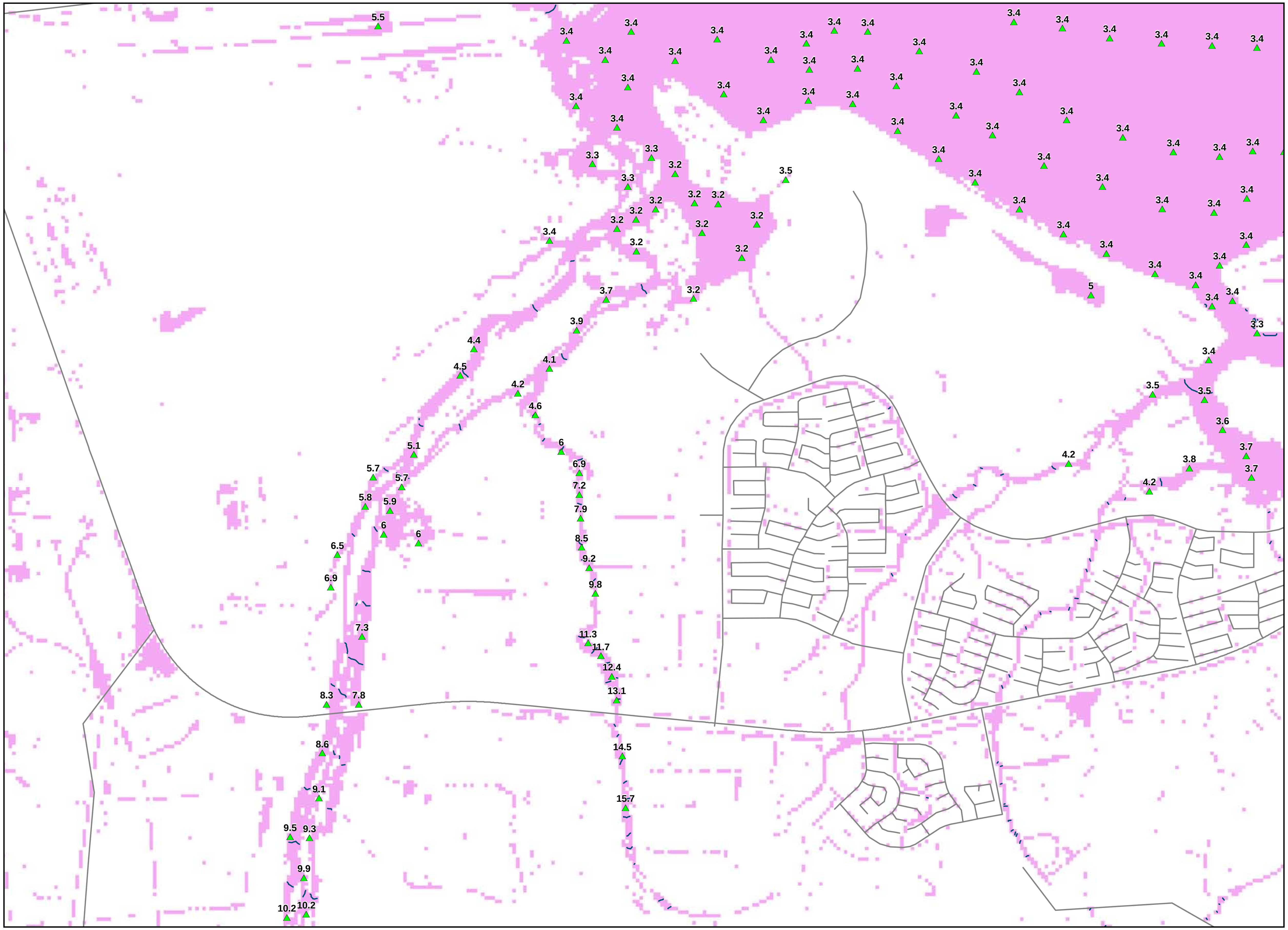
Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

LandCorp

Karratha Coastal Vulnerability Study: Main Report

Figure A3: 2yr ARI Flood Depth - 2060 Climate Scenario



N

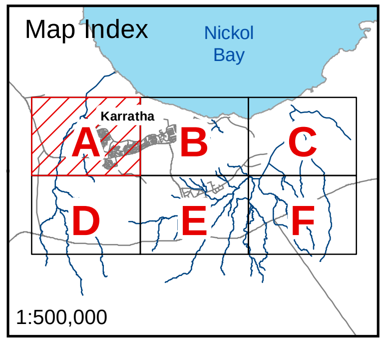
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

2yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812

Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

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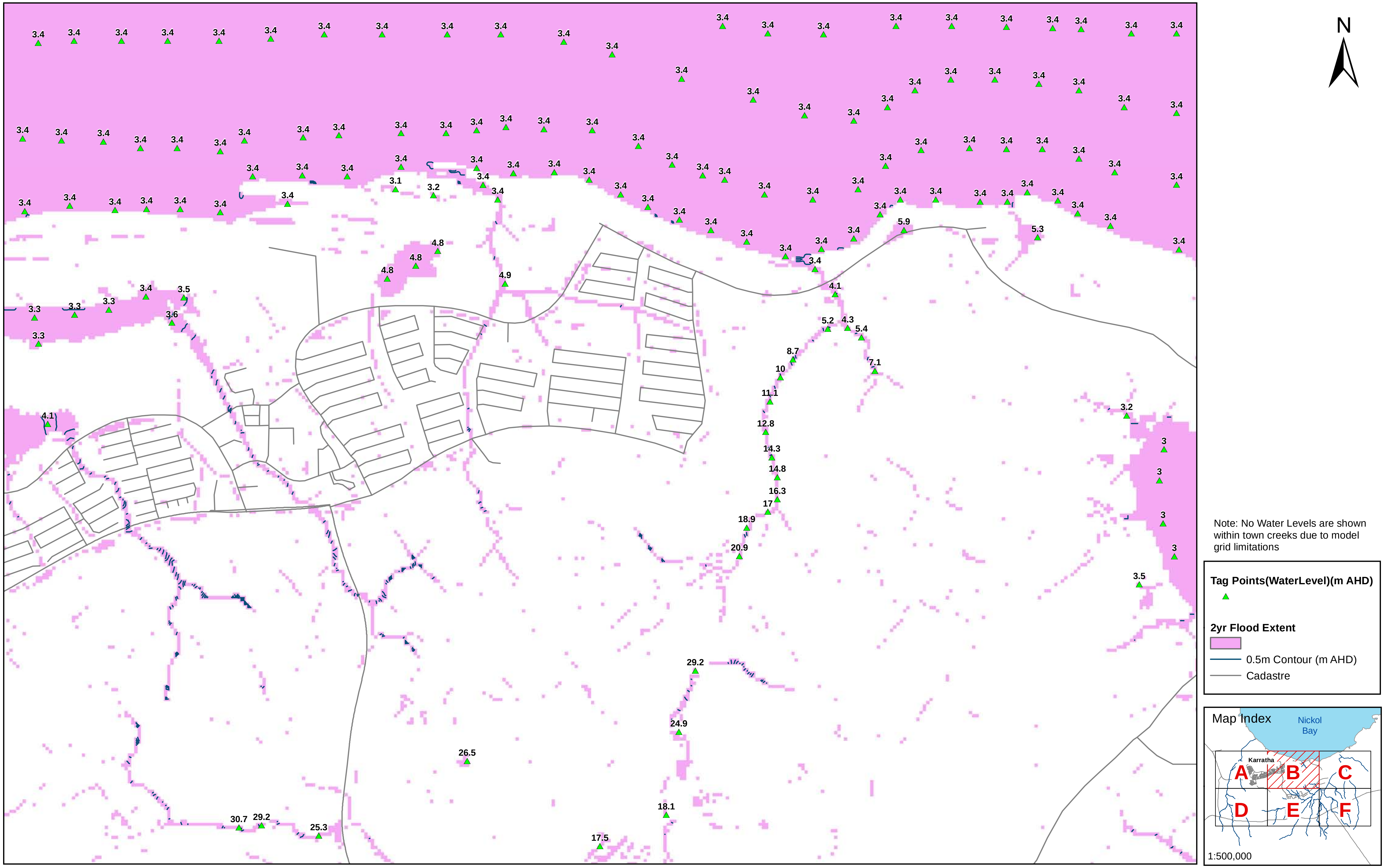
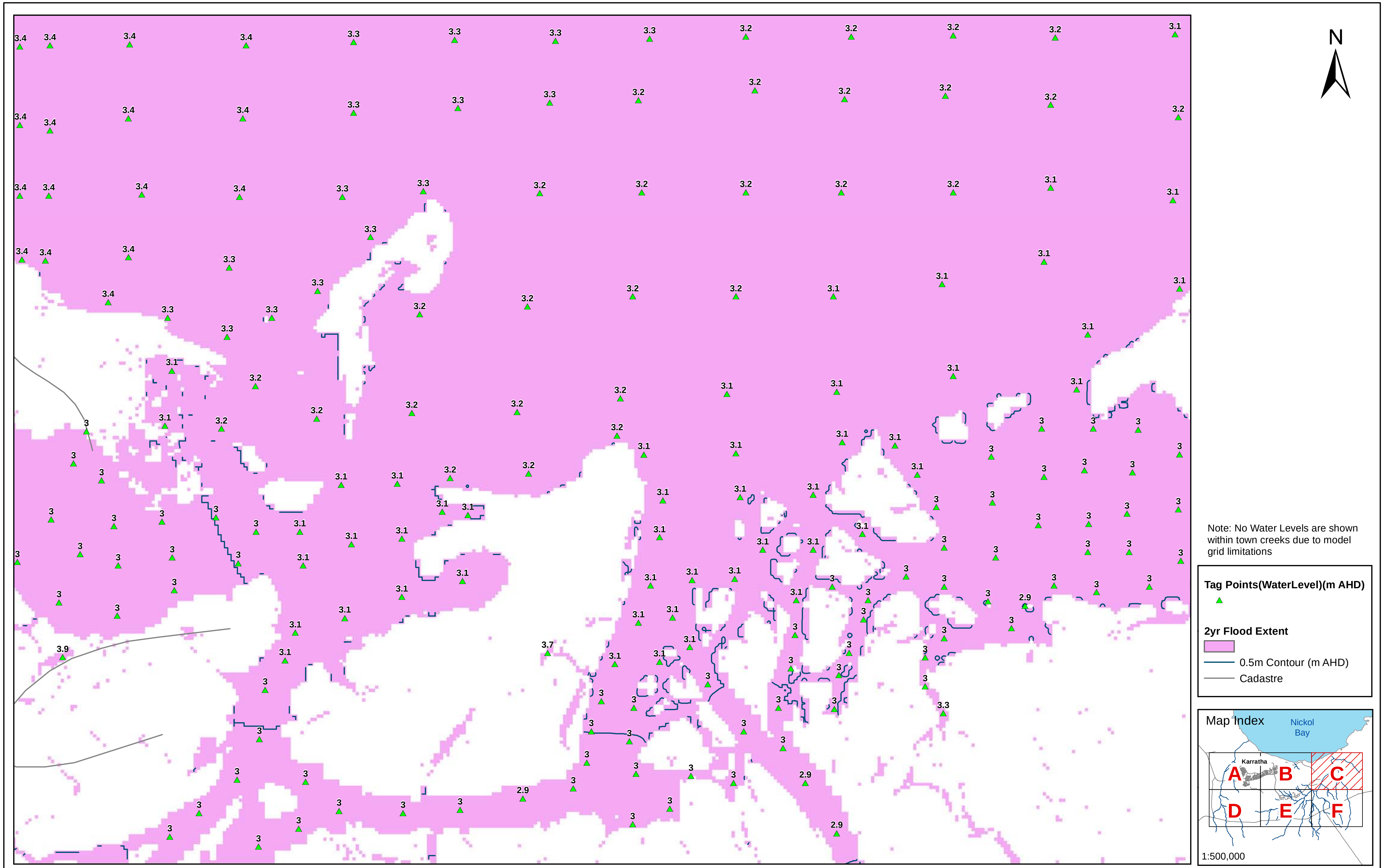
Figure A4A: 2yr ARI Flood Elevation - 2060 Climate Scenario - Sheet A



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure A4B: 2yr ARI Flood Elevation - 2060 Climate Scenario - Sheet B



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
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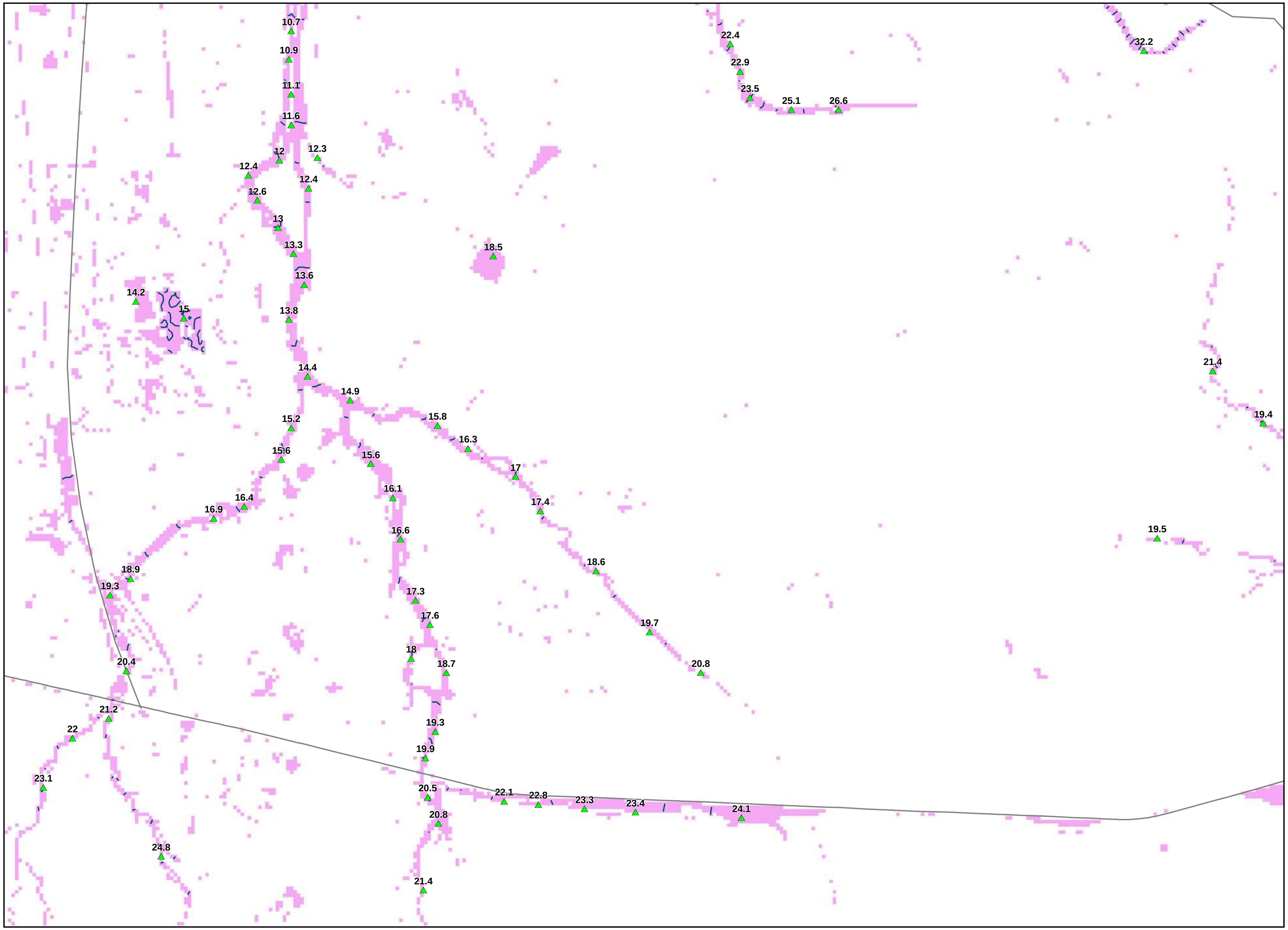
Figure A4C: 2yr ARI Flood Elevation - 2060 Climate Scenario - Sheet C



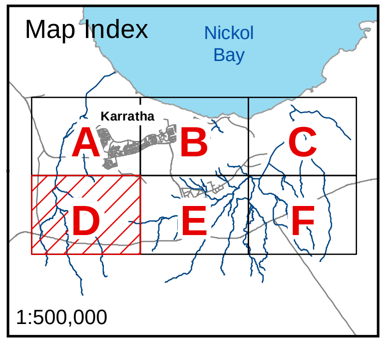
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

2yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

LandCorp
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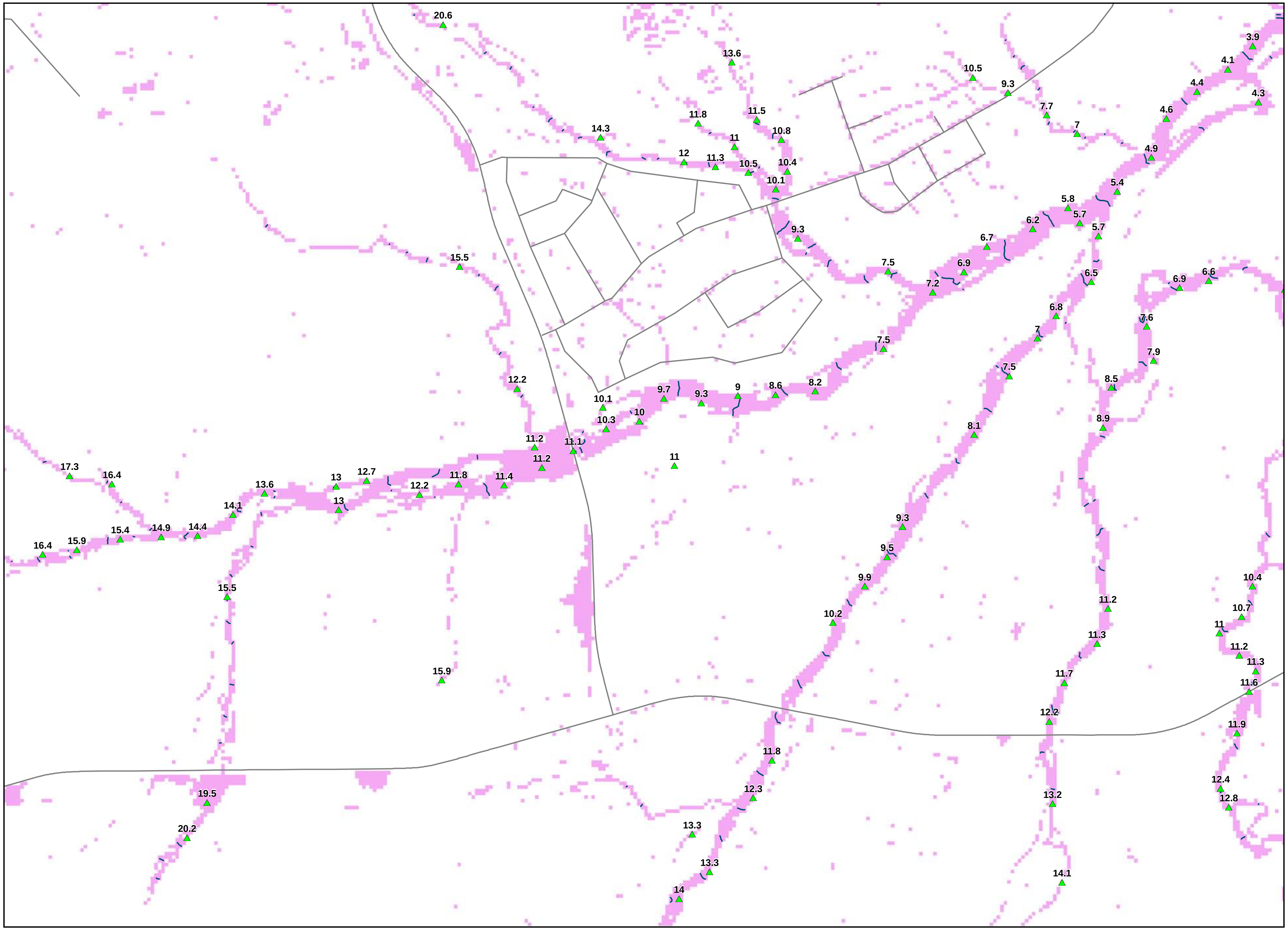
Figure A4D: 2yr ARI Flood Elevation - 2060 Climate Scenario - Sheet D



Note: No Water Levels are shown within town creeks due to model grid limitations

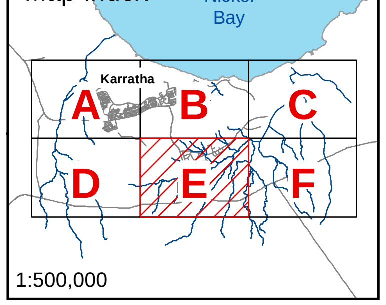
Tag Points(WaterLevel)(m AHD)

2yr Flood Extent

0.5m Contour (m AHD)

Cadastre

Map Index



JDA

Job No. J4812

Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

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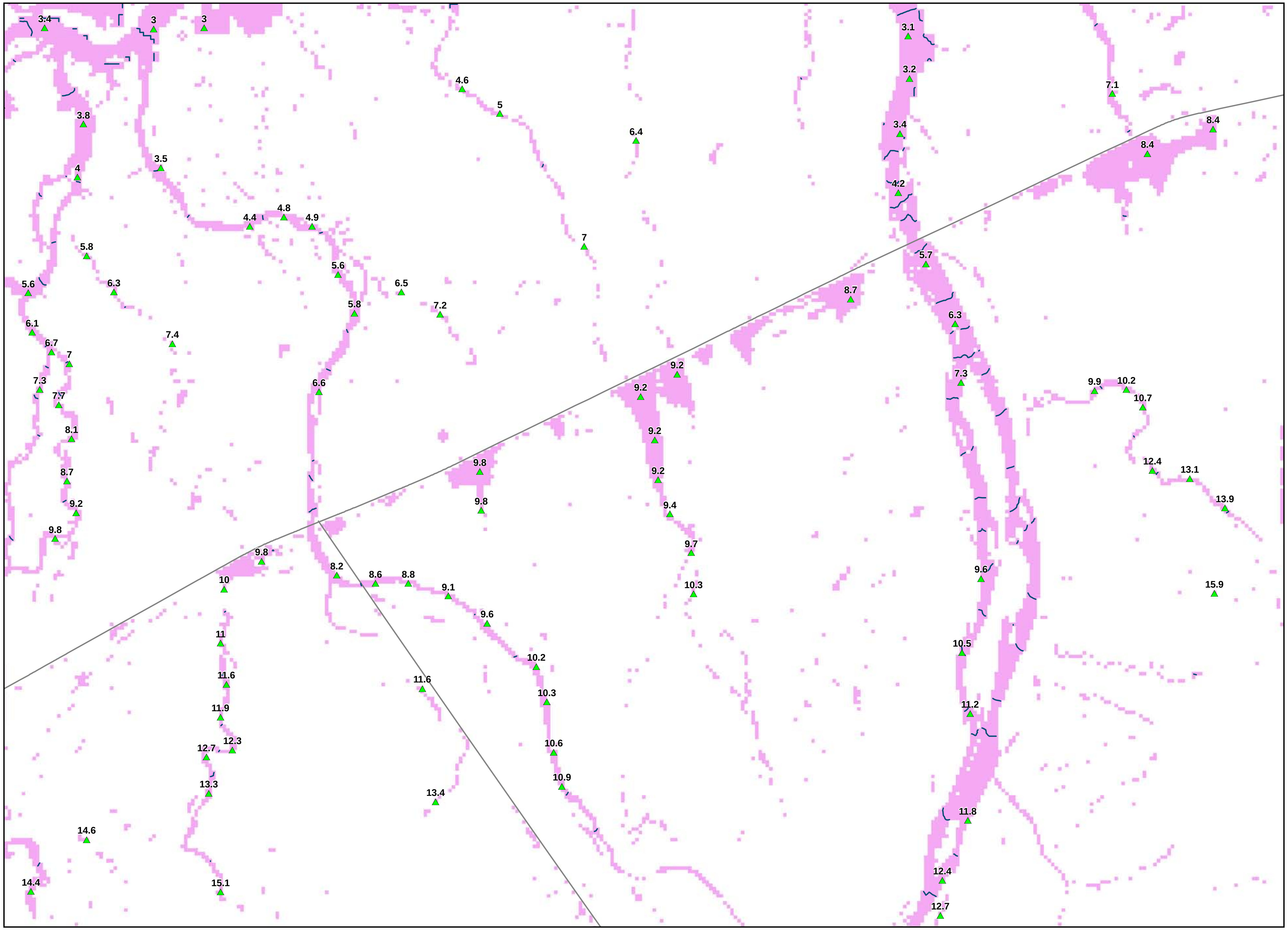
Karratha Coastal Vulnerability Study :Main Report

Figure A4E: 2yr ARI Flood Elevation - 2060 Climate Scenario - Sheet E



Note: No Water Levels are shown within town creeks due to model grid limitations

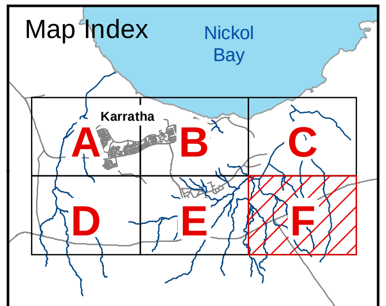
Tag Points(WaterLevel)(m AHD)

2yr Flood Extent

0.5m Contour (m AHD)

Cadastre

Map Index



1:500,000

Job No. J4812

Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

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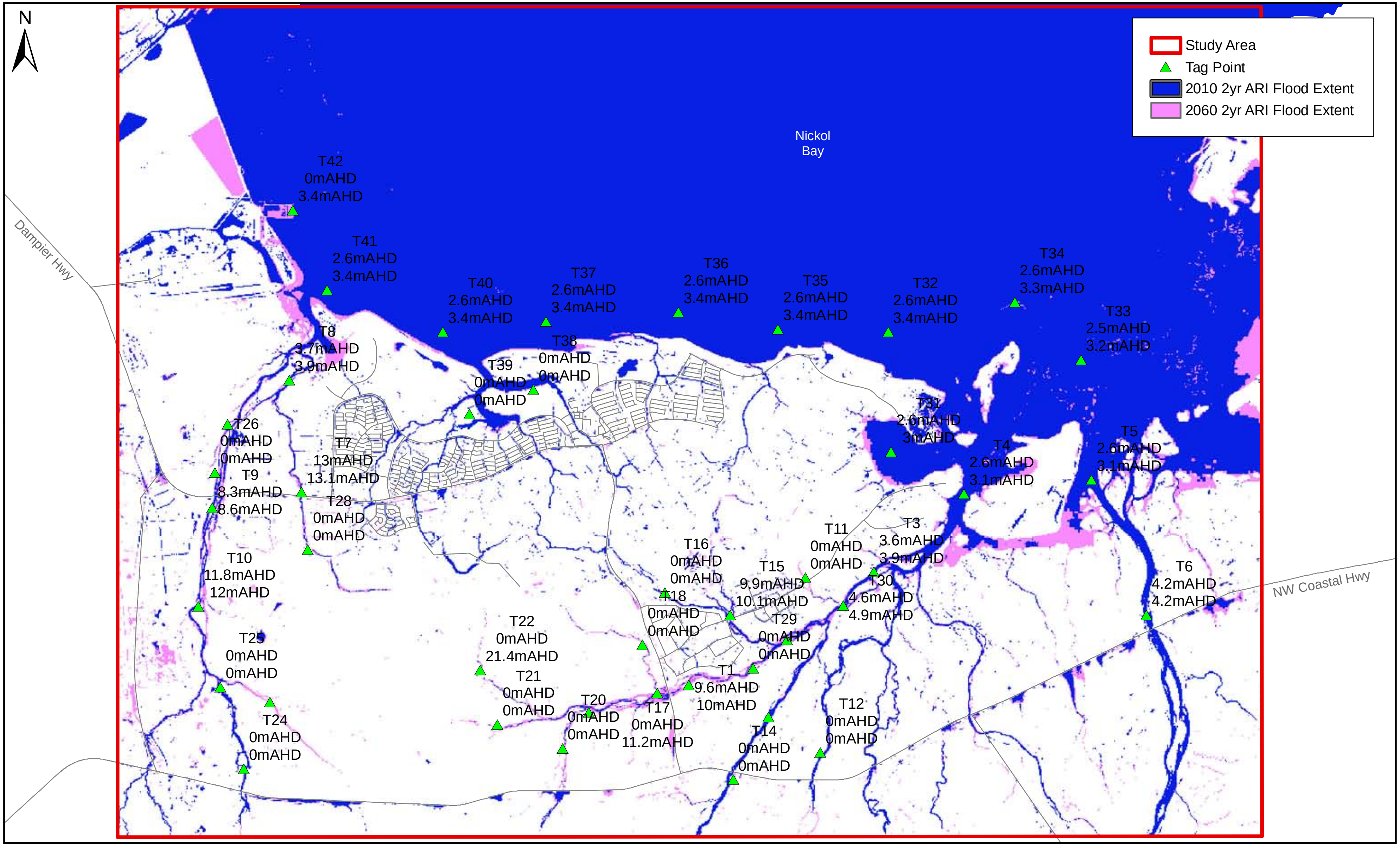
Figure A4F: 2yr ARI Flood Elevation - 2060 Climate Scenario - Sheet F



Data Source: GEMS Modelling and JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

LandCorp

Karratha Coastal Vulnerability Study: Main Report

Figure A5 : Comparison of 2yr (2010) and 2yr (2060) Flood Extent

Data Source: GEMS Modelling and JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

LandCorp

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Figure A6: 2yr ARI Flood Depth - 2110 Climate Scenario

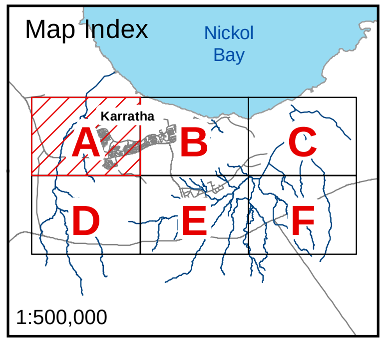
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

2yr Flood Extent

0.5m Contour (m AHD)

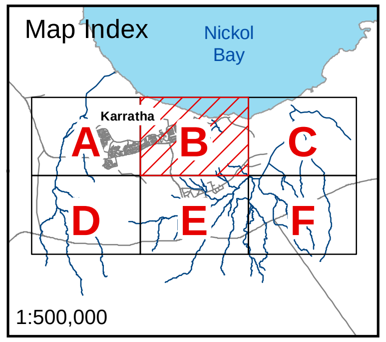
Cadastre



Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

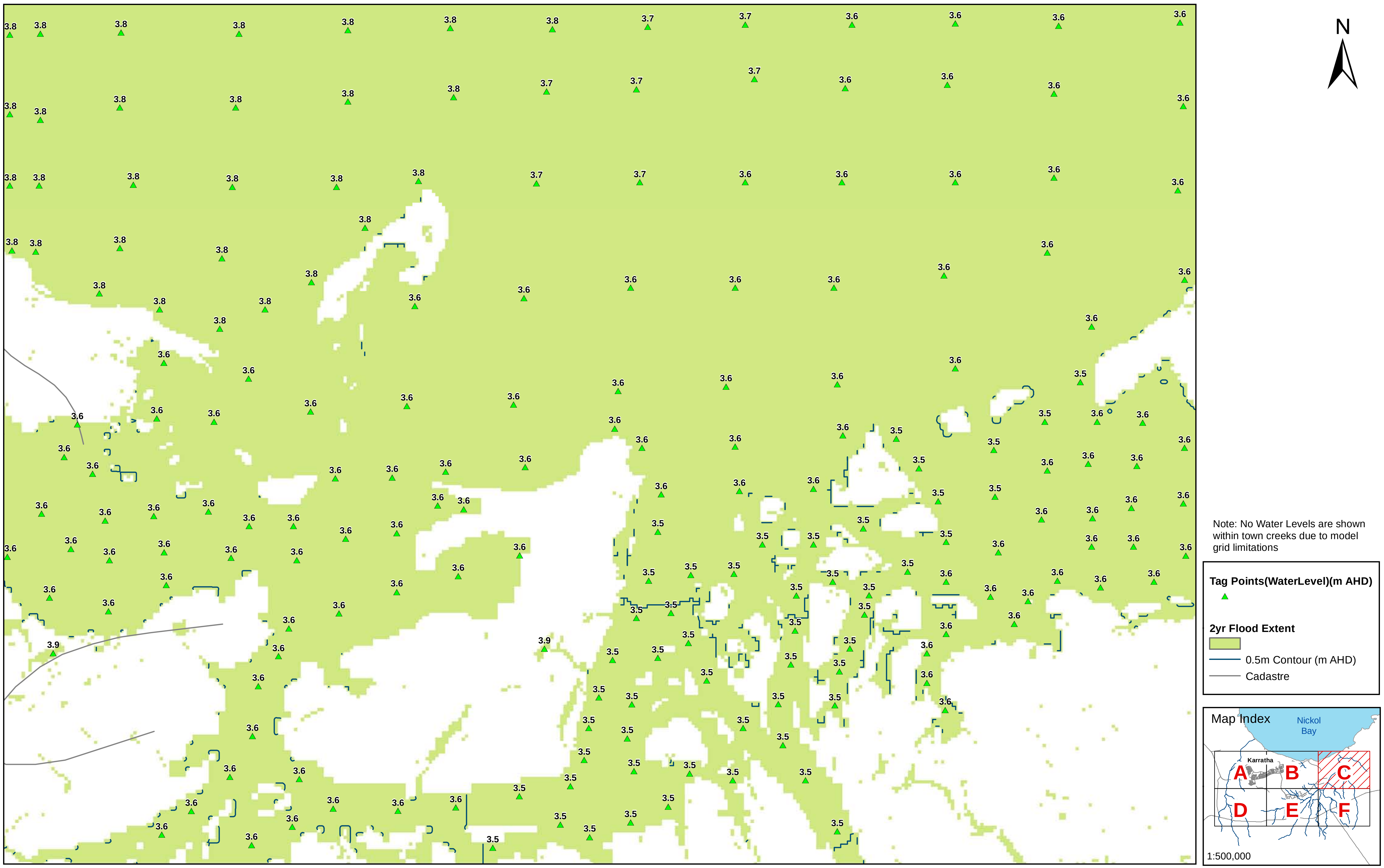
LandCorp
Karratha Coastal Vulnerability Study :Main Report

Figure A7A: 2yr ARI Flood Elevation - 2110 Climate Scenario - Sheet A



Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure A7B: 2yr ARI Flood Elevation - 2110 Climate Scenario - Sheet B



Job No. J4812
Scale:1:22,000
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LandCorp
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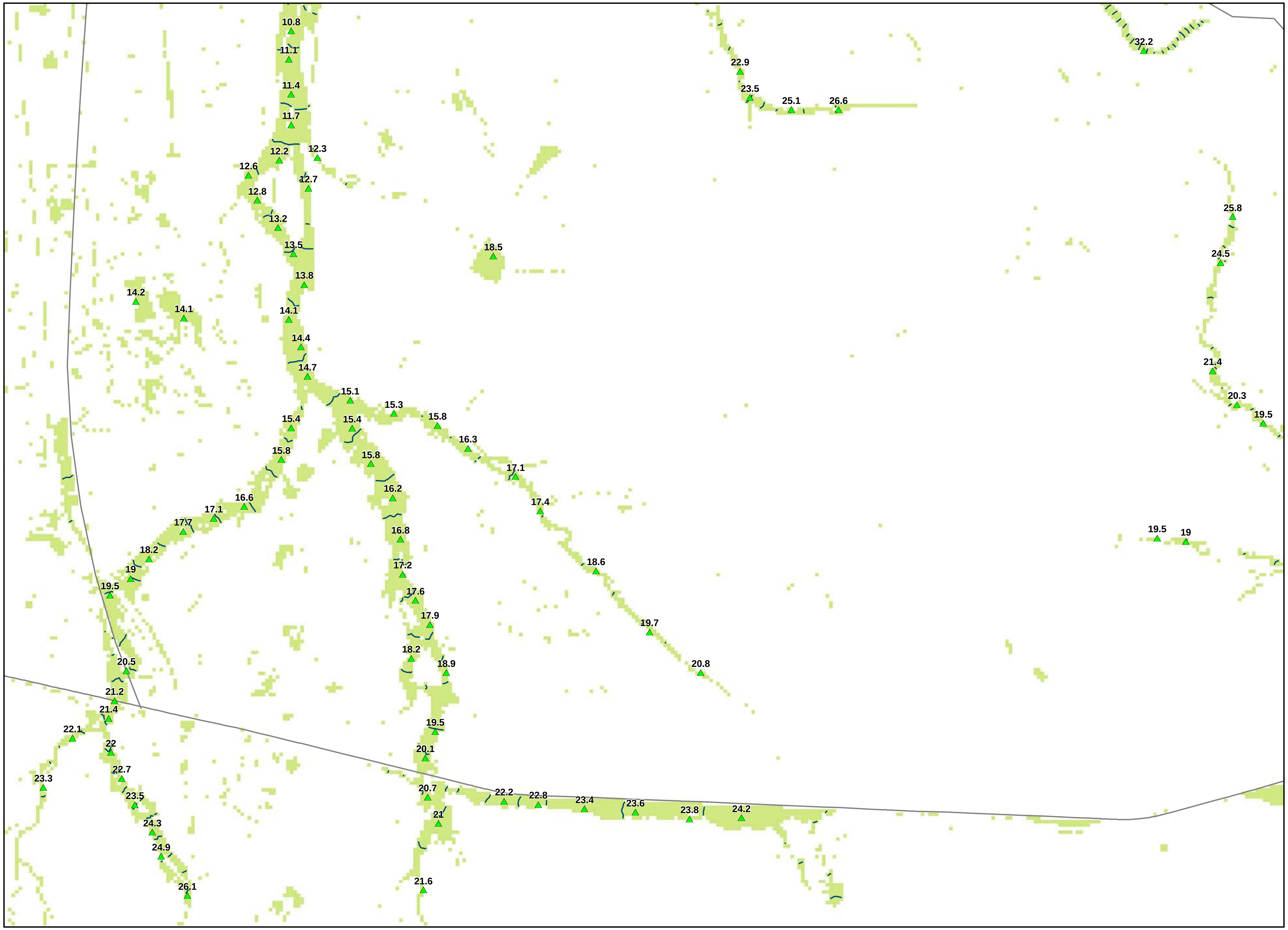
Figure A7C: 2yr ARI Flood Elevation - 2110 Climate Scenario - Sheet C



N

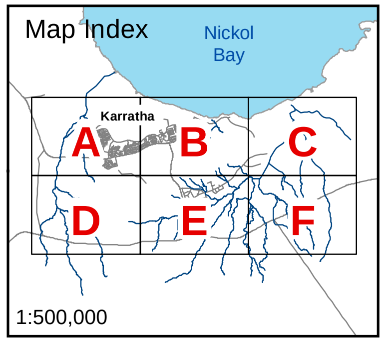
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

2yr Flood Extent

0.5m Contour (m AHD)

Cadastre



JDA

Job No. J4812

Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure A7D: 2yr ARI Flood Elevation - 2110 Climate Scenario - Sheet D

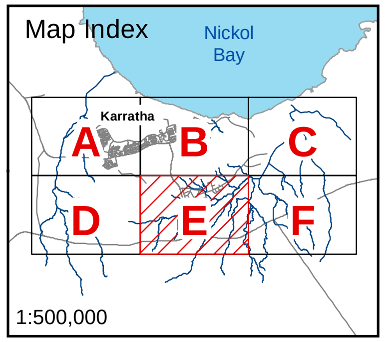
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

2yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
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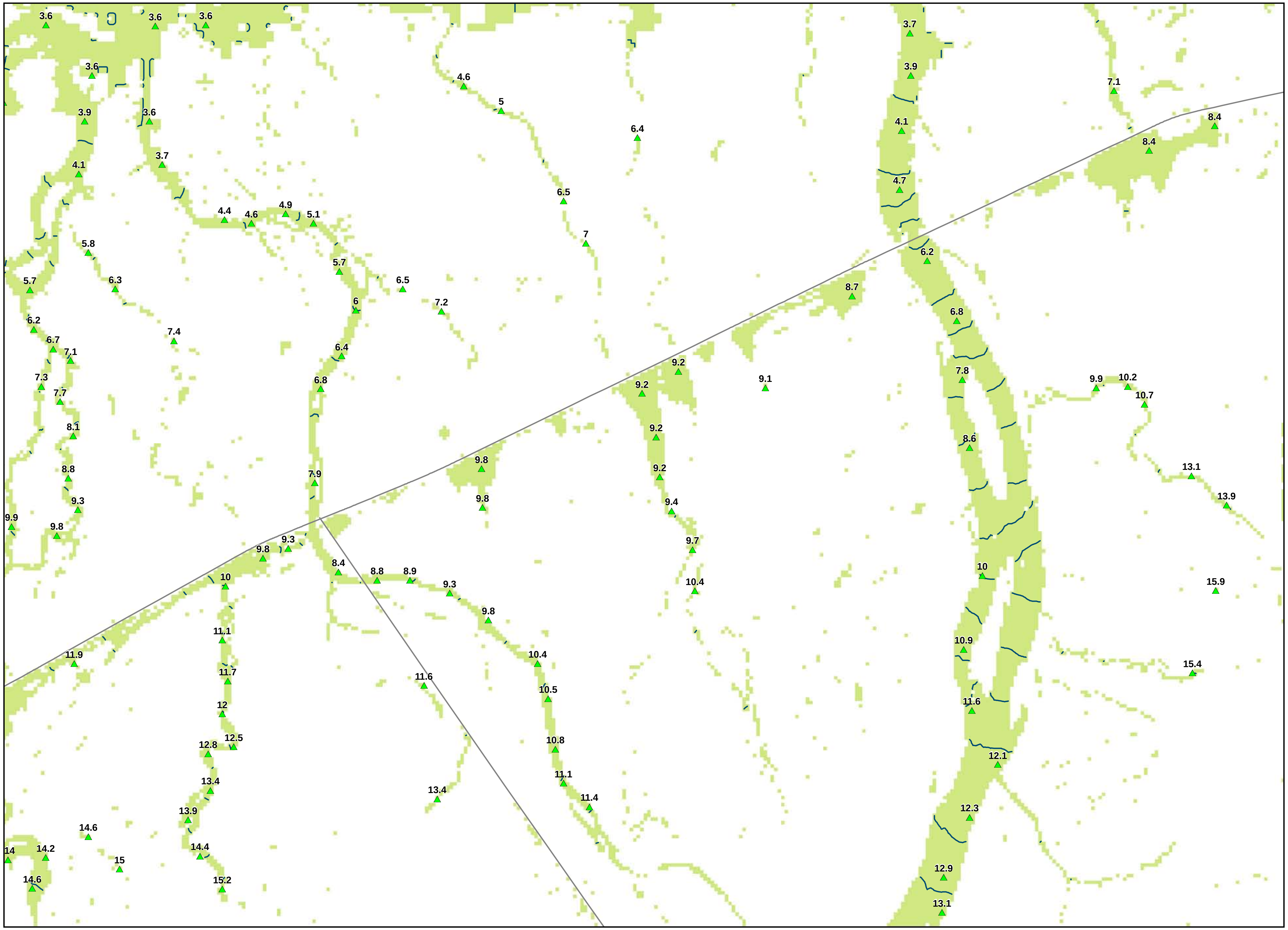
Figure A7E: 2yr ARI Flood Elevation - 2110 Climate Scenario - Sheet E



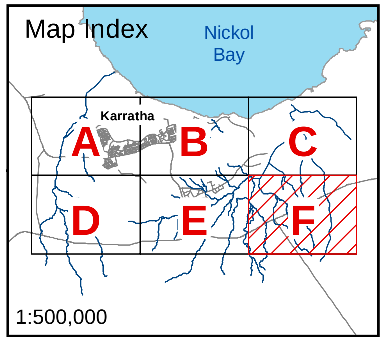
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

2yr Flood Extent

0.5m Contour (m AHD)

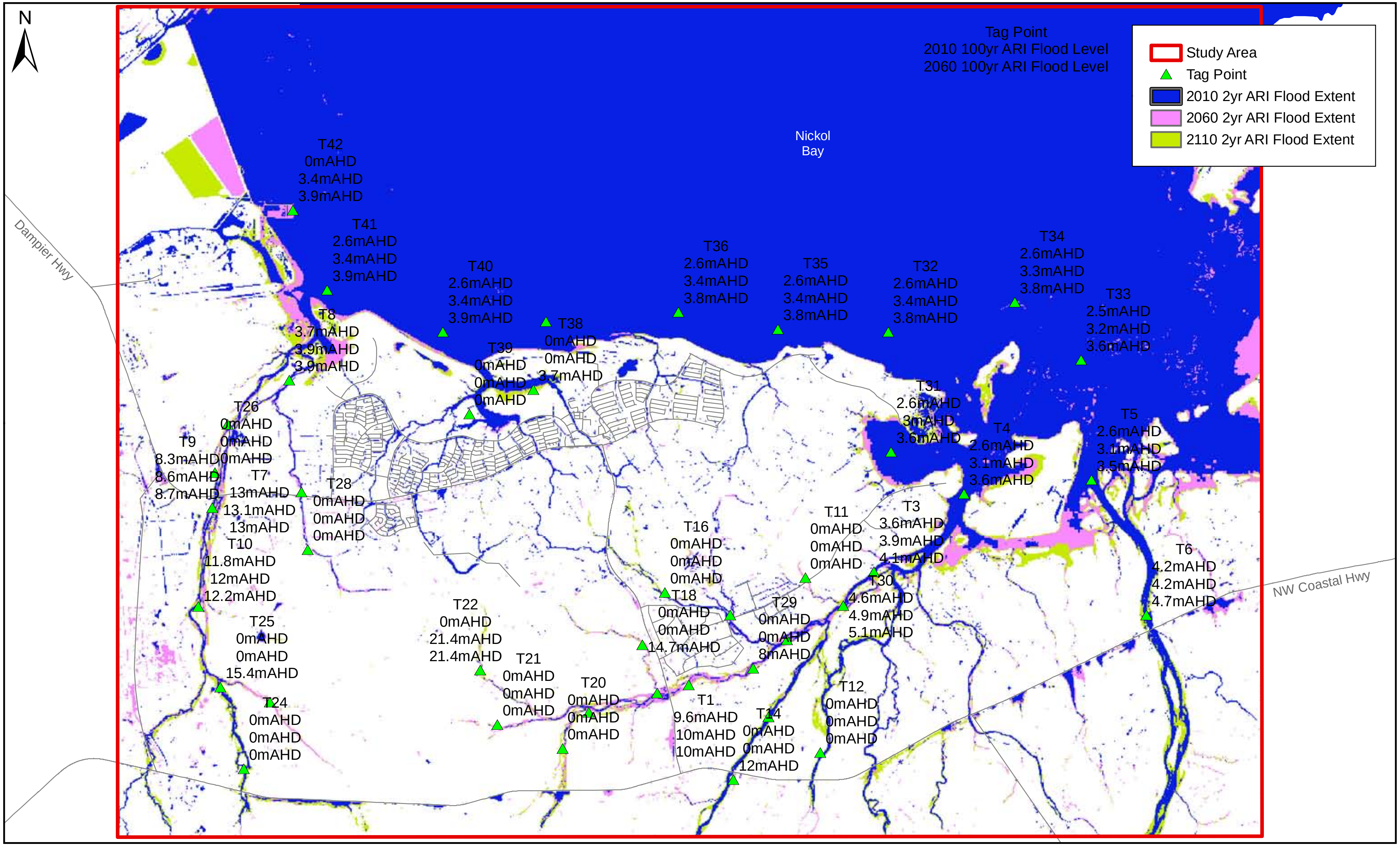
Cadastre



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure A7F: 2yr ARI Flood Elevation - 2110 Climate Scenario - Sheet F



Data Source: GEMS Modelling and JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

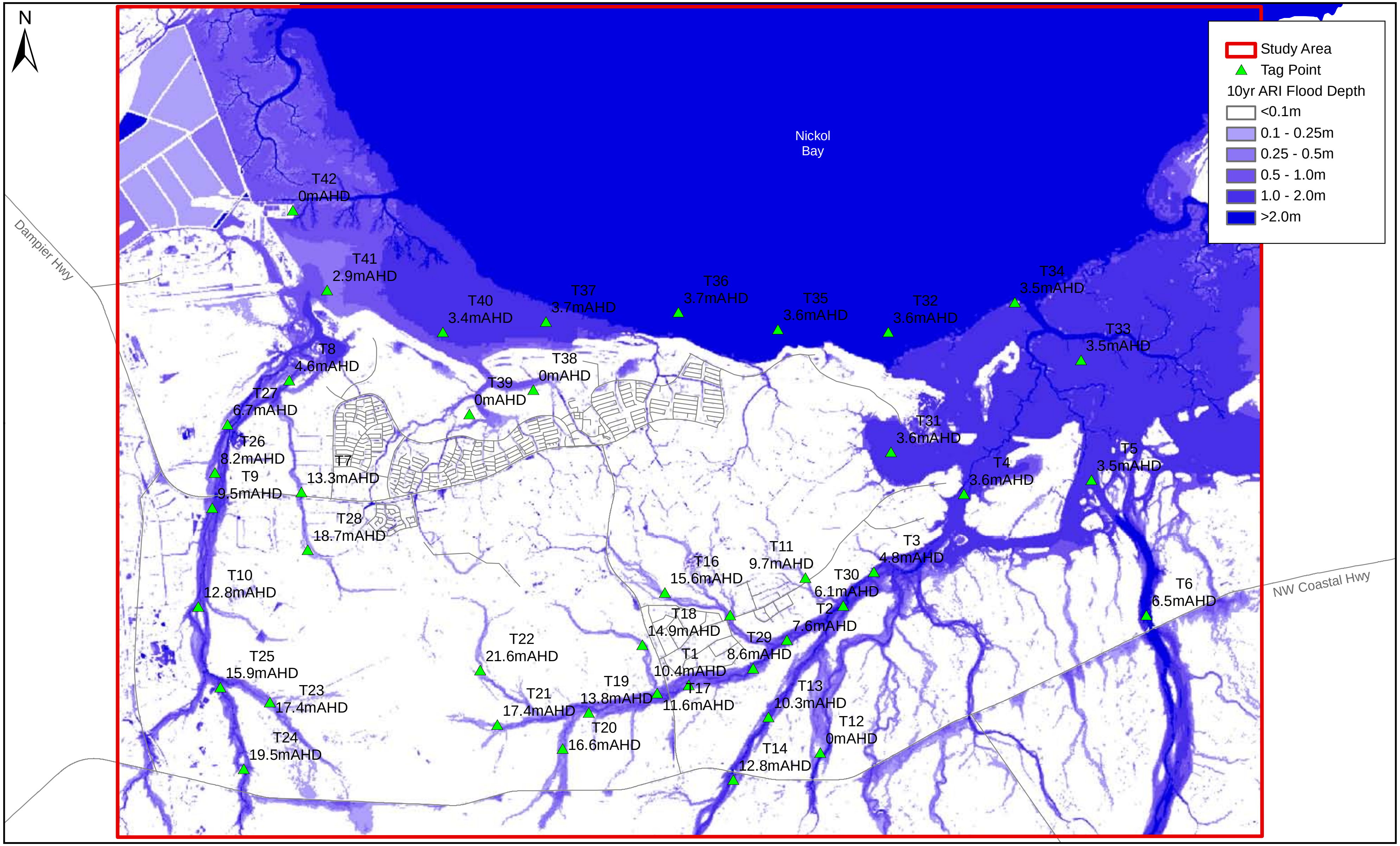
LandCorp

Karratha Coastal Vulnerability Study: Main Report

Figure A8 : Comparison of 2yr (2010), 2yr (2060) and 2yr (2110) Flood Extent

APPENDIX B

10yr ARI Flood Extent, Depth, Level and Flow Velocity for the 2010, 2060 & 2110 Climate Scenarios

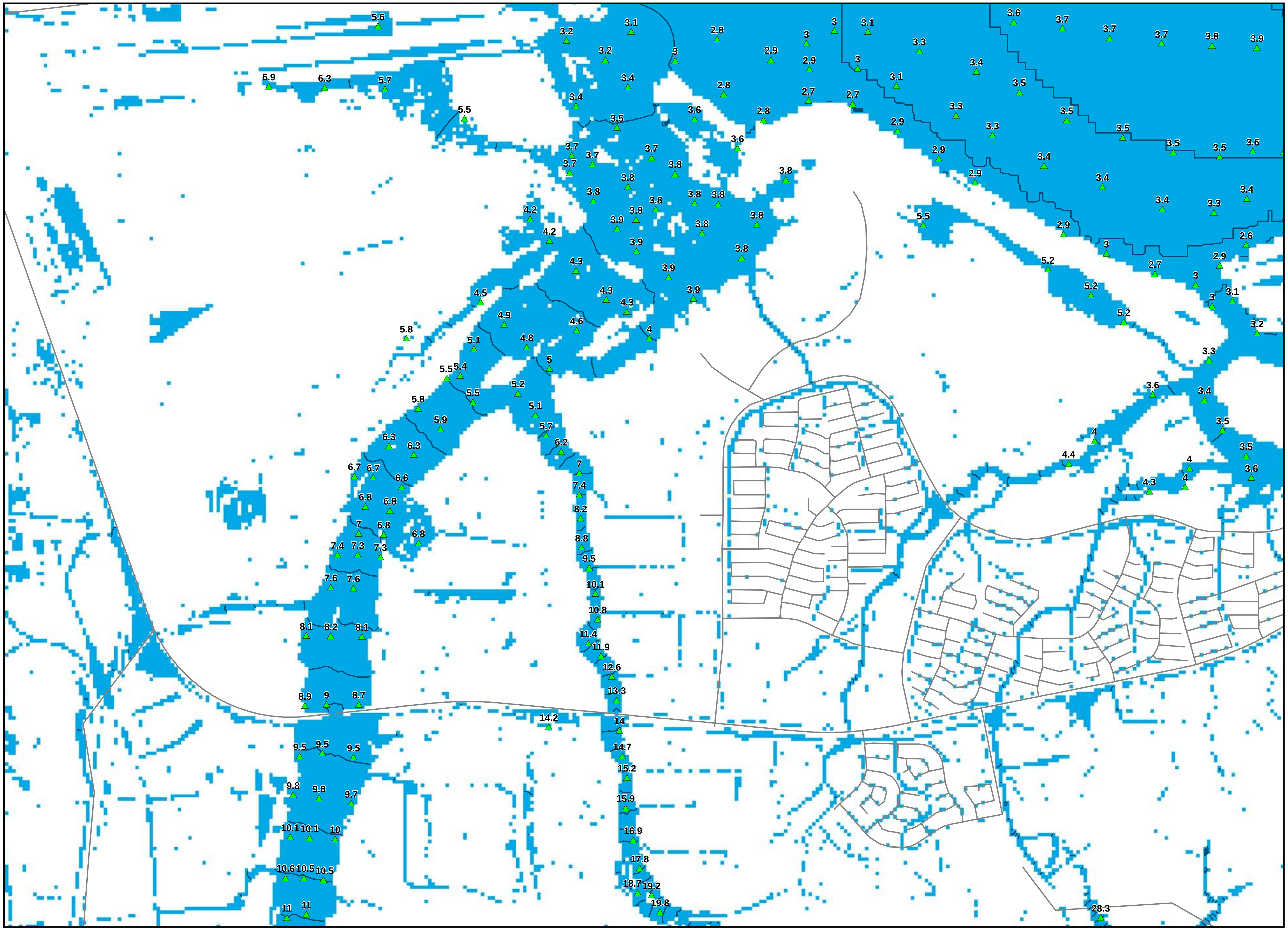


Data Source: GEMS Modelling & JDA Hydraulic Modelling 2011

Job No. J4812
Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

LandCorp
Karratha Coastal Vulnerability Study: Main Report
Figure B1: 10yr ARI Flood Depth - 2010 Climate Scenario



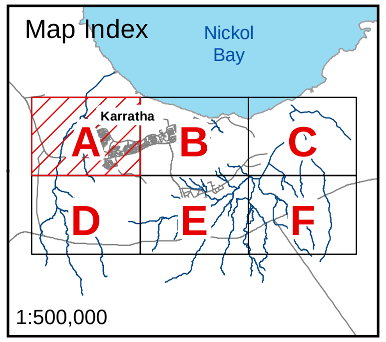
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

10yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812

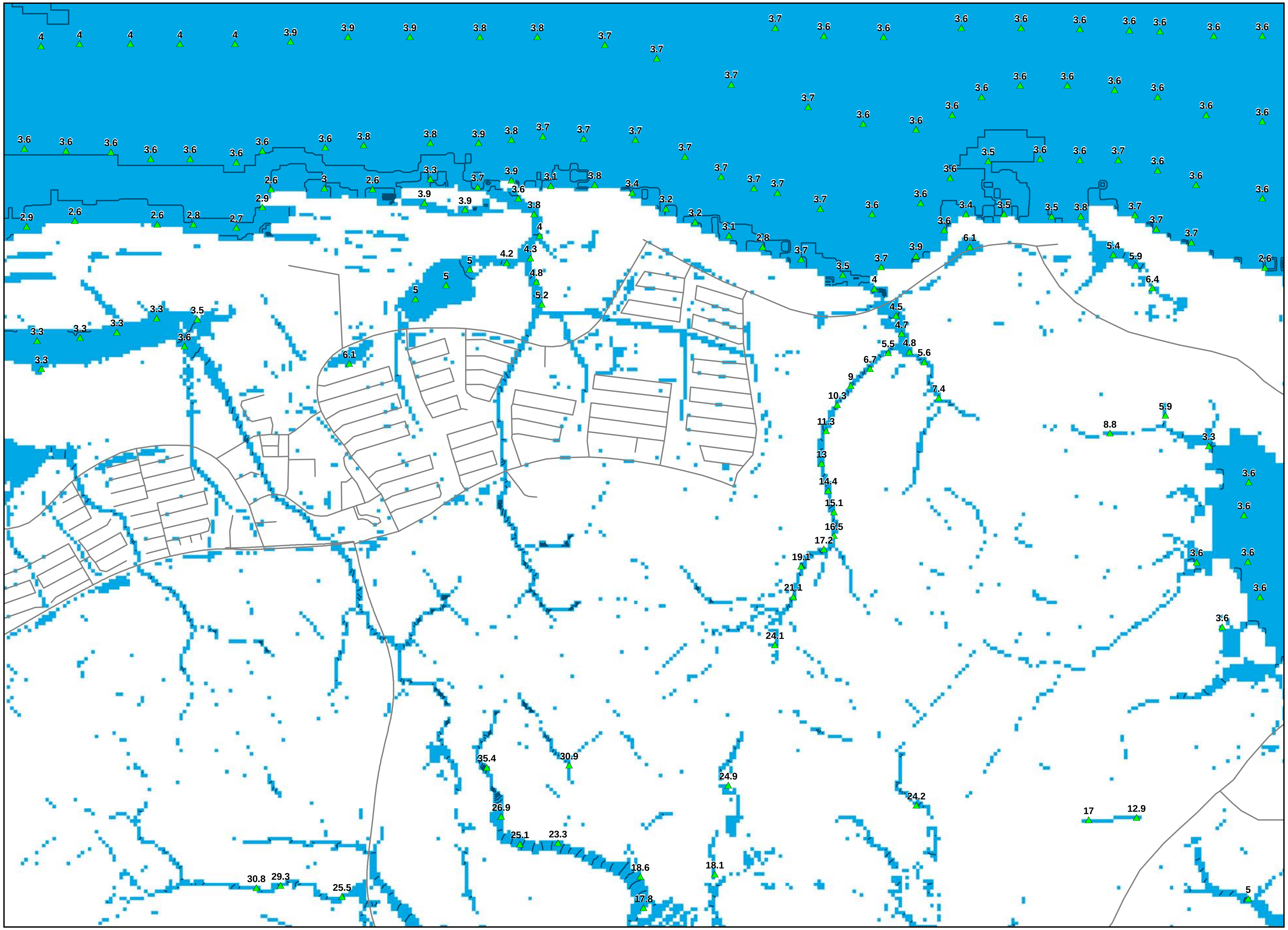
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure B2A: 10yr ARI Flood Elevation - 2010 Climate Scenario - Sheet A



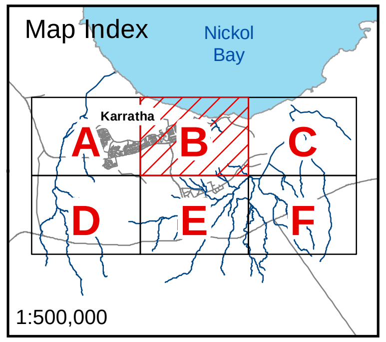
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

10yr Flood Extent

0.5m Contour (m AHD)

Cadastre



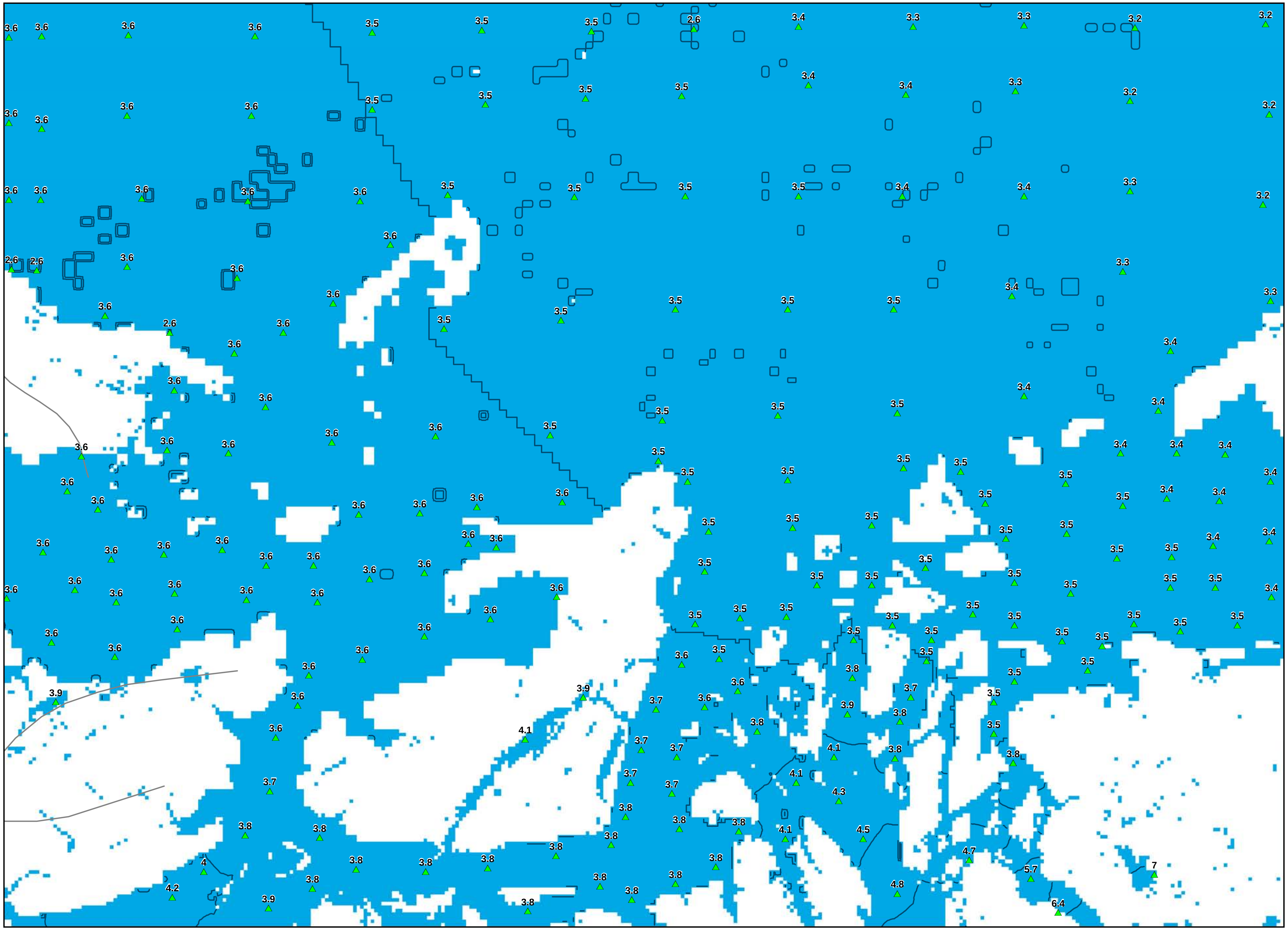
Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure B2B: 10yr ARI Flood Elevation - 2010 Climate Scenario - Sheet B



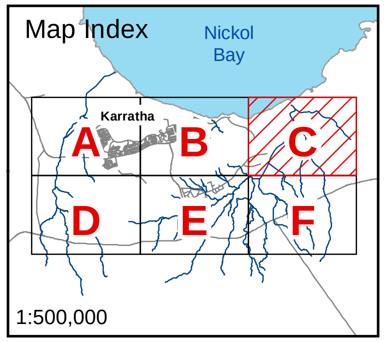
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

10yr Flood Extent

0.5m Contour (m AHD)

Cadastre



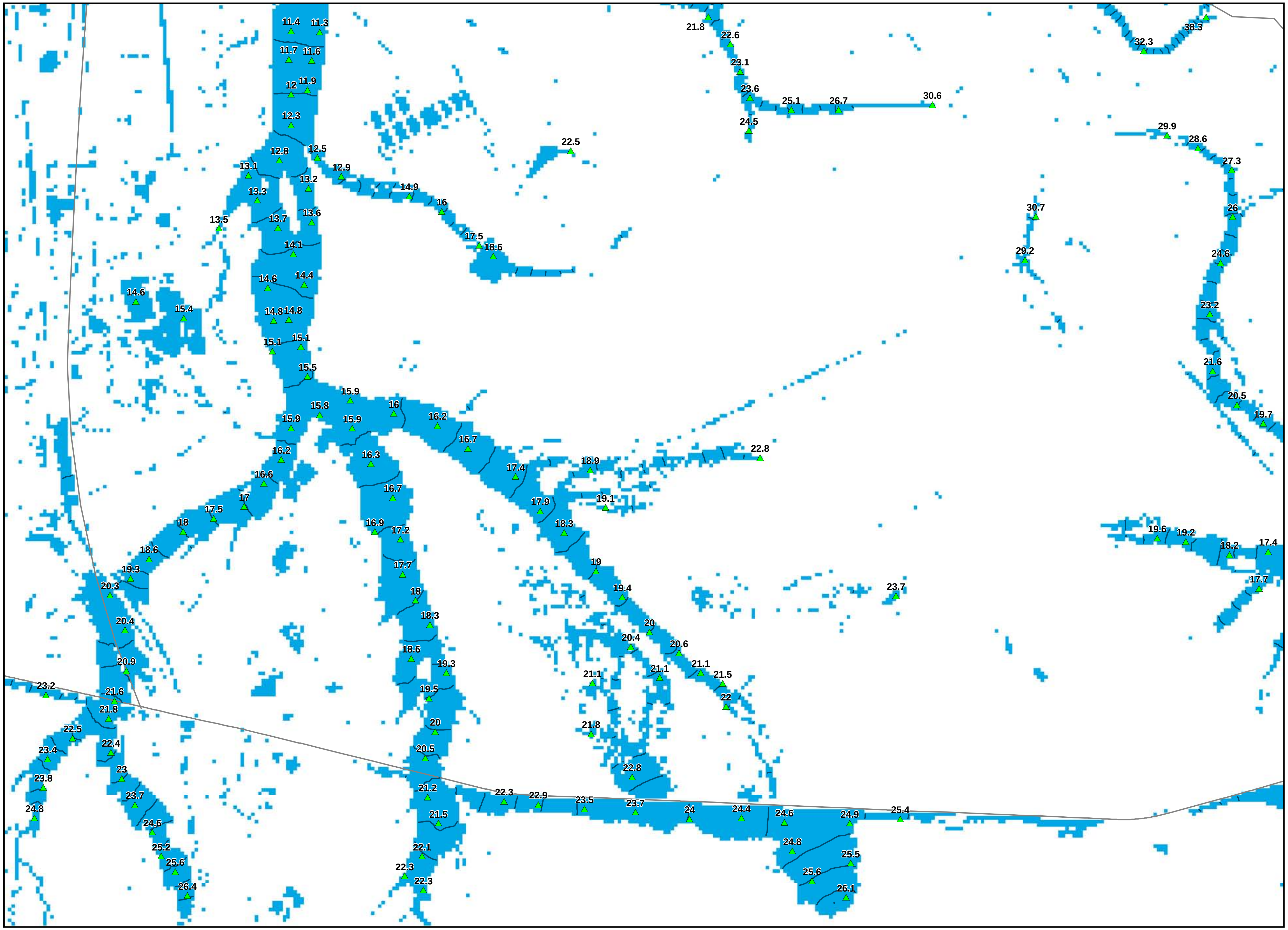
Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure B2C: 10yr ARI Flood Elevation - 2010 Climate Scenario - Sheet C



N

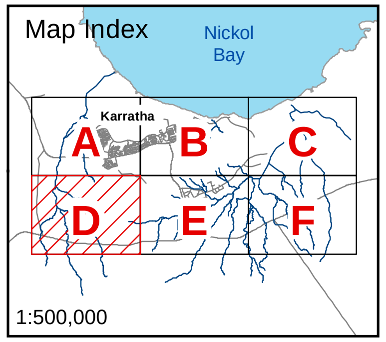
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

10yr Flood Extent

0.5m Contour (m AHD)

Cadastre



JDA

Job No. J4812
Scale:1:22,000

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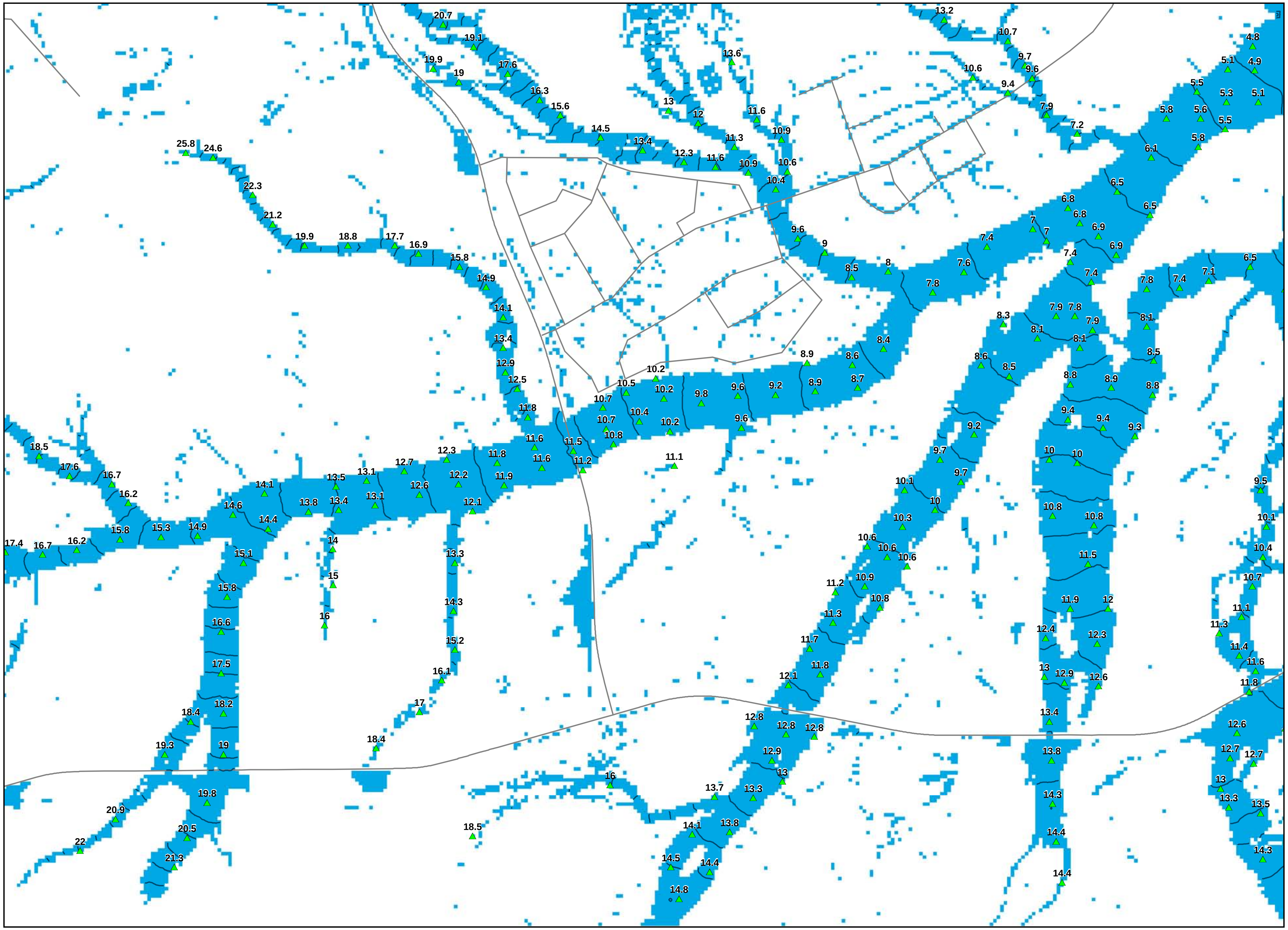
LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure B2D: 10yr ARI Flood Elevation - 2010 Climate Scenario - Sheet D



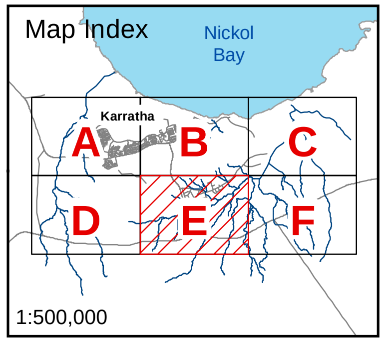
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

10yr Flood Extent

0.5m Contour (m AHD)

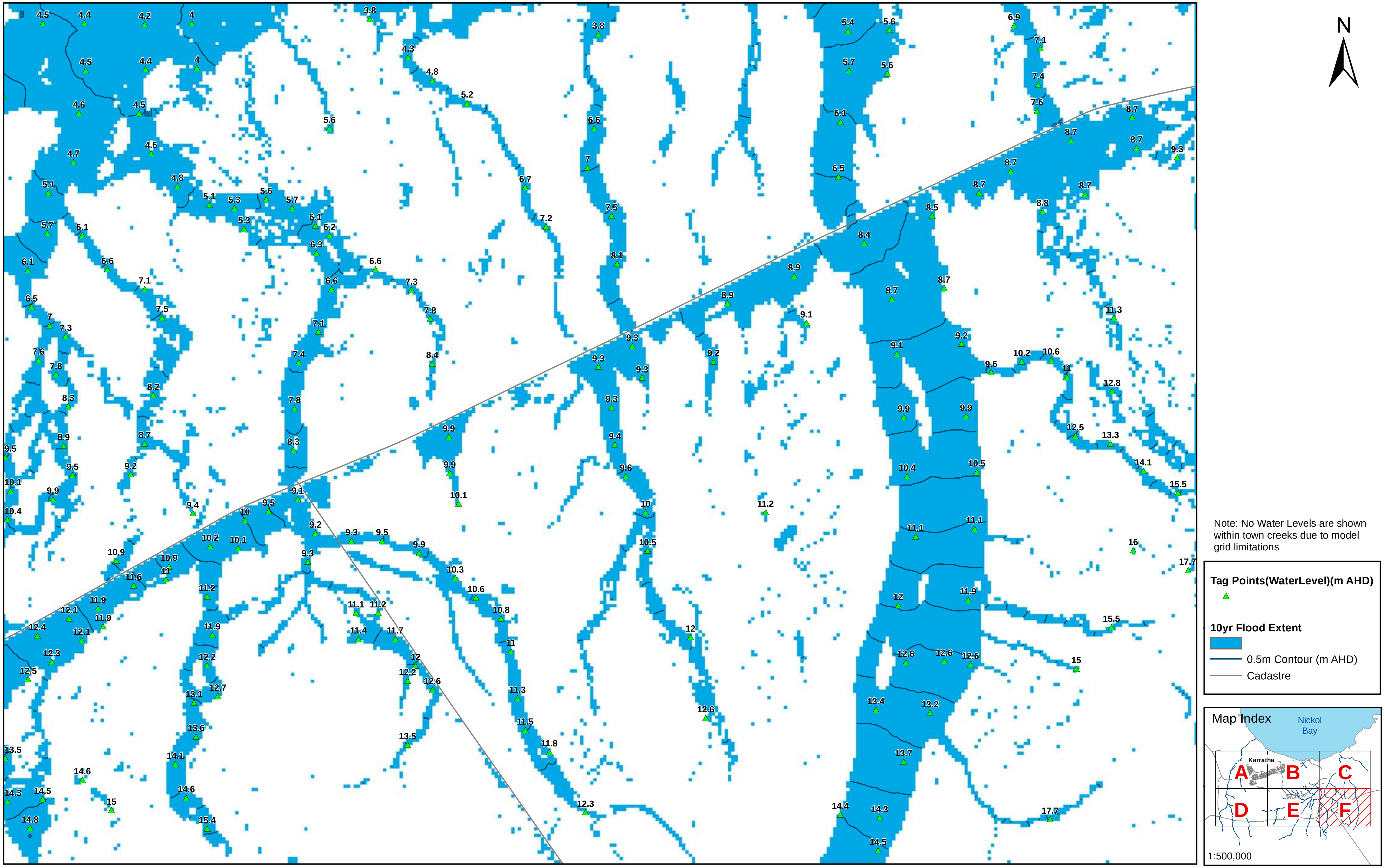
Cadastre



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

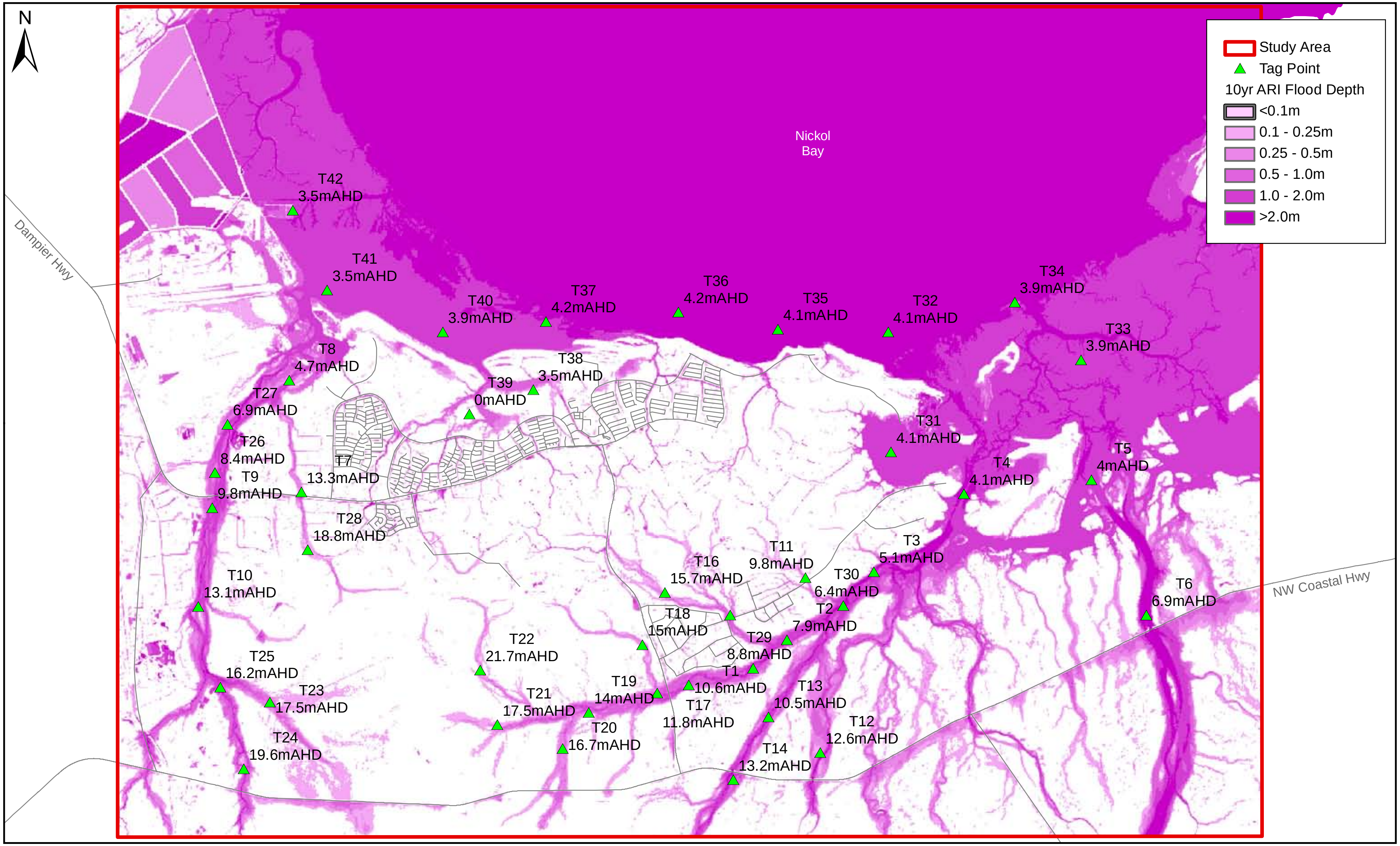
LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure B2E: 10yr ARI Flood Elevation - 2010 Climate Scenario - Sheet E



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure B2F: 10yr ARI Flood Elevation - 2010 Climate Scenario - Sheet F



Data Source: GEMS Modelling & JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

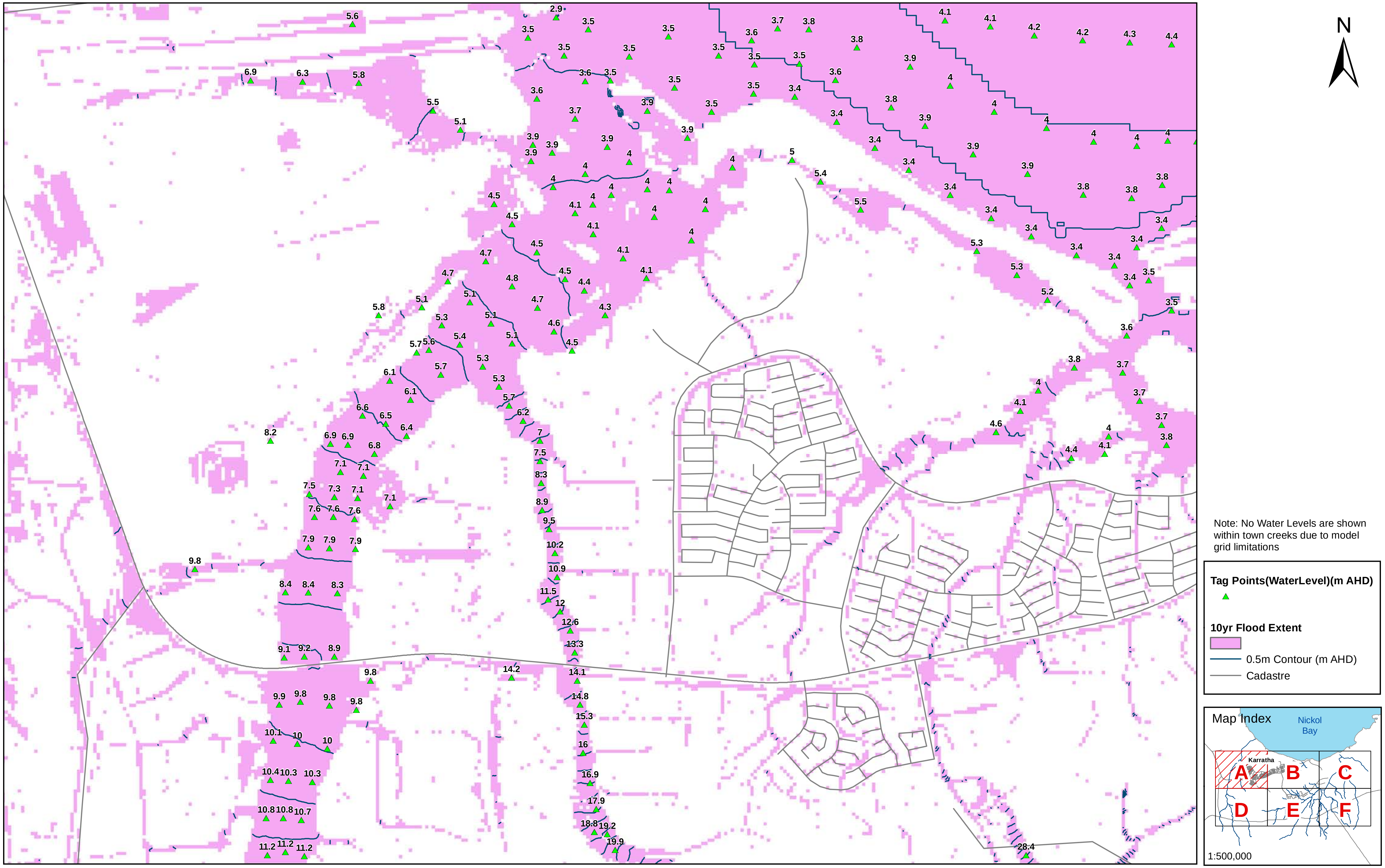
Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

LandCorp

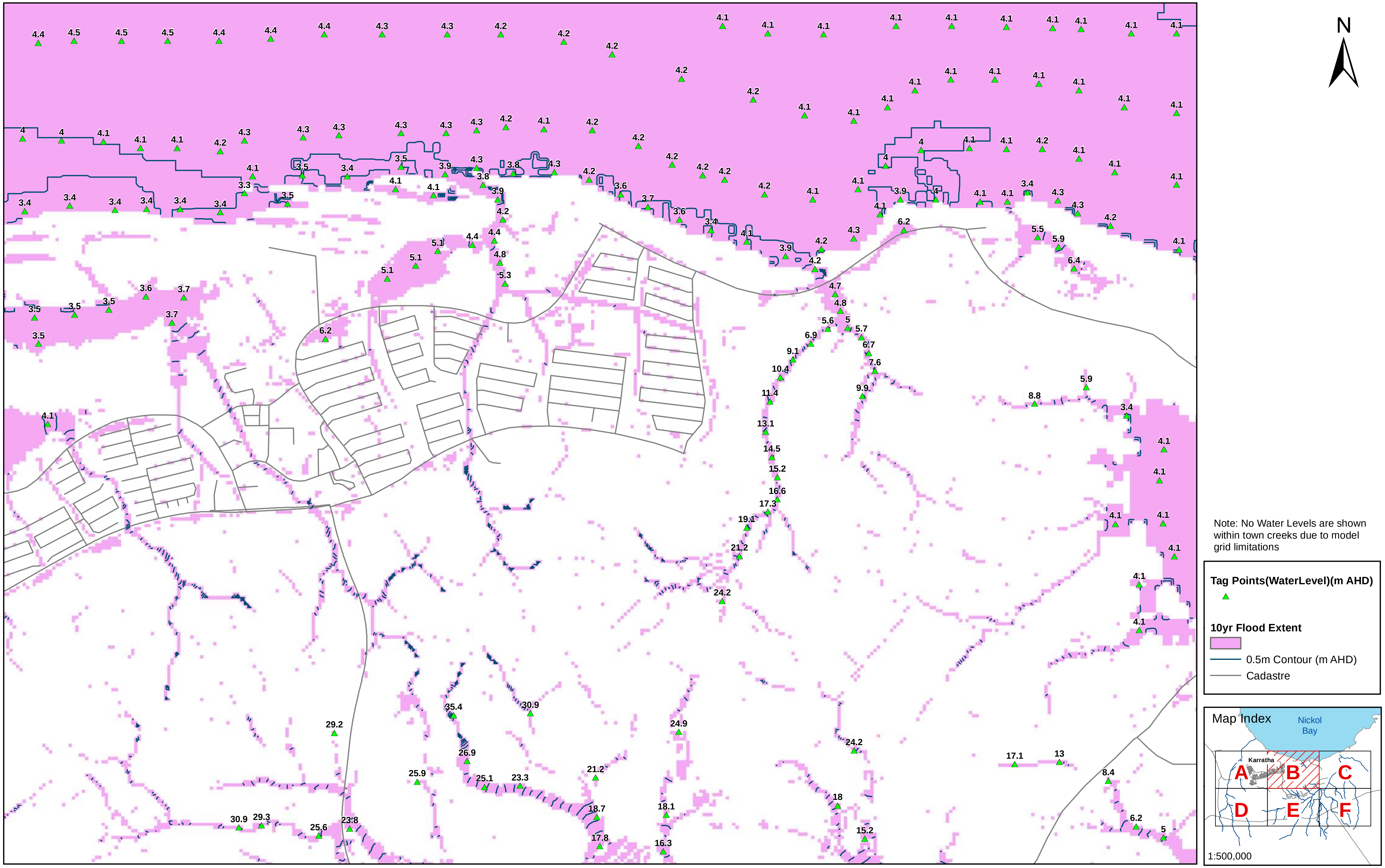
Karratha Coastal Vulnerability Study: Main Report

Figure A3: 10yr ARI Flood Depth - 2060 Climate Scenario



Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

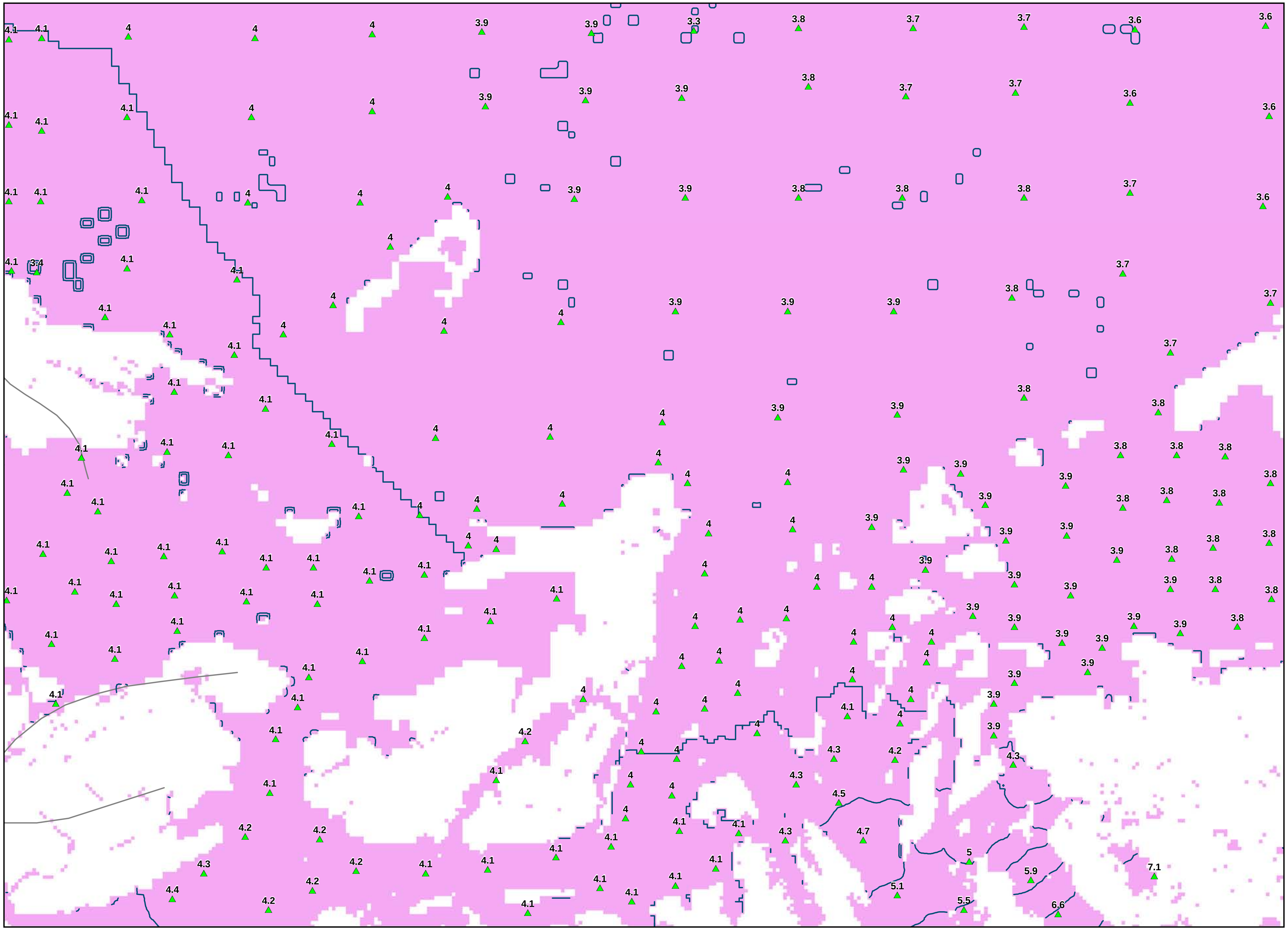
LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure B4A: 10yr ARI Flood Elevation - 2060 Climate Scenario - Sheet A



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure B4B: 10yr ARI Flood Elevation - 2060 Climate Scenario - Sheet B



N

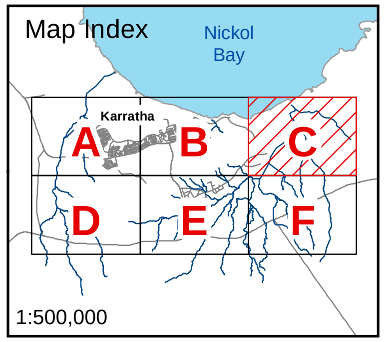
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

10yr Flood Extent

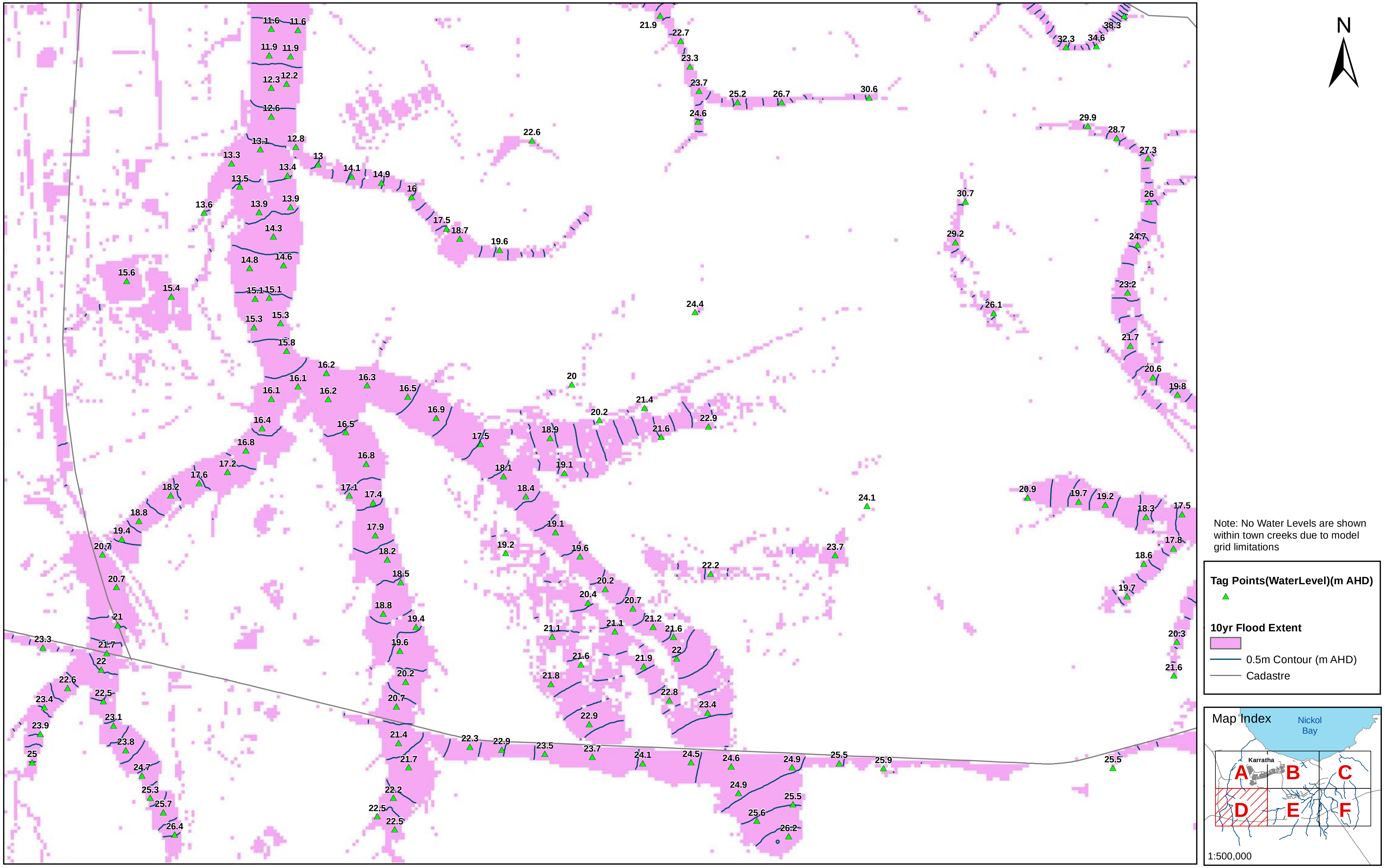
0.5m Contour (m AHD)

Cadastre



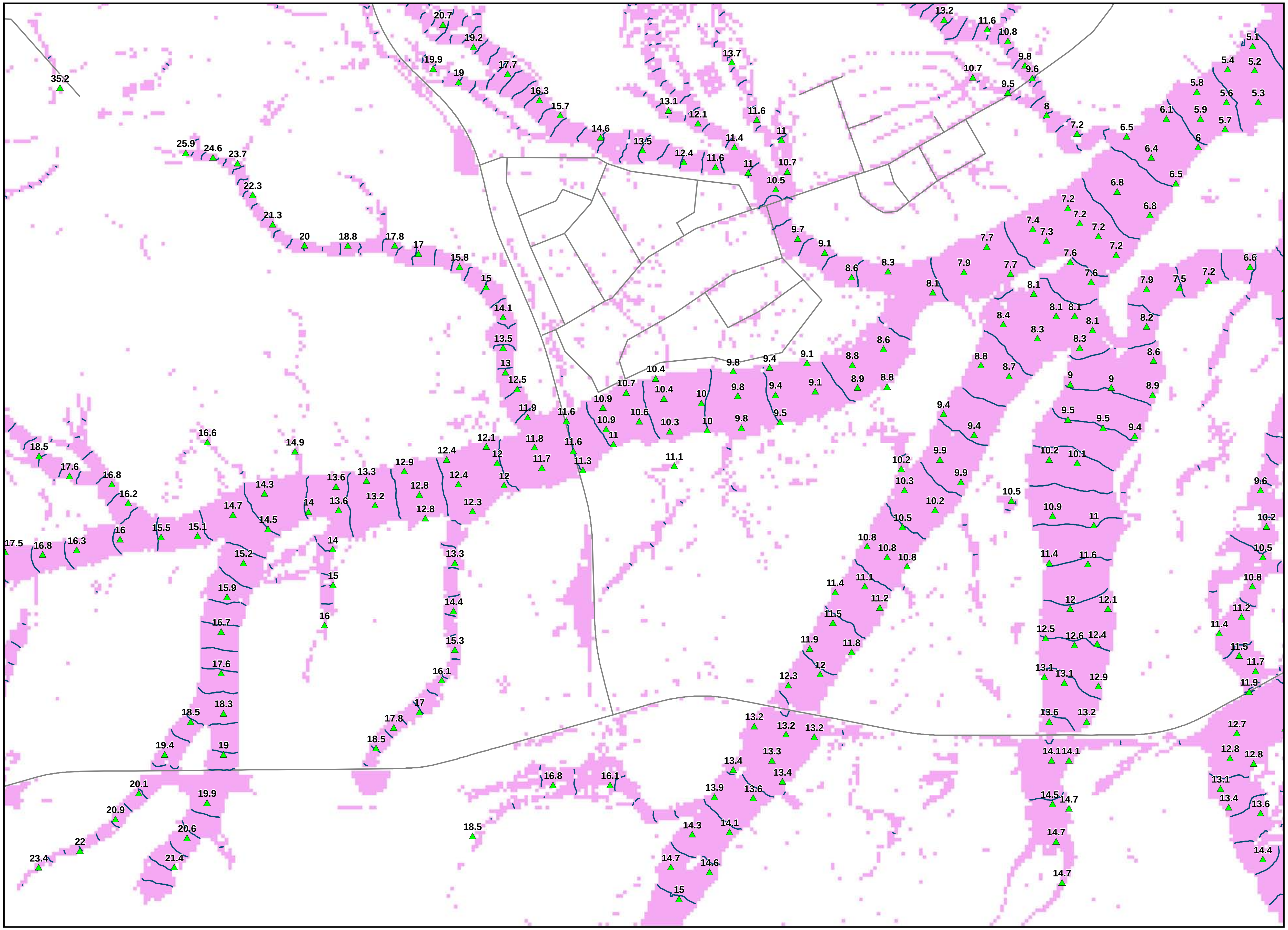
Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure B4C: 10yr ARI Flood Elevation - 2060 Climate Scenario - Sheet C



Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure B4D: 10yr ARI Flood Elevation - 2060 Climate Scenario - Sheet D



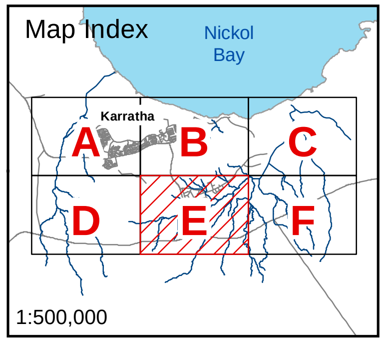
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

10yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812

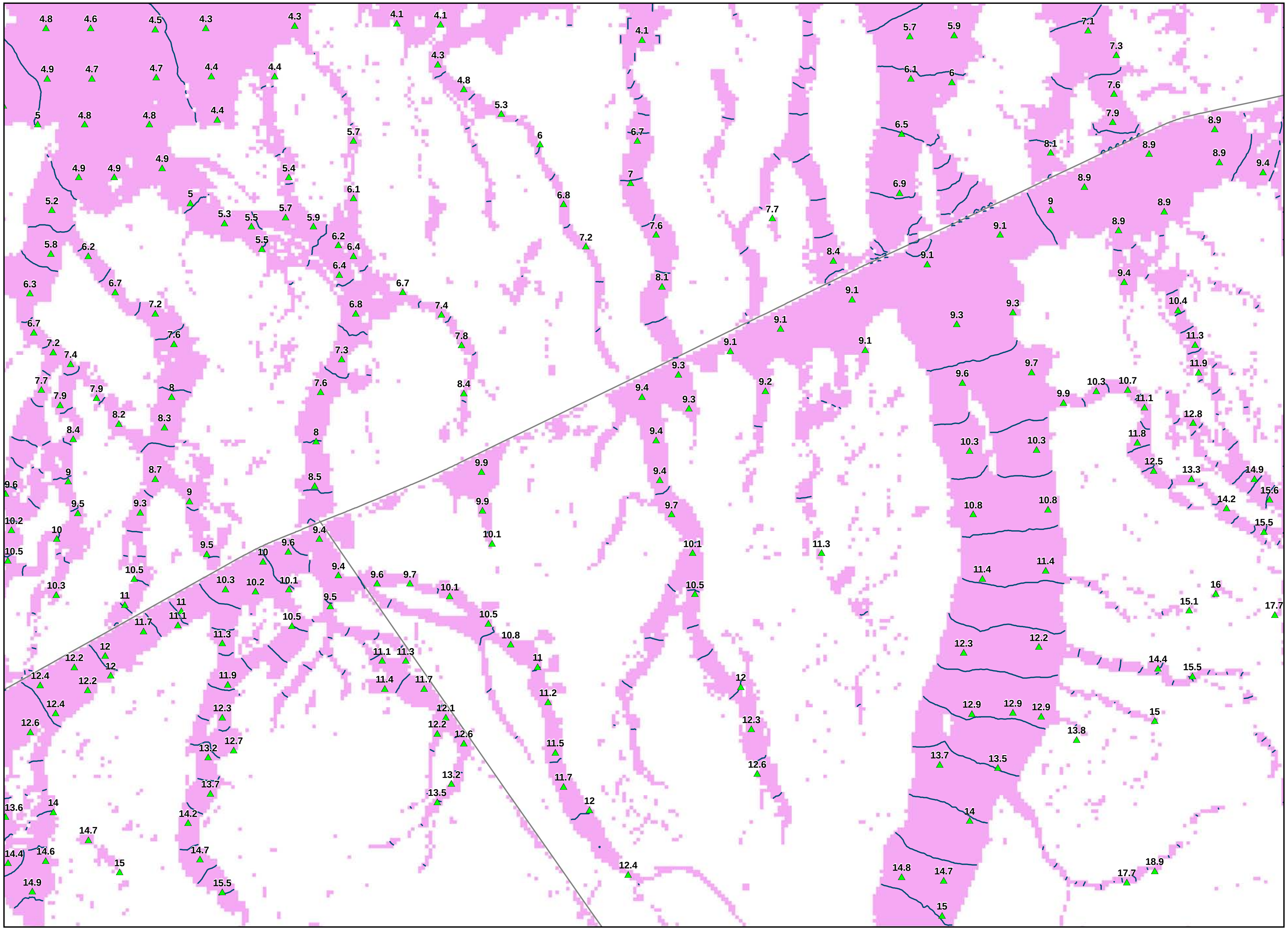
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure B4E: 10yr ARI Flood Elevation - 2060 Climate Scenario - Sheet E



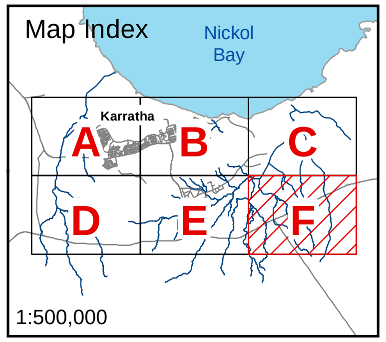
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

10yr Flood Extent

0.5m Contour (m AHD)

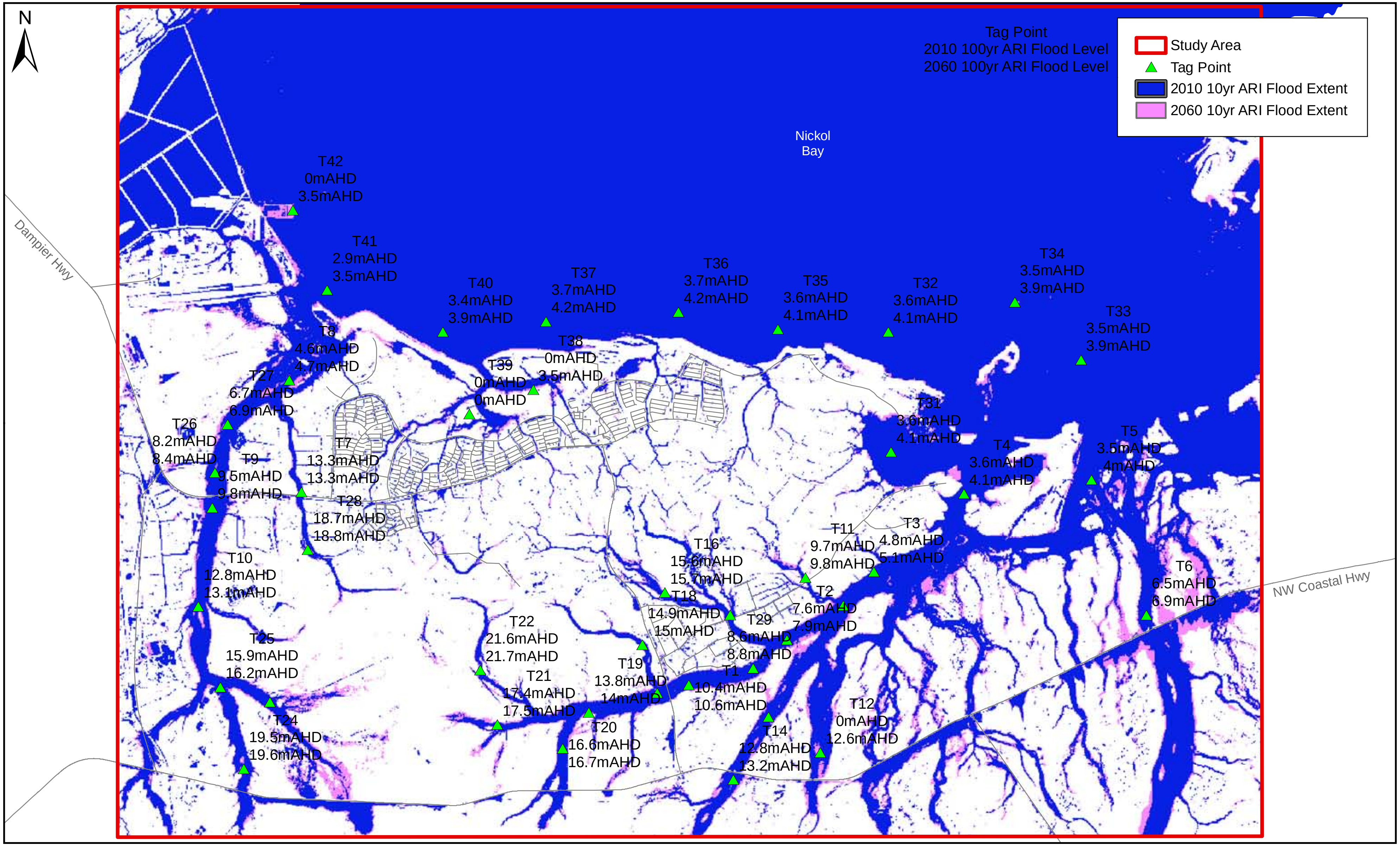
Cadastre



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure B4F: 10yr ARI Flood Elevation - 2060 Climate Scenario - Sheet F



Data Source: GEMS Modelling and JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

LandCorp

Karratha Coastal Vulnerability Study: Main Report

Figure B5 : Comparison of 10yr (2010) and 10yr (2060) Flood Extent

Data Source: GEMS Modelling and JDA Hydraulic Modelling 2011

JDA

Job No. J4812

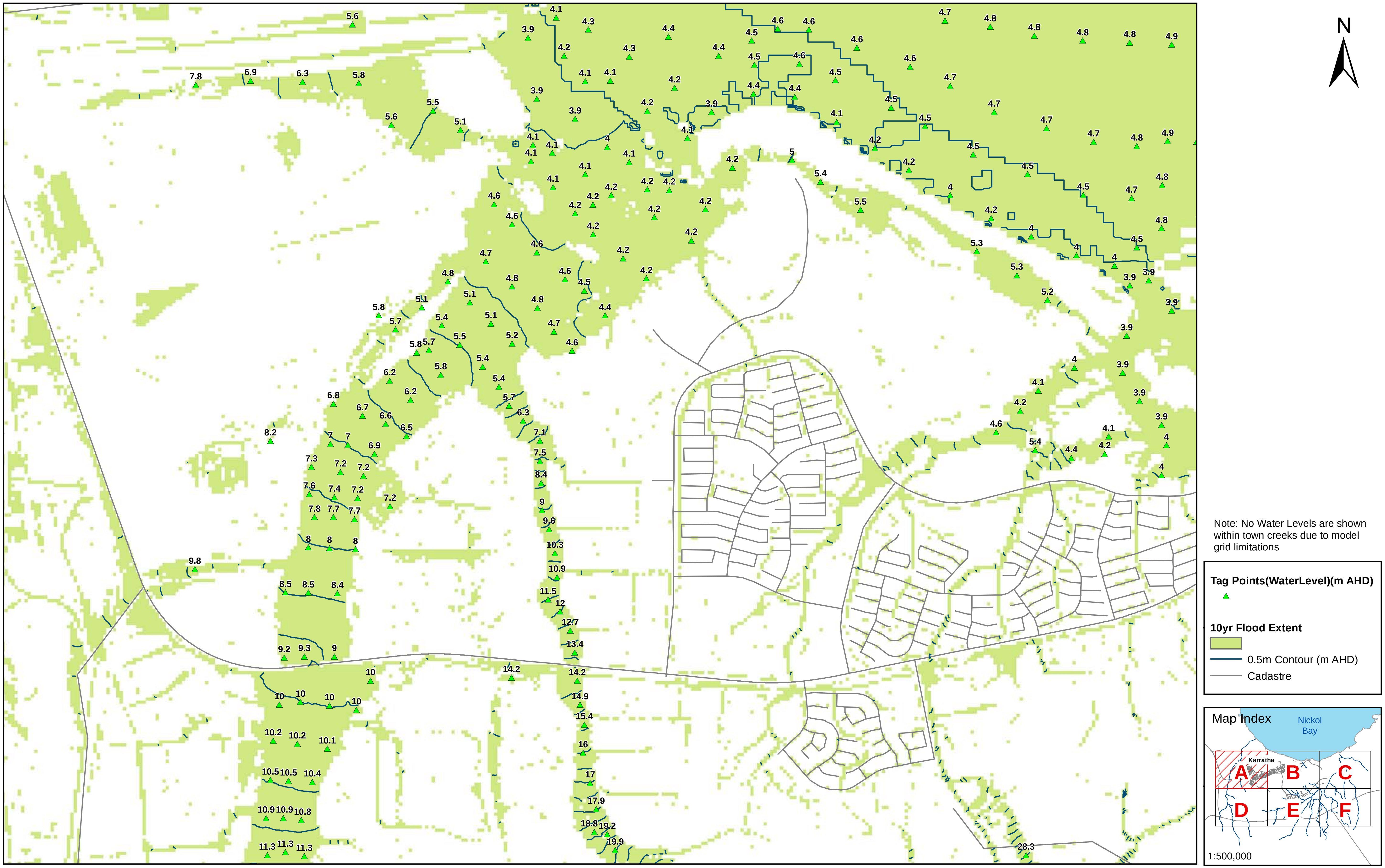
Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

LandCorp

Karratha Coastal Vulnerability Study: Main Report

Figure B6: 10yr ARI Flood Depth - 2110 Climate Scenario

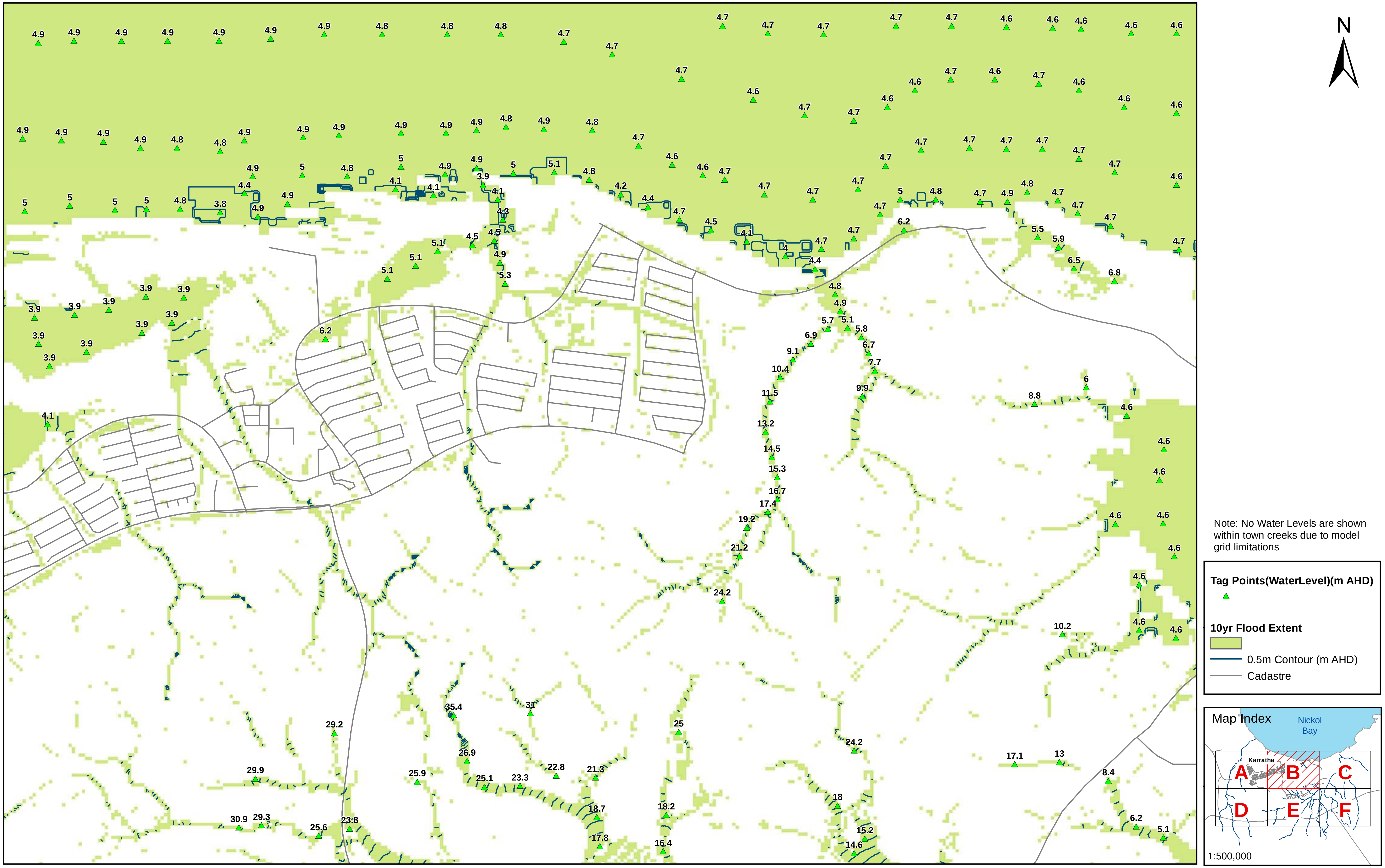


Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report

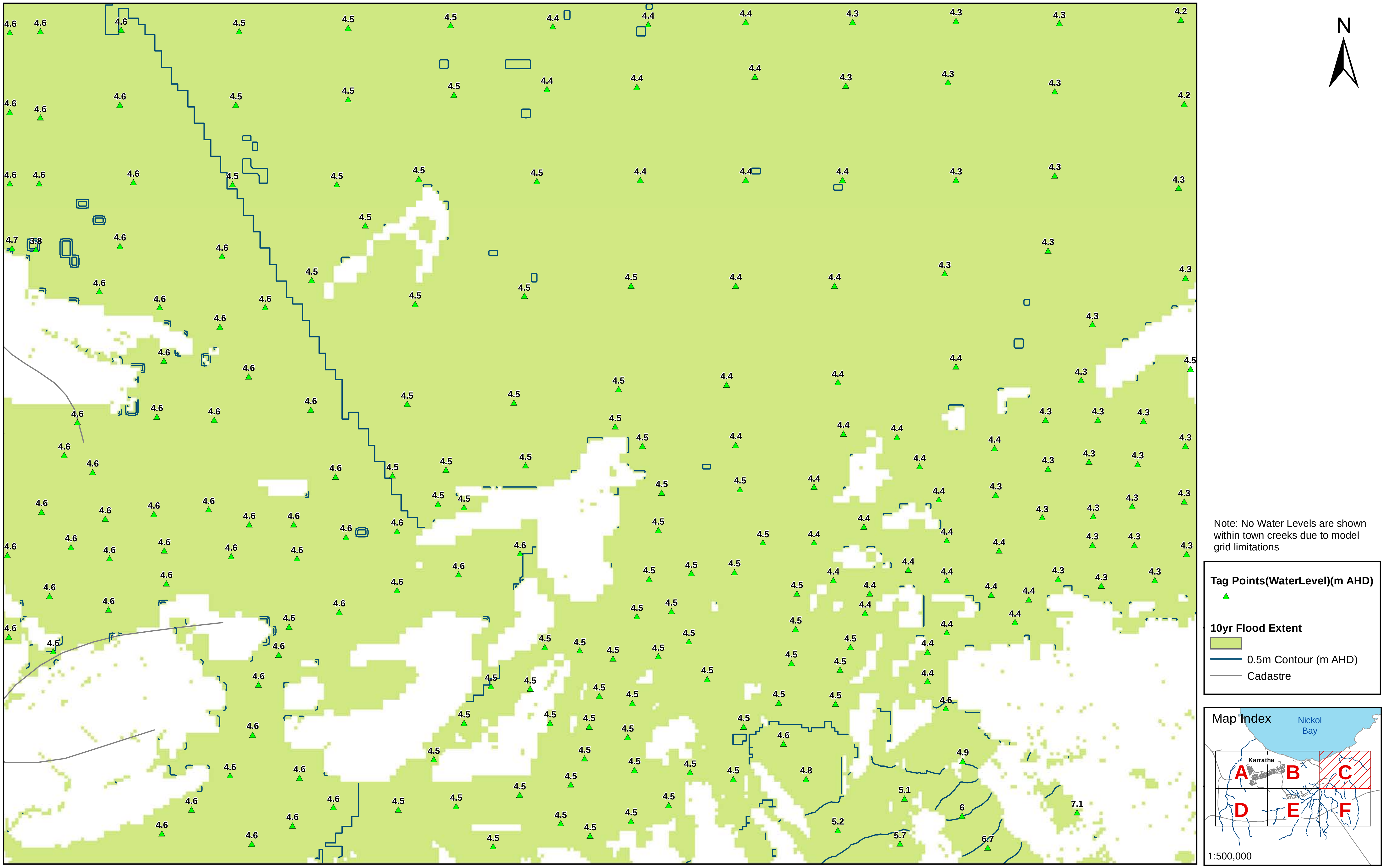
Figure B7A: 10yr ARI Flood Elevation - 2110 Climate Scenario - Sheet A



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

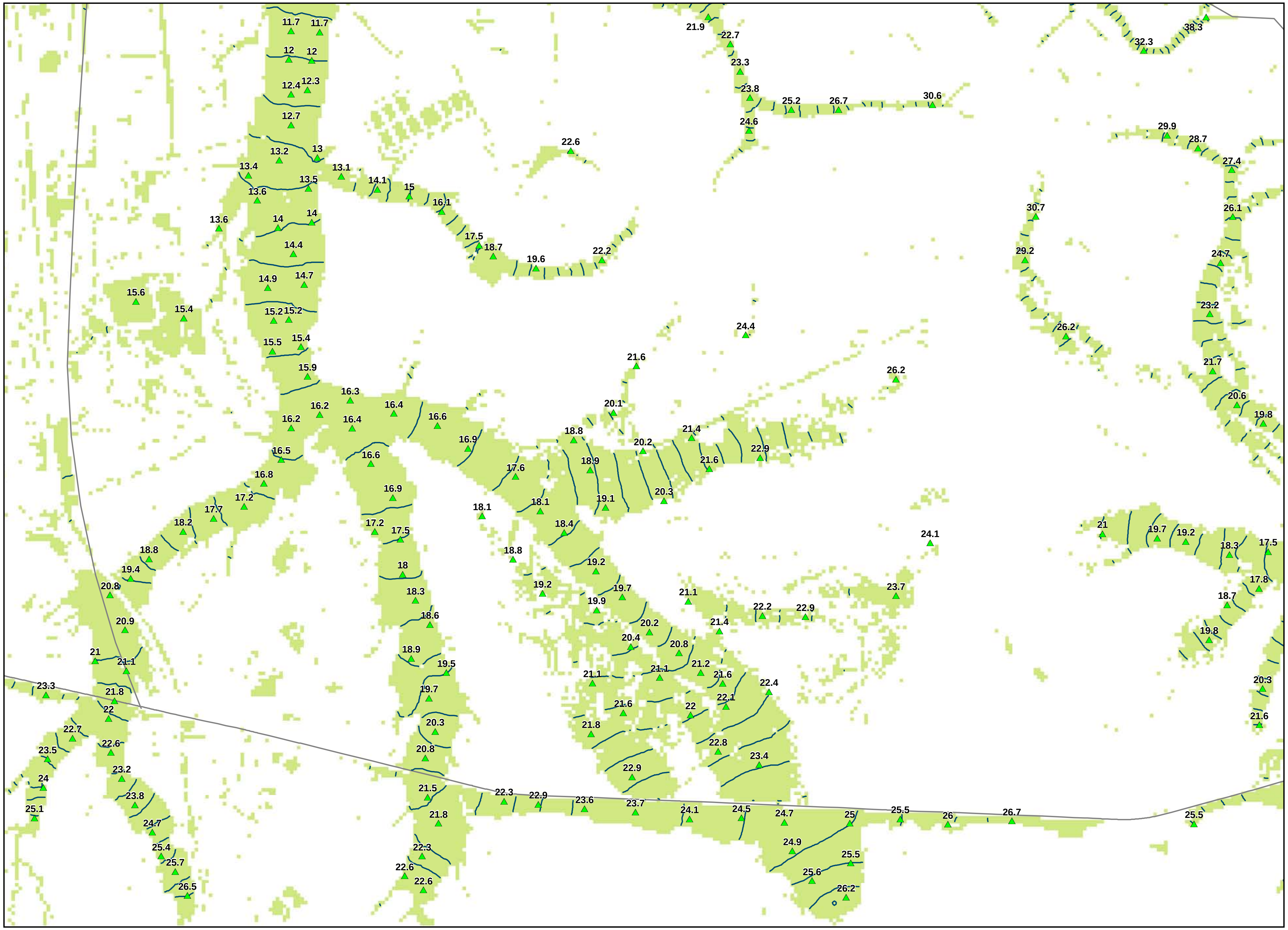
LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure B7B: 10yr ARI Flood Elevation - 2110 Climate Scenario - Sheet B



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure B7C: 10yr ARI Flood Elevation - 2110 Climate Scenario - Sheet C



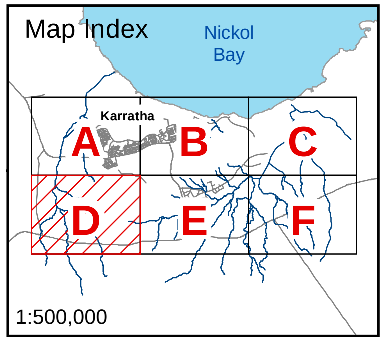
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

10yr Flood Extent

0.5m Contour (m AHD)

Cadastre



JDA

Job No. J4812

Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure B7D: 10yr ARI Flood Elevation - 2110 Climate Scenario - Sheet D

N

Note: No Water Levels are shown within town creeks due to model grid limitations

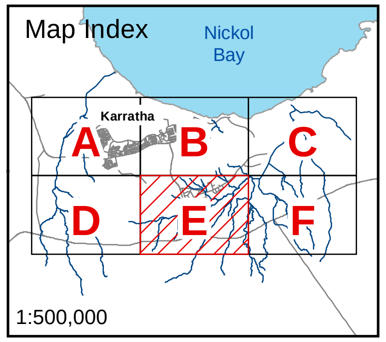
Tag Points(WaterLevel)(m AHD)

10yr Flood Extent

0.5m Contour (m AHD)

Cadastre

Map Index

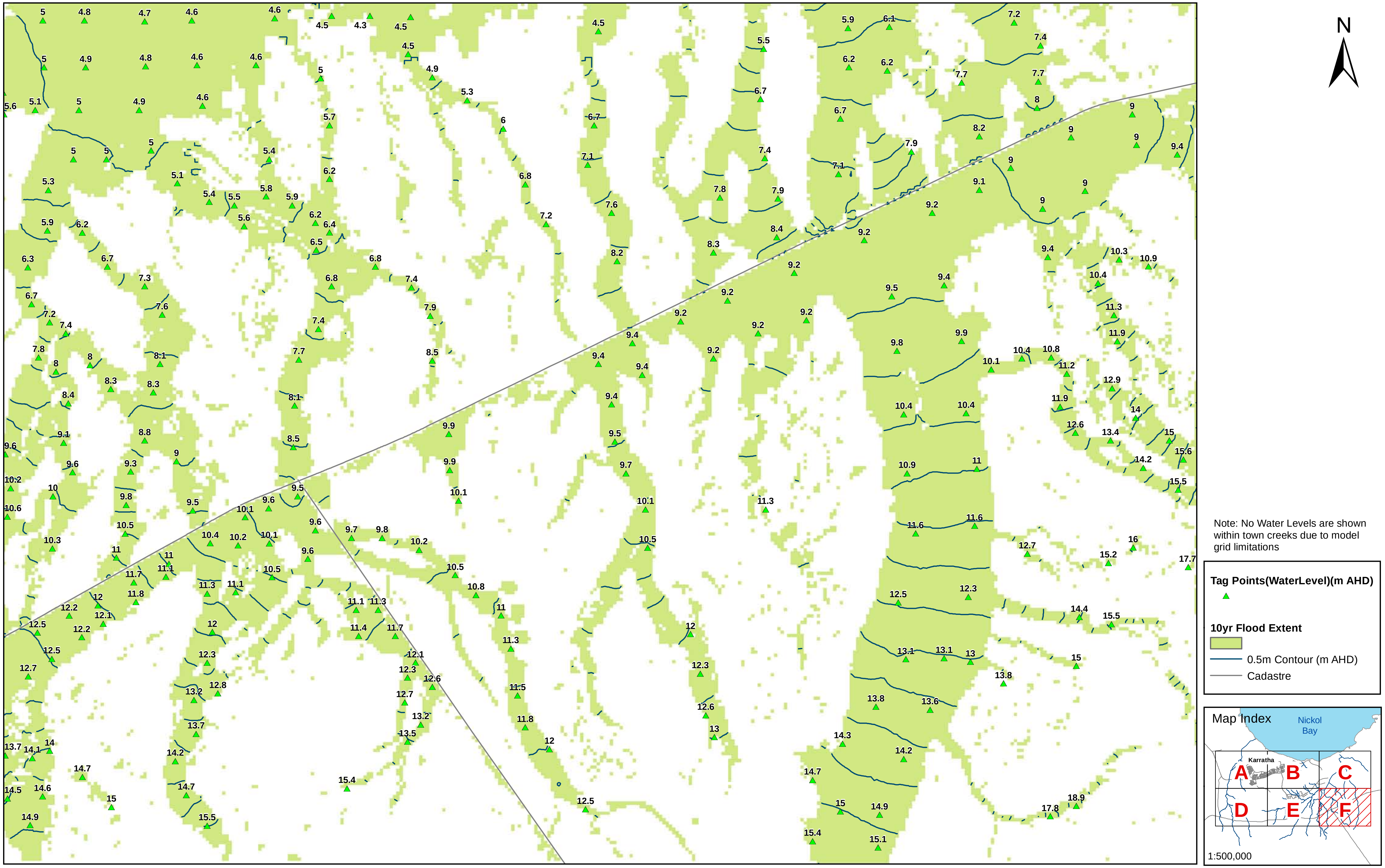


1:500,000

Job No. J4812
Scale:1:22,000

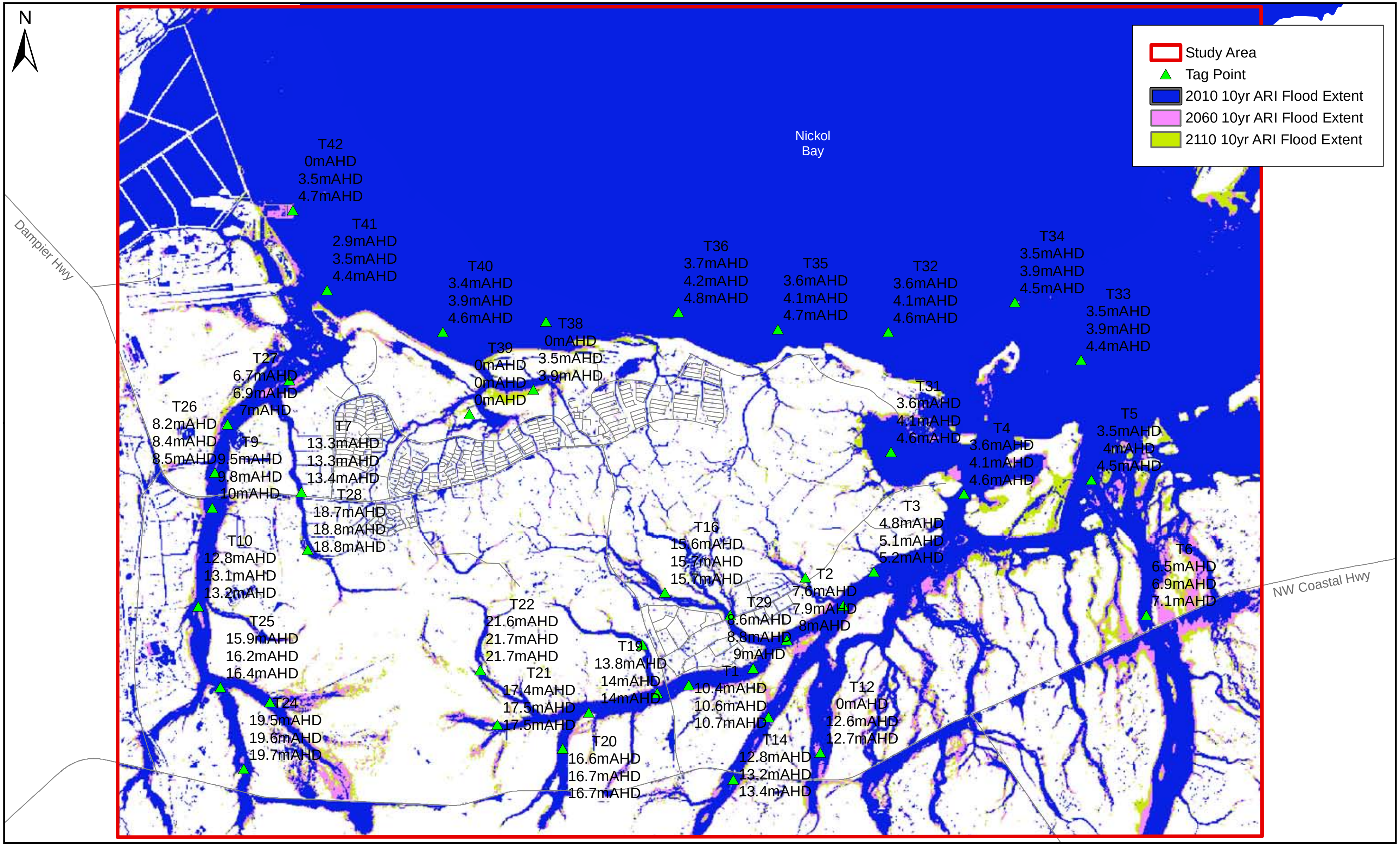
0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure B7E: 10yr ARI Flood Elevation - 2110 Climate Scenario - Sheet E



Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure B7F: 10yr ARI Flood Elevation - 2110 Climate Scenario - Sheet F



Data Source: GEMS Modelling and JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

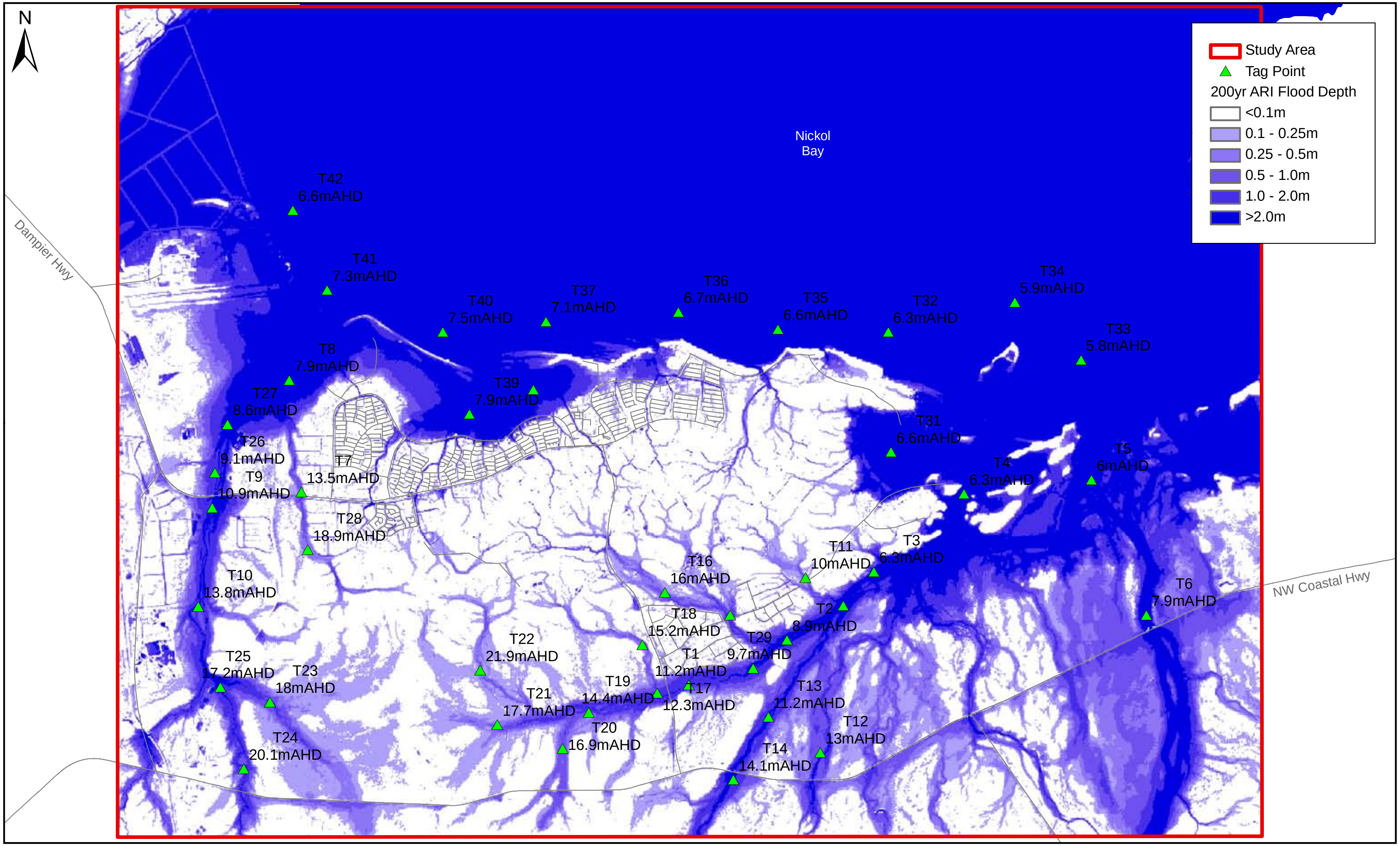
LandCorp

Karratha Coastal Vulnerability Study: Main Report

Figure B8 : Comparison of 10yr (2010), 10yr (2060) and 10yr (2110) Flood Extent

APPENDIX C

200yr ARI Flood Extent, Depth, Level and Flow Velocity for the 2010, 2060 & 2110 Climate Scenarios



Data Source: GEMS Modelling & JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

LandCorp

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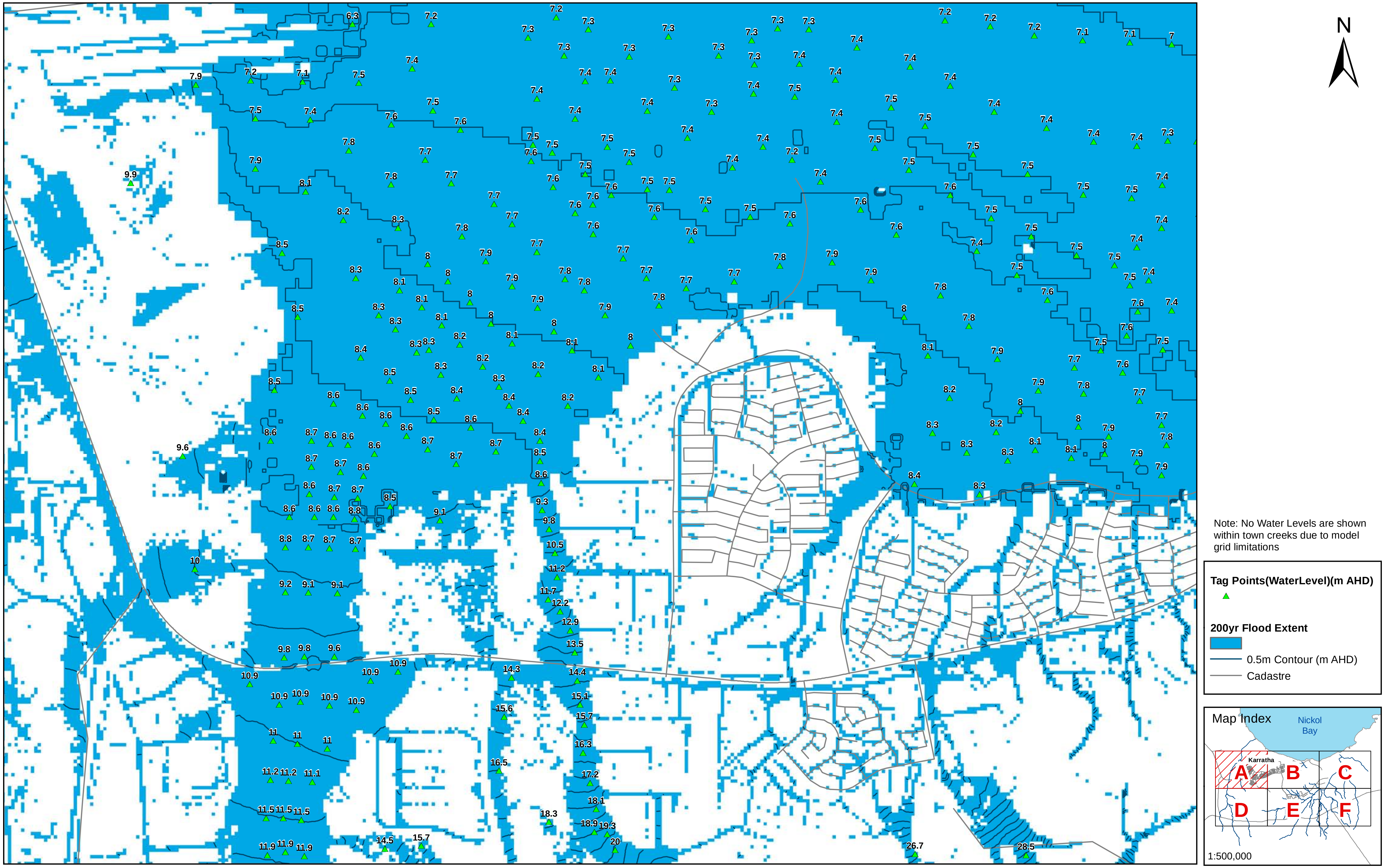
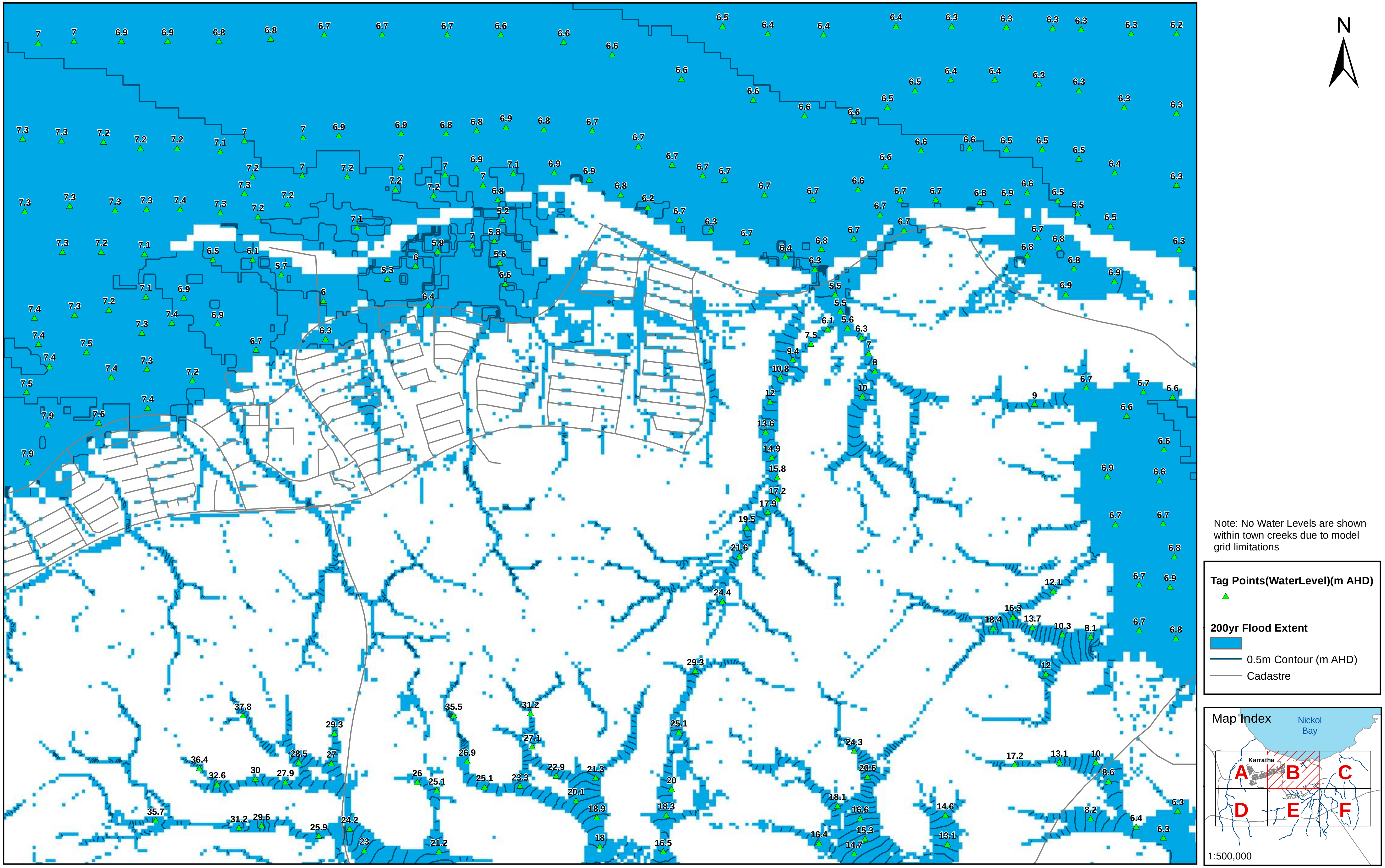
Figure C1: 200yr ARI Flood Depth - 2010 Climate Scenario



Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure C2A: 200yr ARI Flood Elevation - 2010 Climate Scenario - Sheet A



JDA

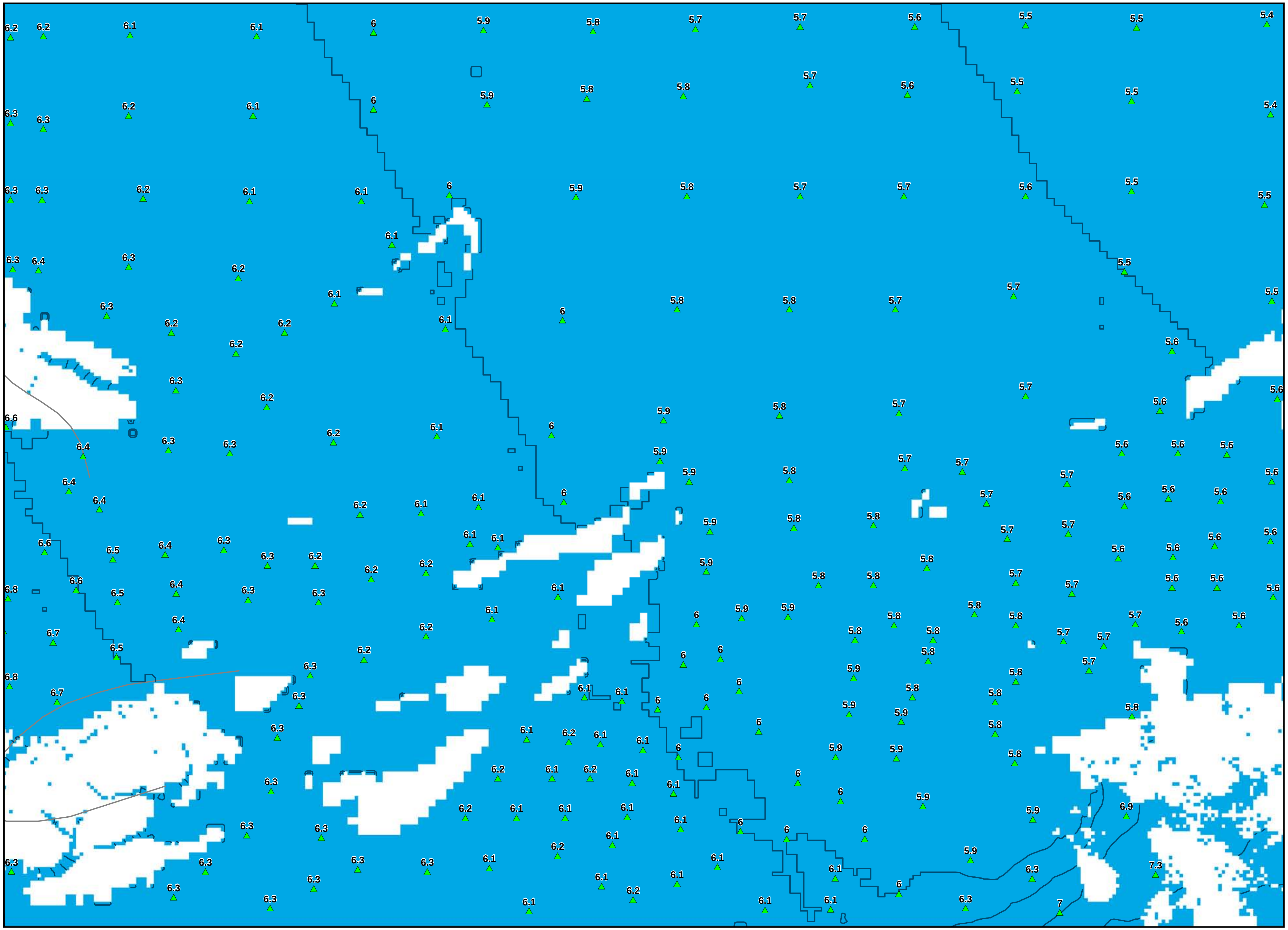
Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure C2B: 200yr ARI Flood Elevation - 2010 Climate Scenario - Sheet B



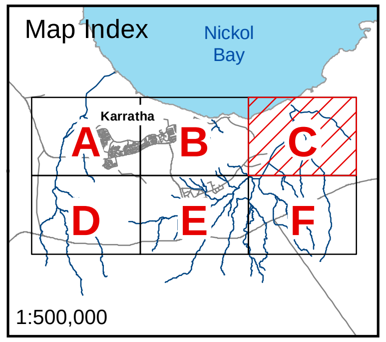
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

200yr Flood Extent

0.5m Contour (m AHD)

Cadastre



JDA

Job No. J4812

Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

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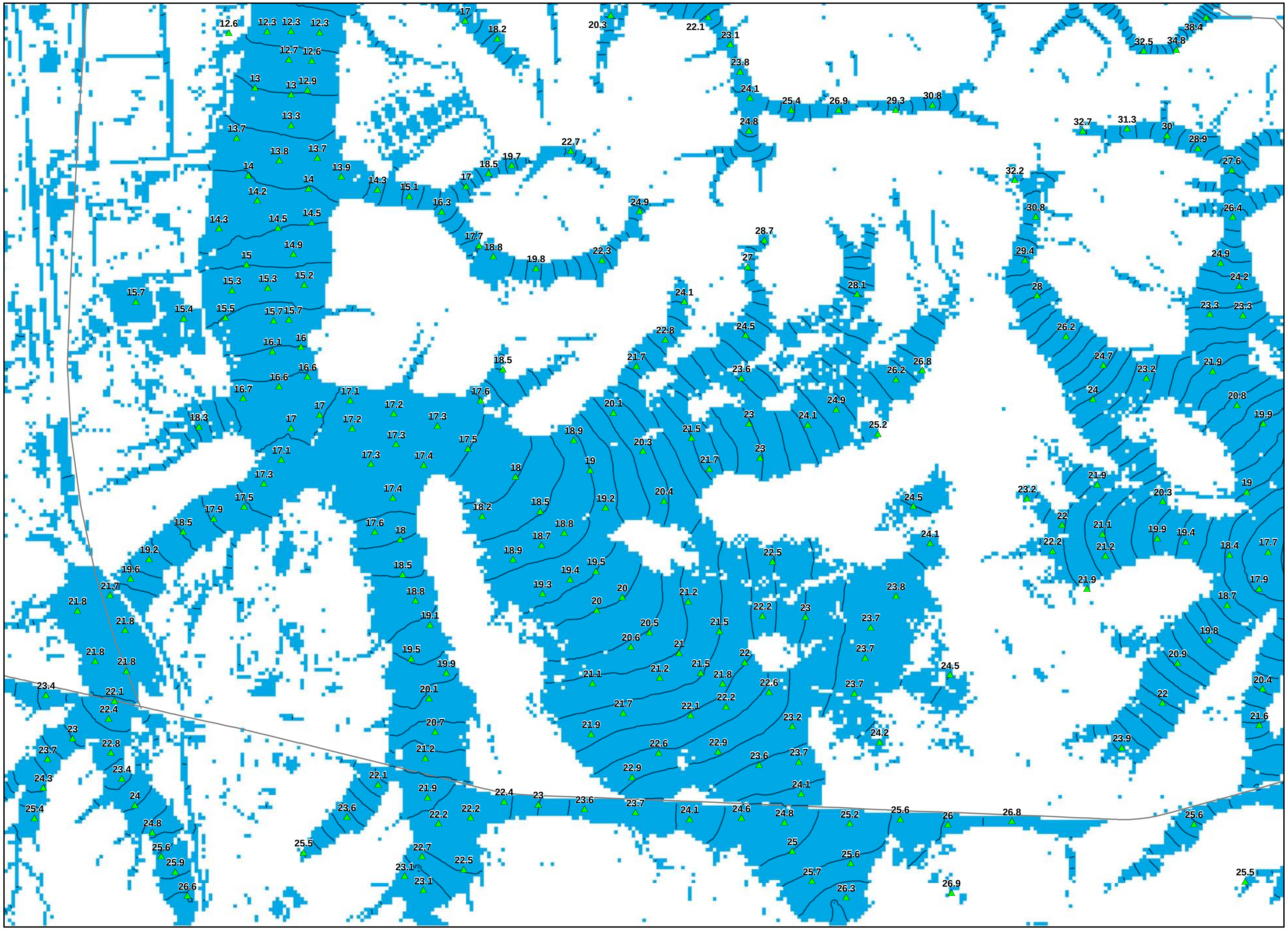
Figure C2C: 200yr ARI Flood Elevation - 2010 Climate Scenario - Sheet C



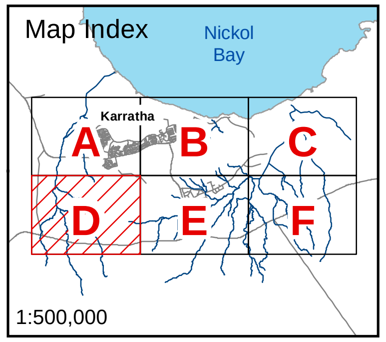
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

200yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812

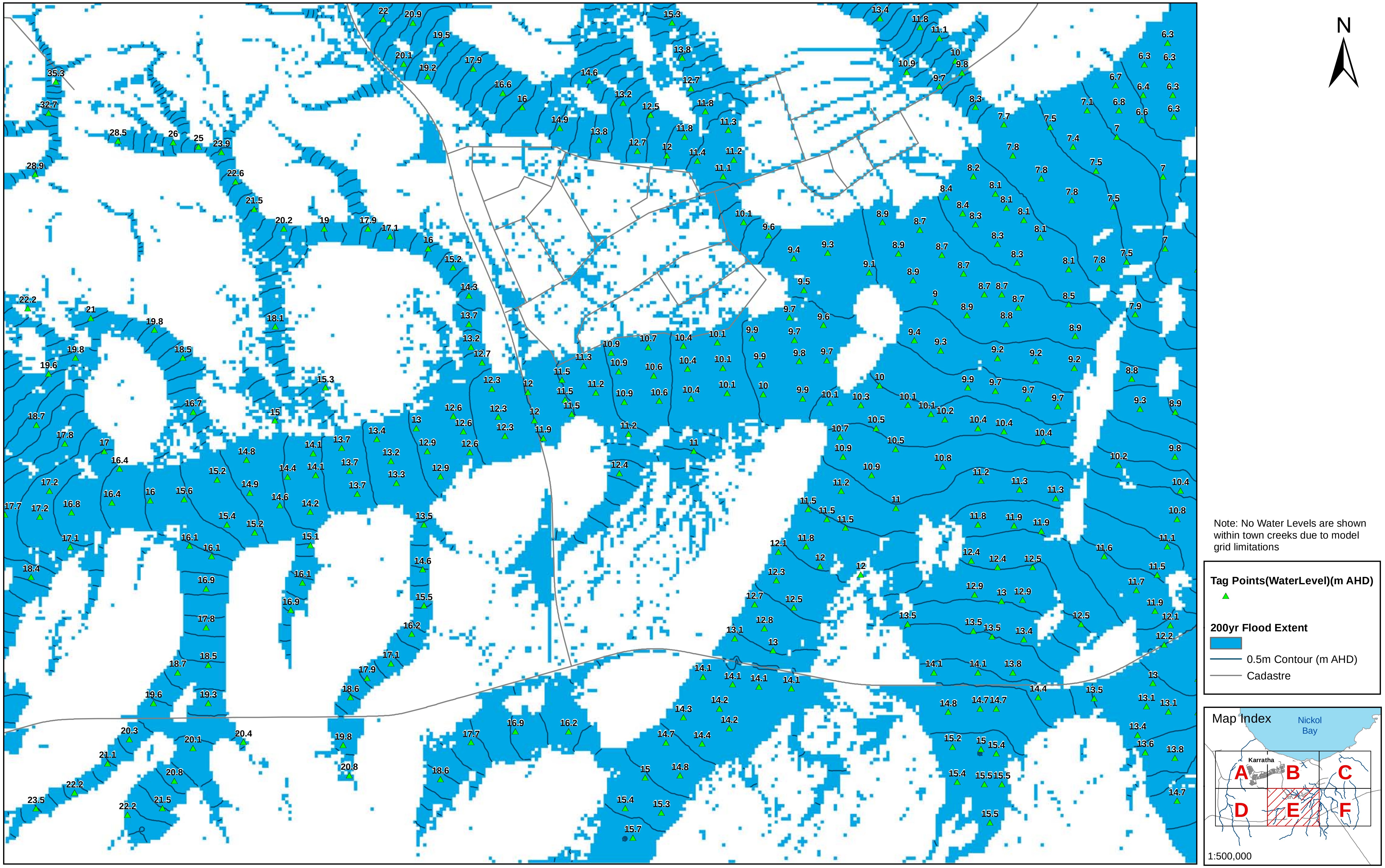
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure C2D: 200yr ARI Flood Elevation - 2010 Climate Scenario - Sheet D



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

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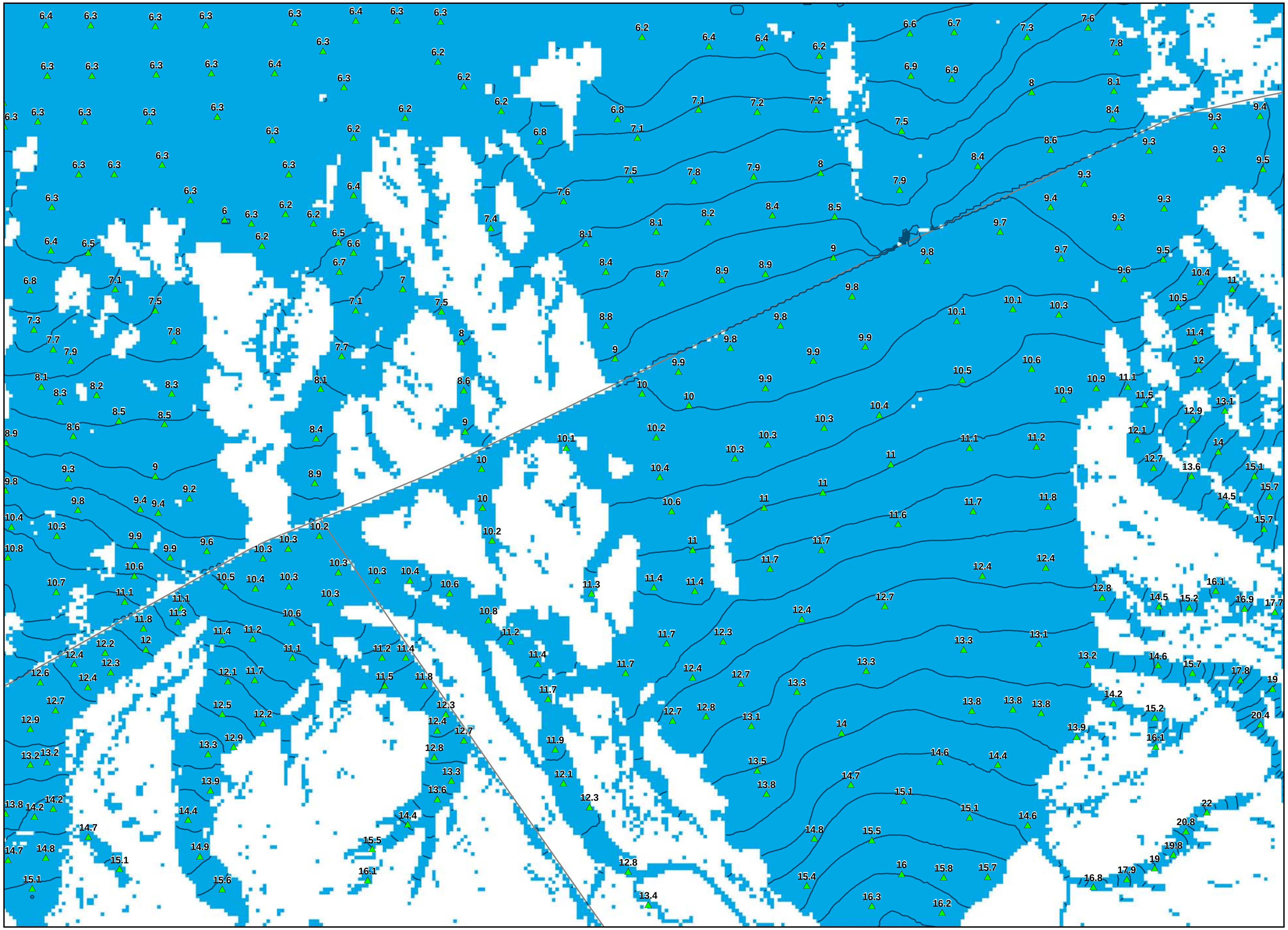
Figure C2E: 200yr ARI Flood Elevation - 2010 Climate Scenario - Sheet E



N

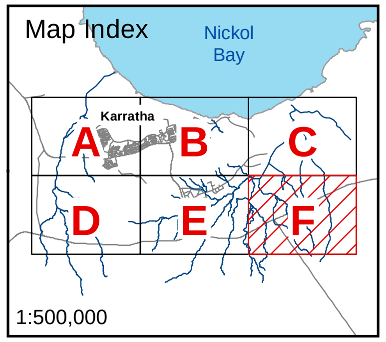
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

200yr Flood Extent

0.5m Contour (m AHD)

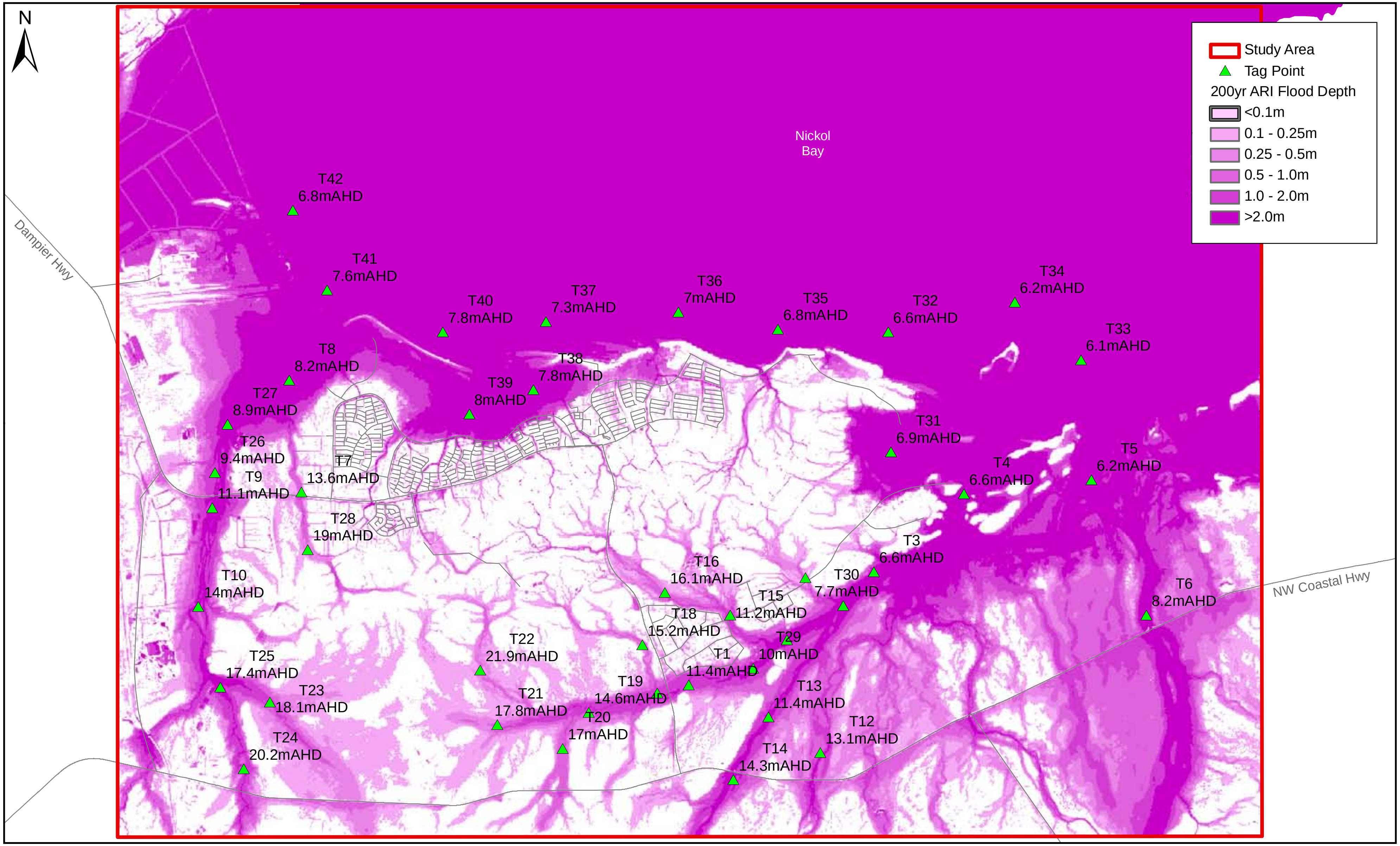
Cadastre



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure C2F: 200yr ARI Flood Elevation - 2010 Climate Scenario - Sheet F



Data Source: GEMS Modelling & JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

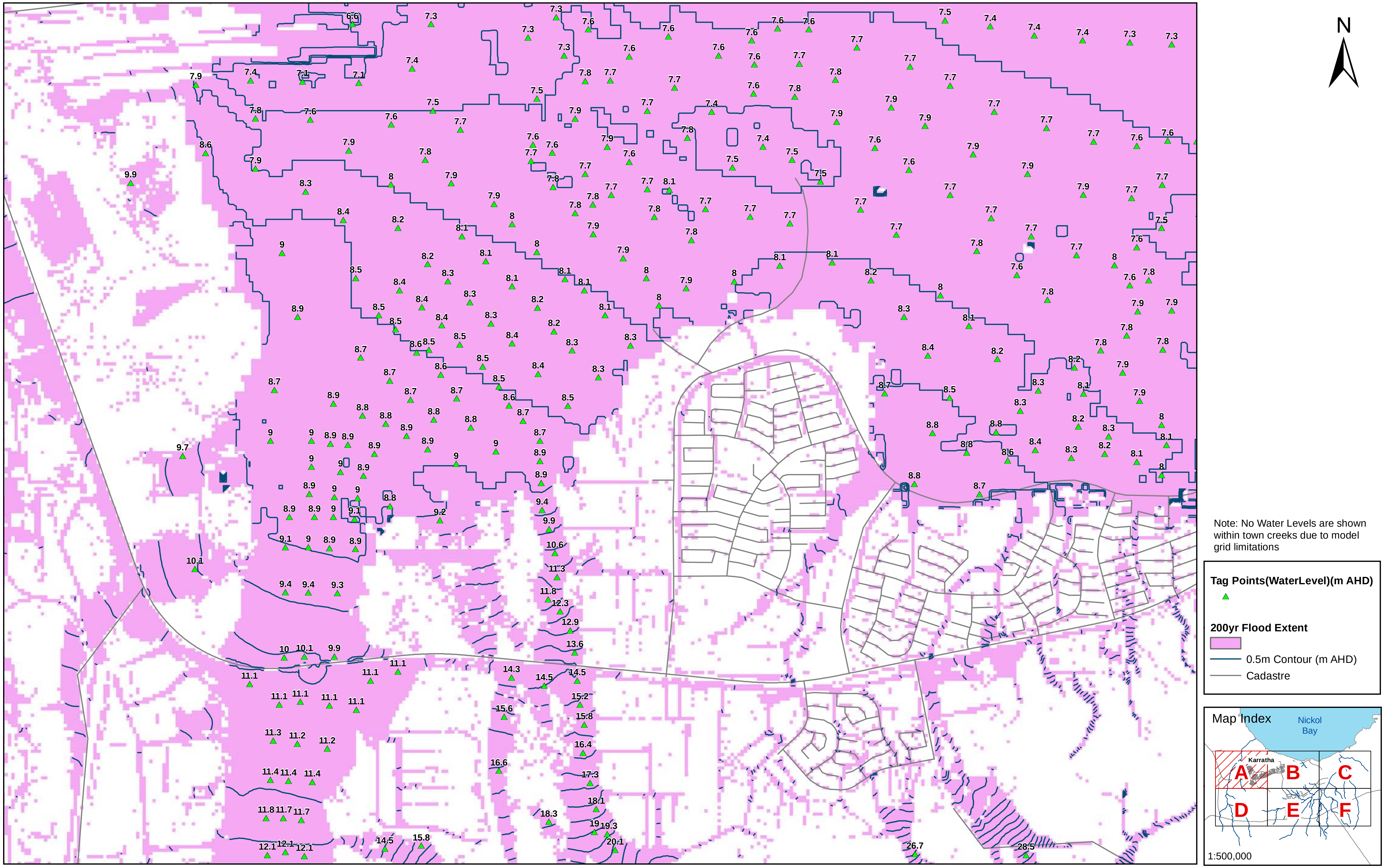
Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

LandCorp

Karratha Coastal Vulnerability Study: Main Report

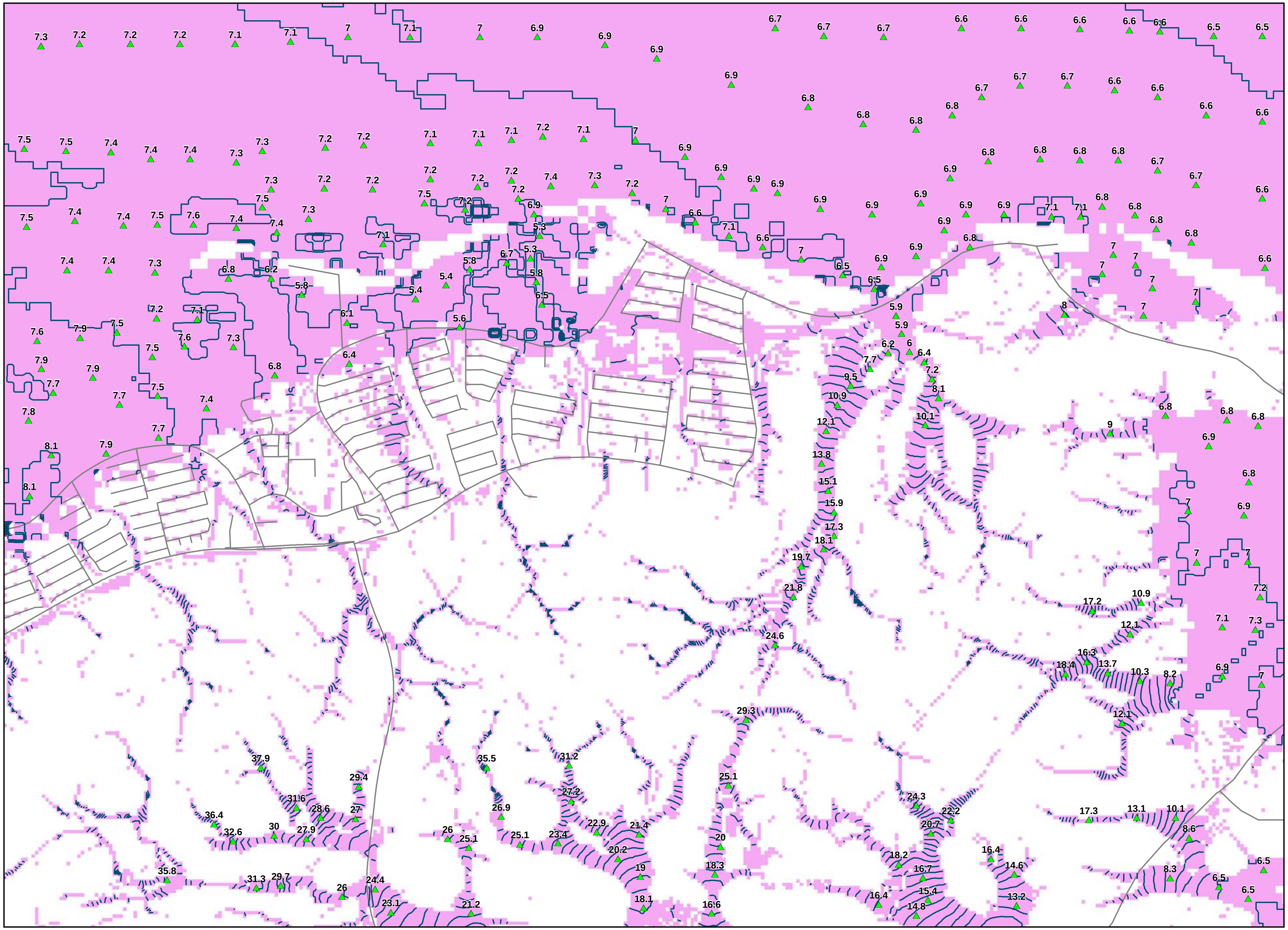
FigureC3: 200yr ARI Flood Depth - 2060 Climate Scenario



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure C4A: 200yr ARI Flood Elevation - 2060 Climate Scenario - Sheet A



N

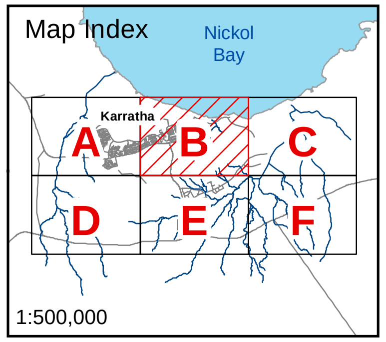
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

200yr Flood Extent

0.5m Contour (m AHD)

Cadastre



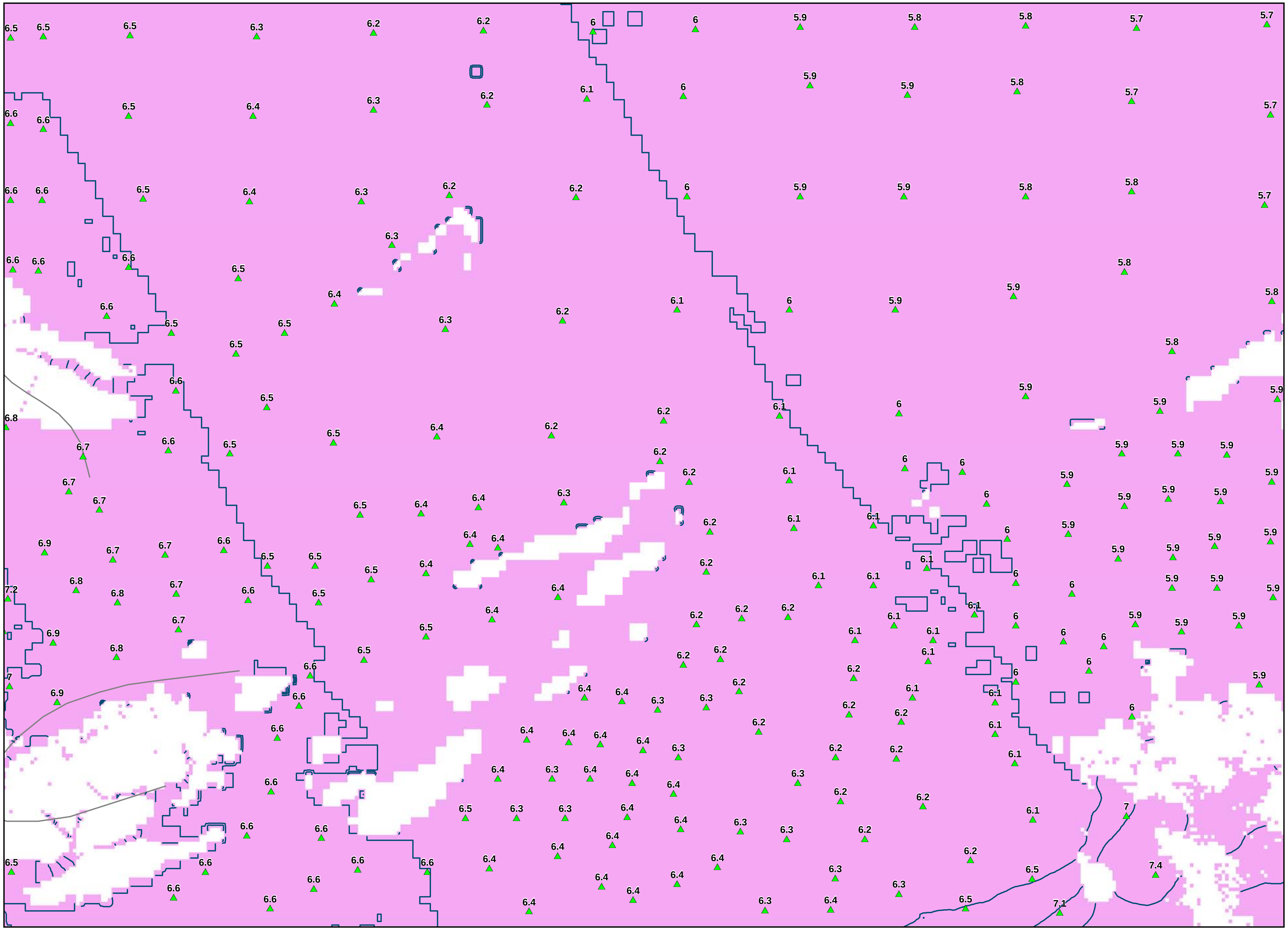
Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure C4A: 200yr ARI Flood Elevation - 2060 Climate Scenario - Sheet A



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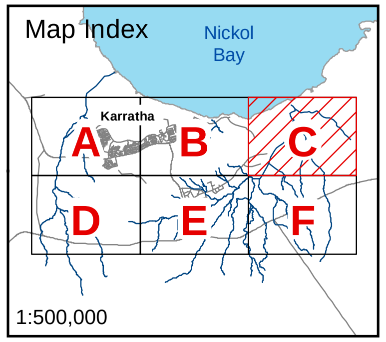
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

200yr Flood Extent

0.5m Contour (m AHD)

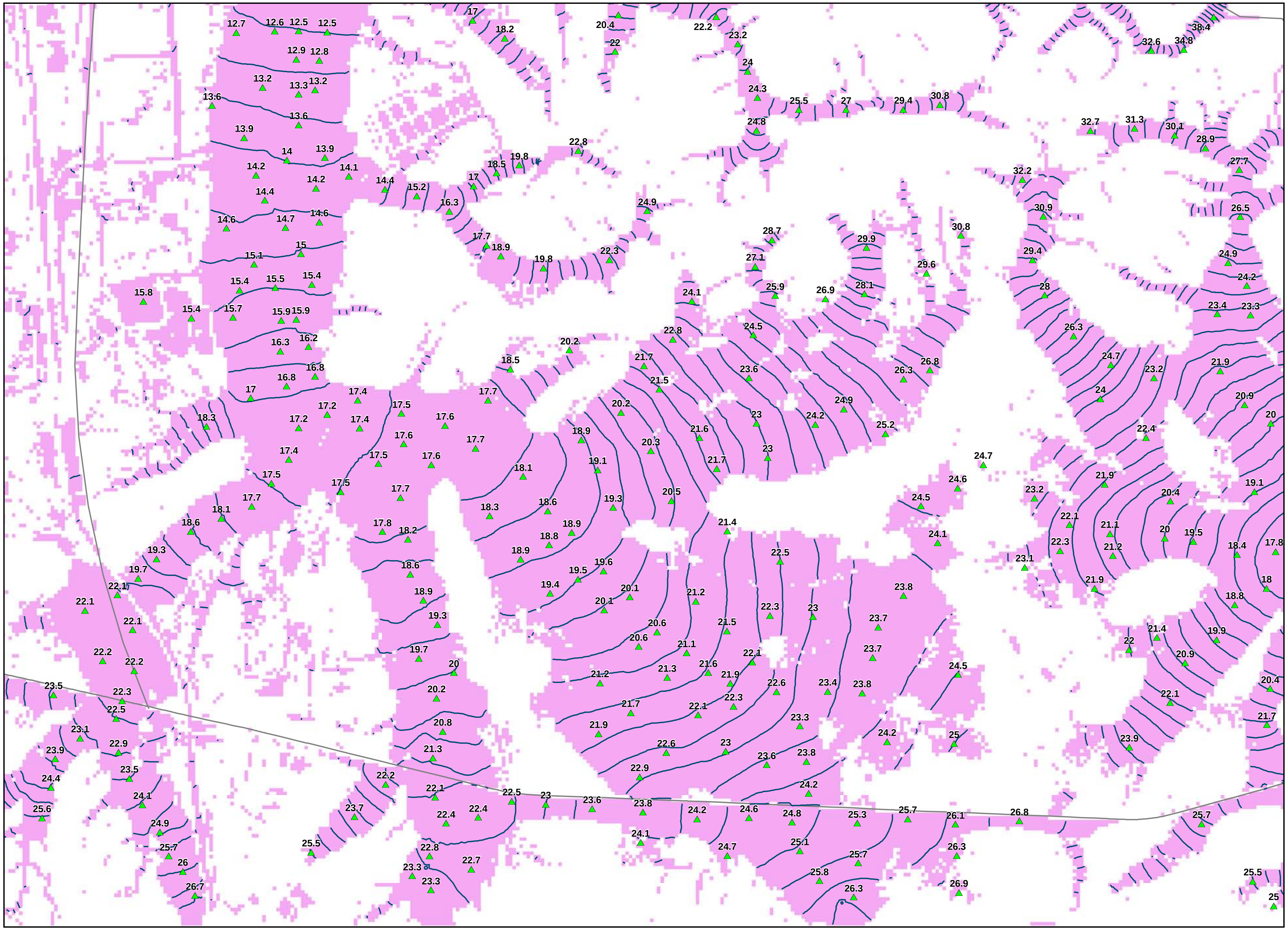
Cadastre



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure C4C: 200yr ARI Flood Elevation - 2060 Climate Scenario - Sheet C



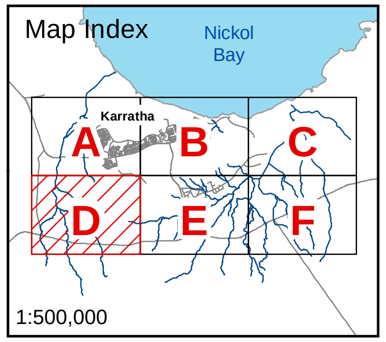
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

200yr Flood Extent

0.5m Contour (m AHD)

Cadastre



JDA

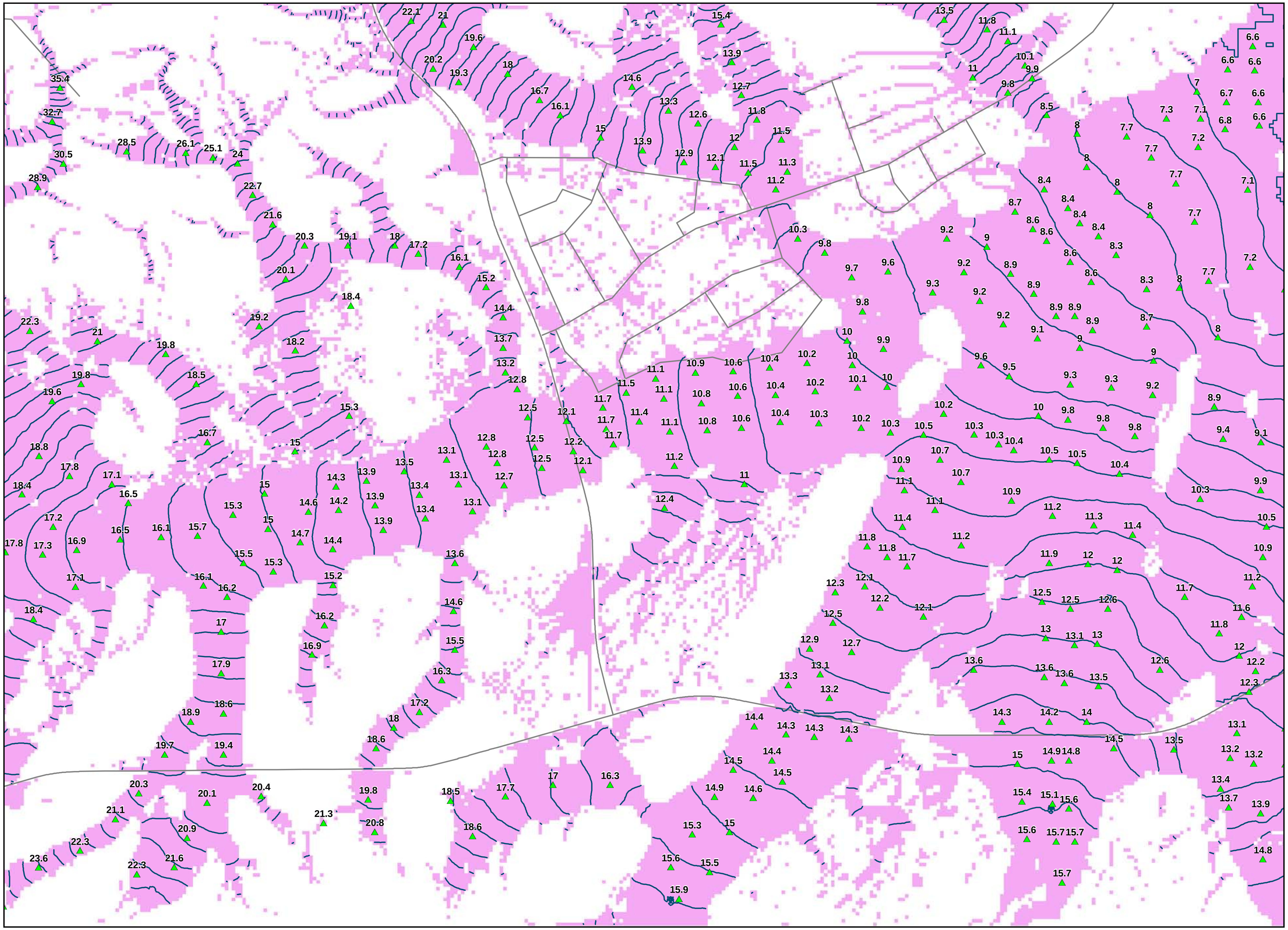
Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure C4D: 200yr ARI Flood Elevation - 2060 Climate Scenario - Sheet D



Note: No Water Levels are shown within town creeks due to model grid limitations

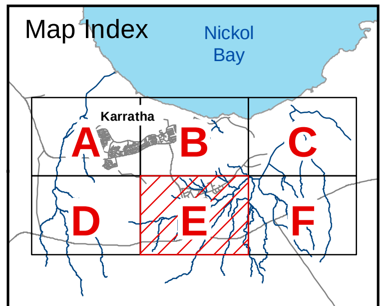
Tag Points(WaterLevel)(m AHD)

200yr Flood Extent

0.5m Contour (m AHD)

Cadastre

Map Index



1:500,000

JDA

Job No. J4812

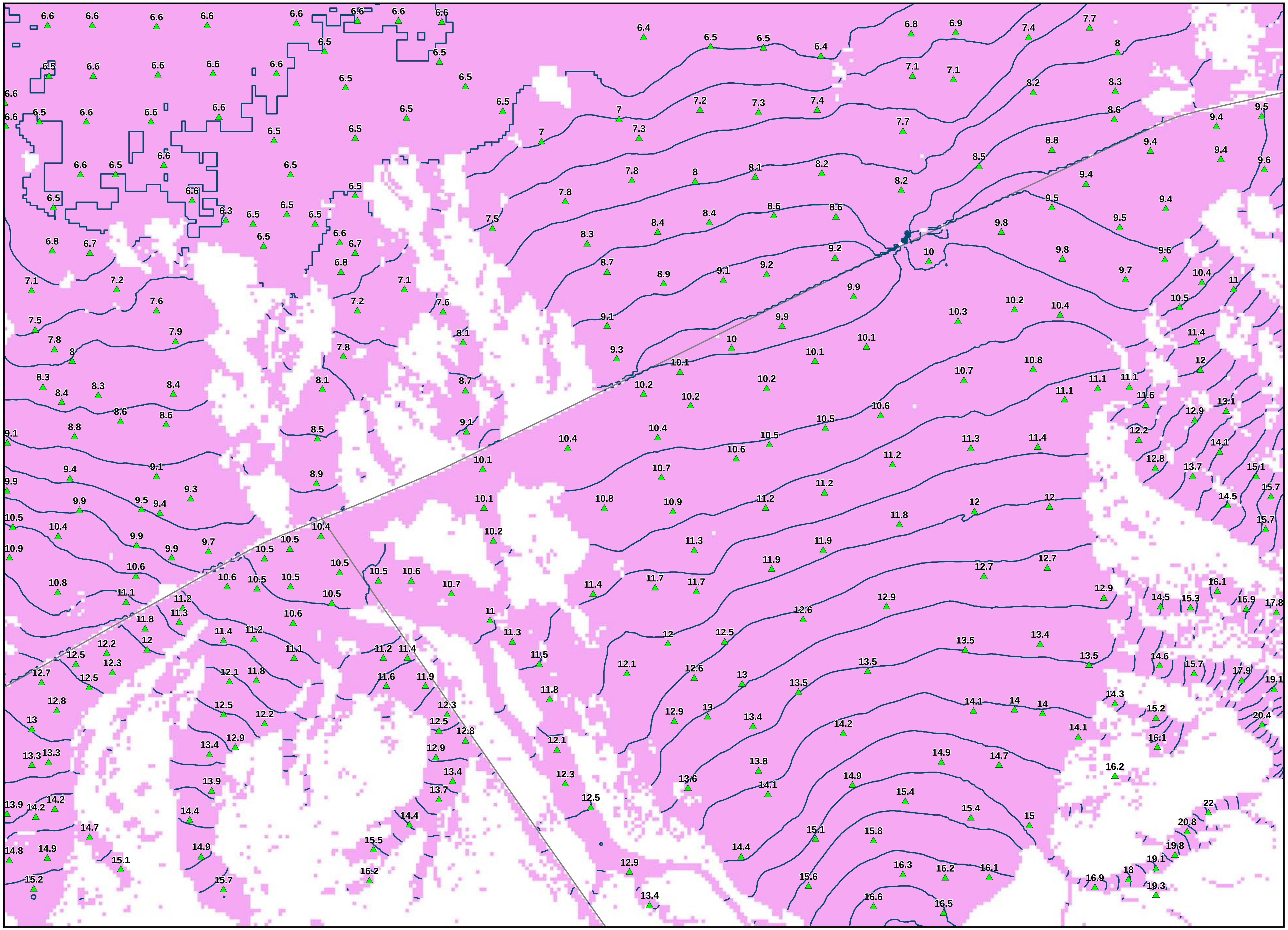
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure C4E: 200yr ARI Flood Elevation - 2060 Climate Scenario - Sheet E



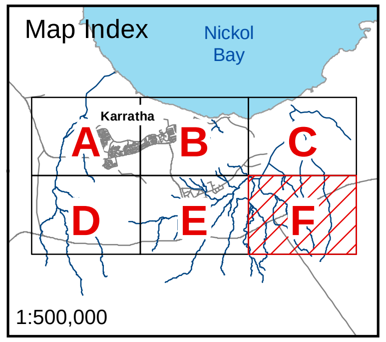
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

200yr Flood Extent

0.5m Contour (m AHD)

Cadastre



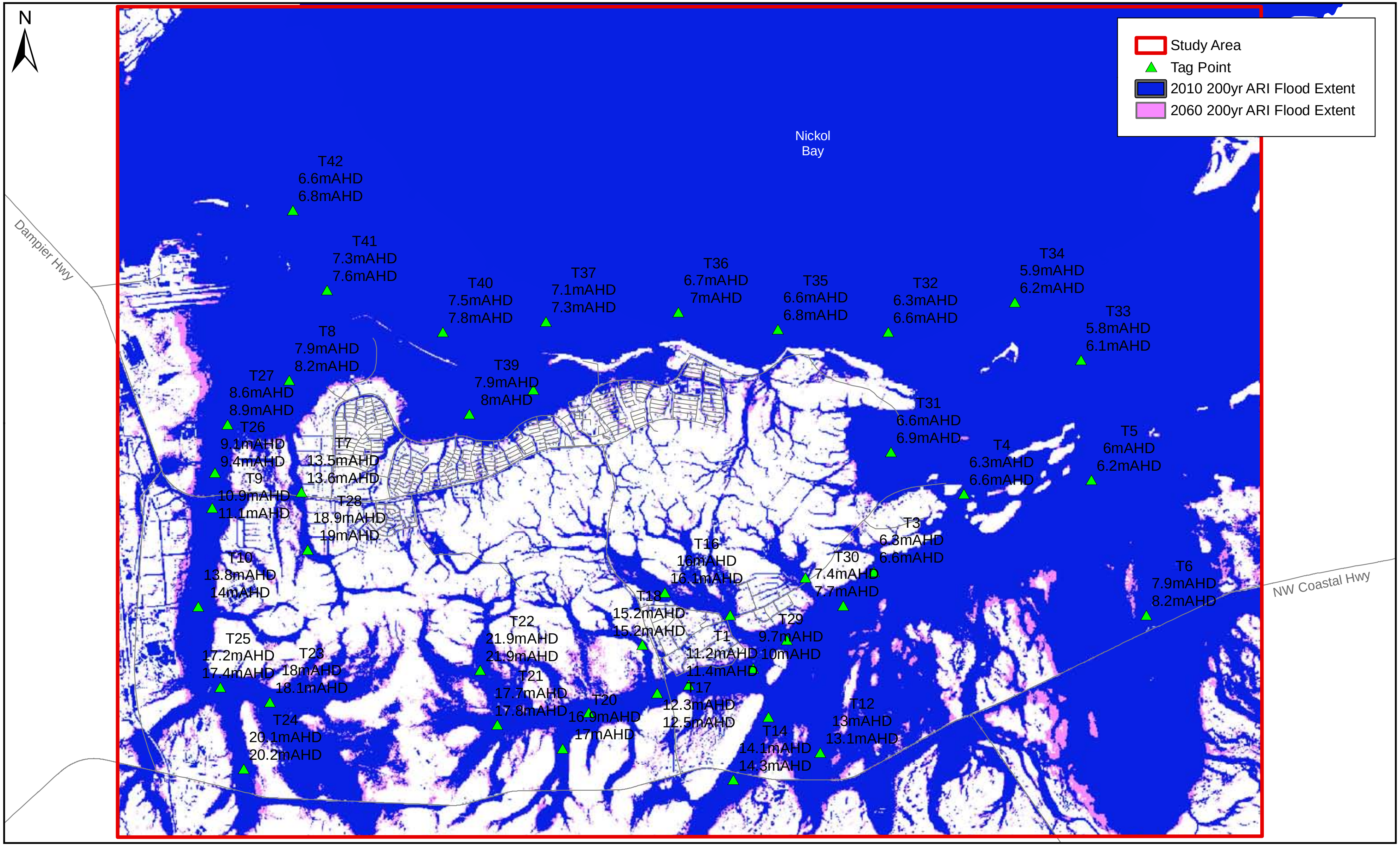
Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure C4F: 200yr ARI Flood Elevation - 2060 Climate Scenario - Sheet F



Data Source: GEMS Modelling and JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

LandCorp

Karratha Coastal Vulnerability Study: Main Report

Figure C5 : Comparison of 200yr (2010) and 200yr (2060) Flood Extent

Data Source: GEMS Modelling and JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

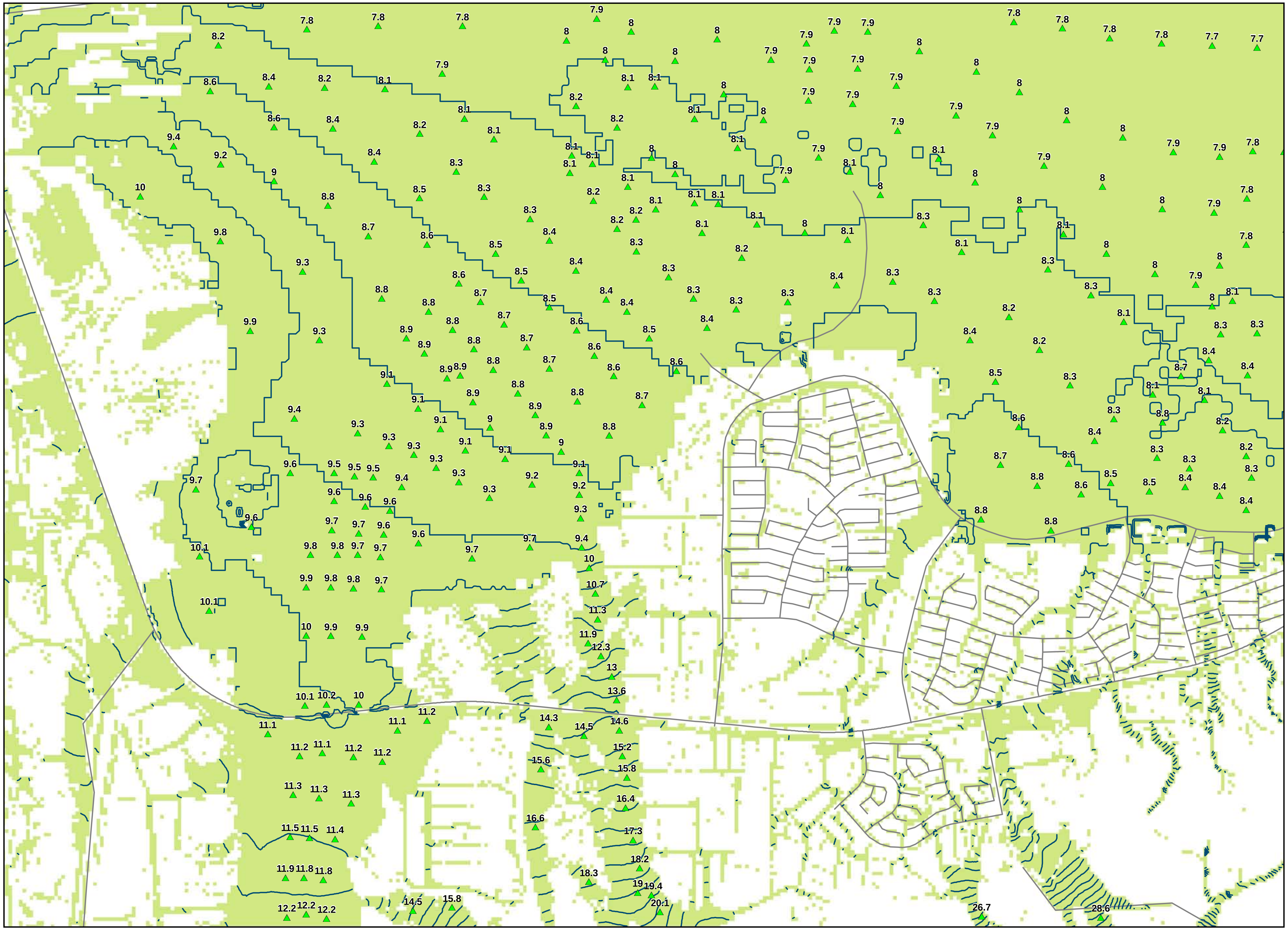
Job No. J4812

Scale:1:100,000

LandCorp

Karratha Coastal Vulnerability Study: Main Report

Figure C6: 200yr ARI Flood Depth - 2110 Climate Scenario



N

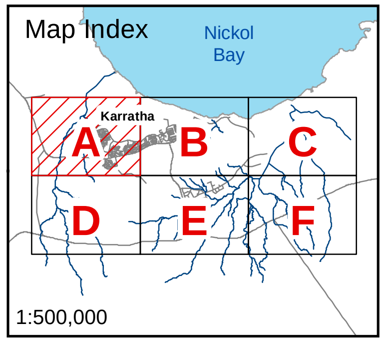
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

200yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812

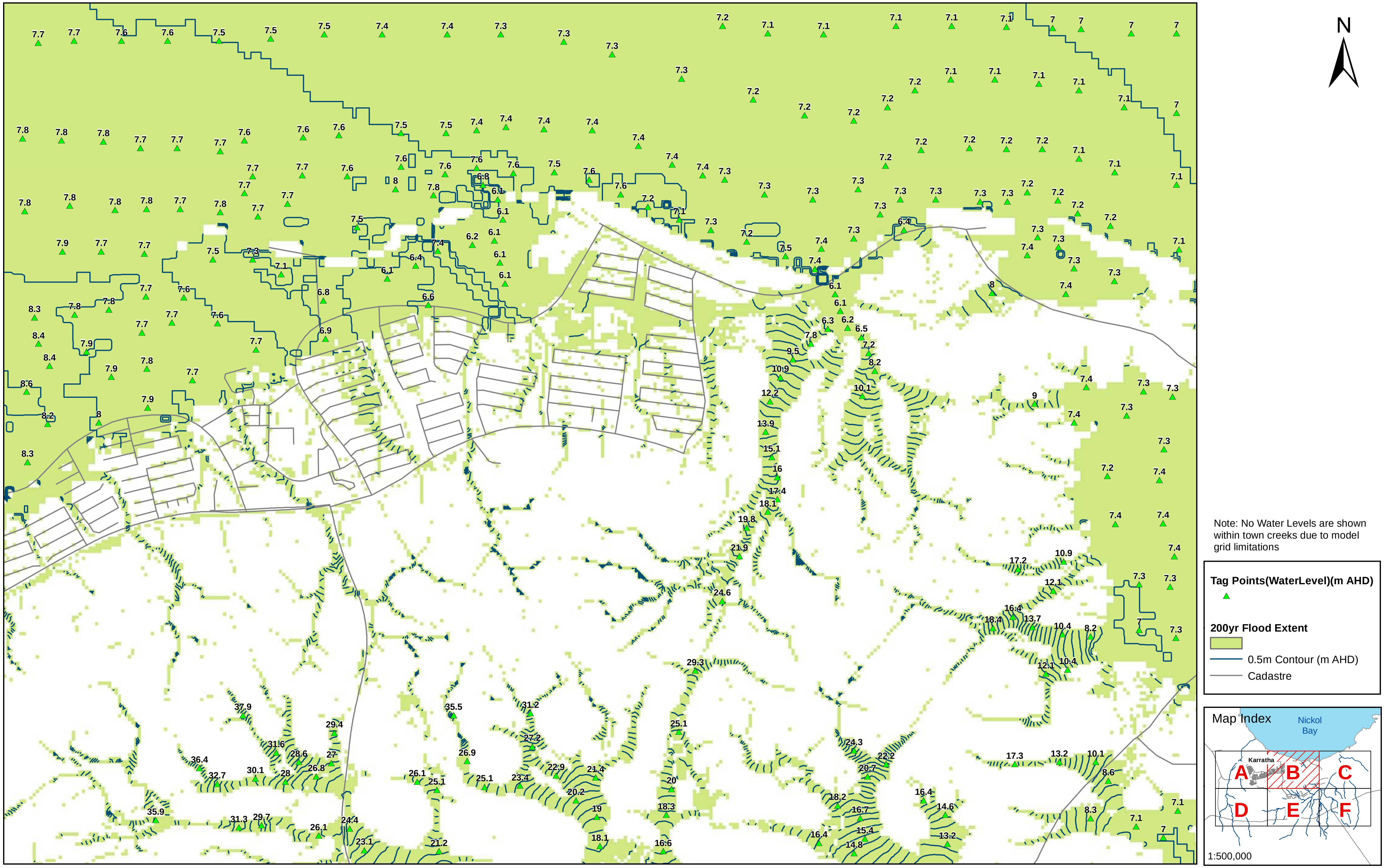
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

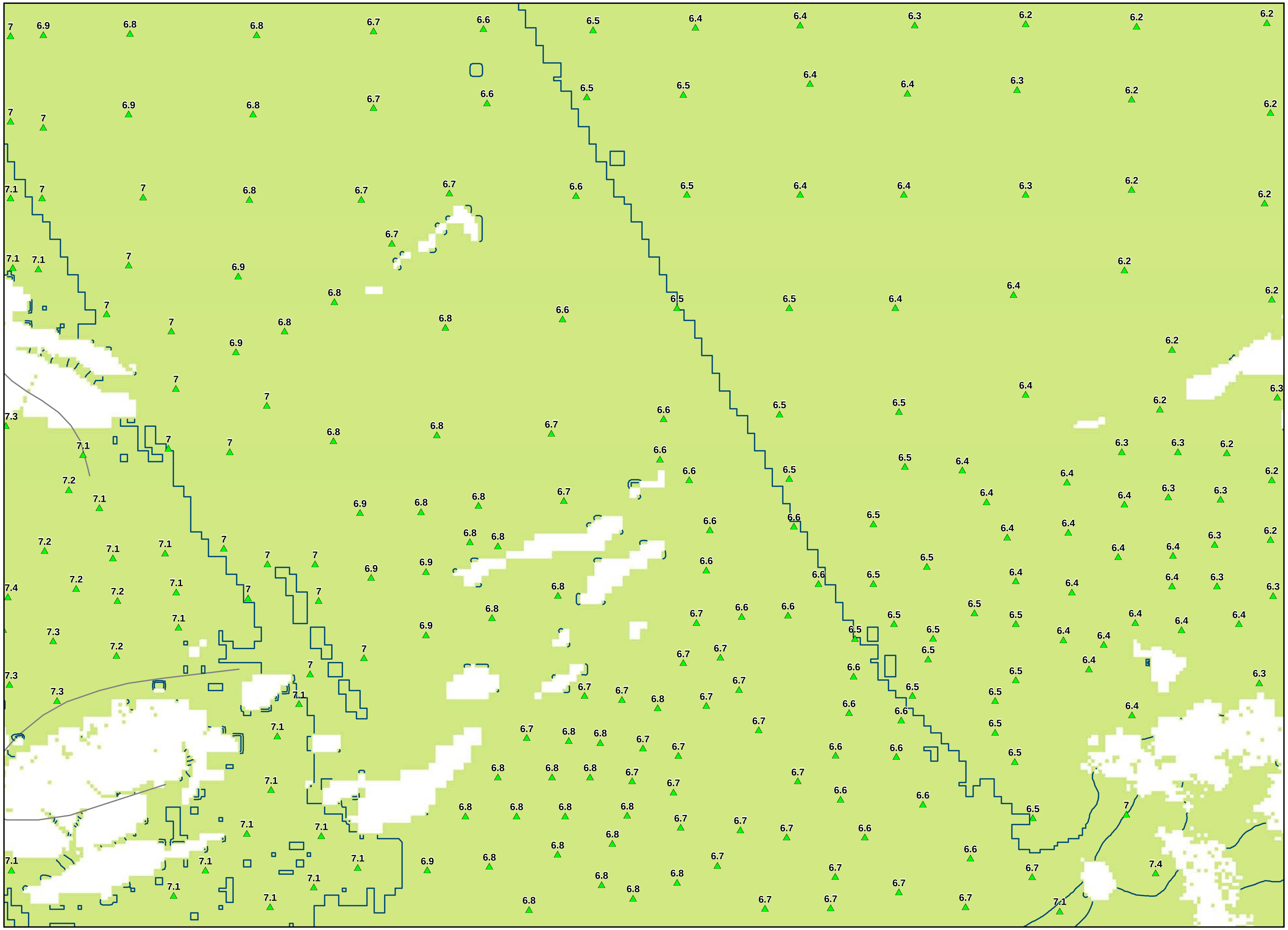
Figure C7A: 200yr ARI Flood Elevation - 2110 Climate Scenario - Sheet A



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure C7B: 200yr ARI Flood Elevation - 2110 Climate Scenario - Sheet B



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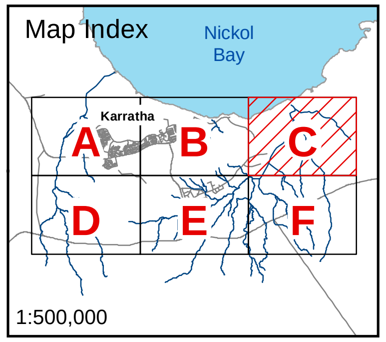
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

200yr Flood Extent

0.5m Contour (m AHD)

Cadastre



JDA

Job No. J4812

Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure C7C: 200yr ARI Flood Elevation - 2110 Climate Scenario - Sheet C

N

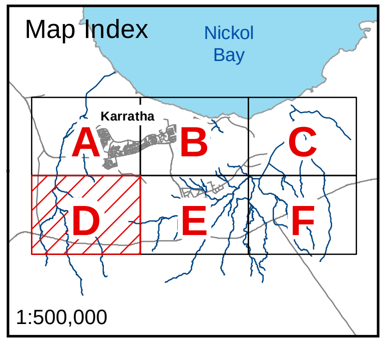
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

200yr Flood Extent

0.5m Contour (m AHD)

Cadastre



JDA

Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure C7D: 200yr ARI Flood Elevation - 2110 Climate Scenario - Sheet D

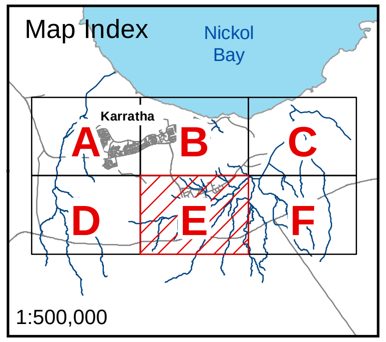
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

200yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812

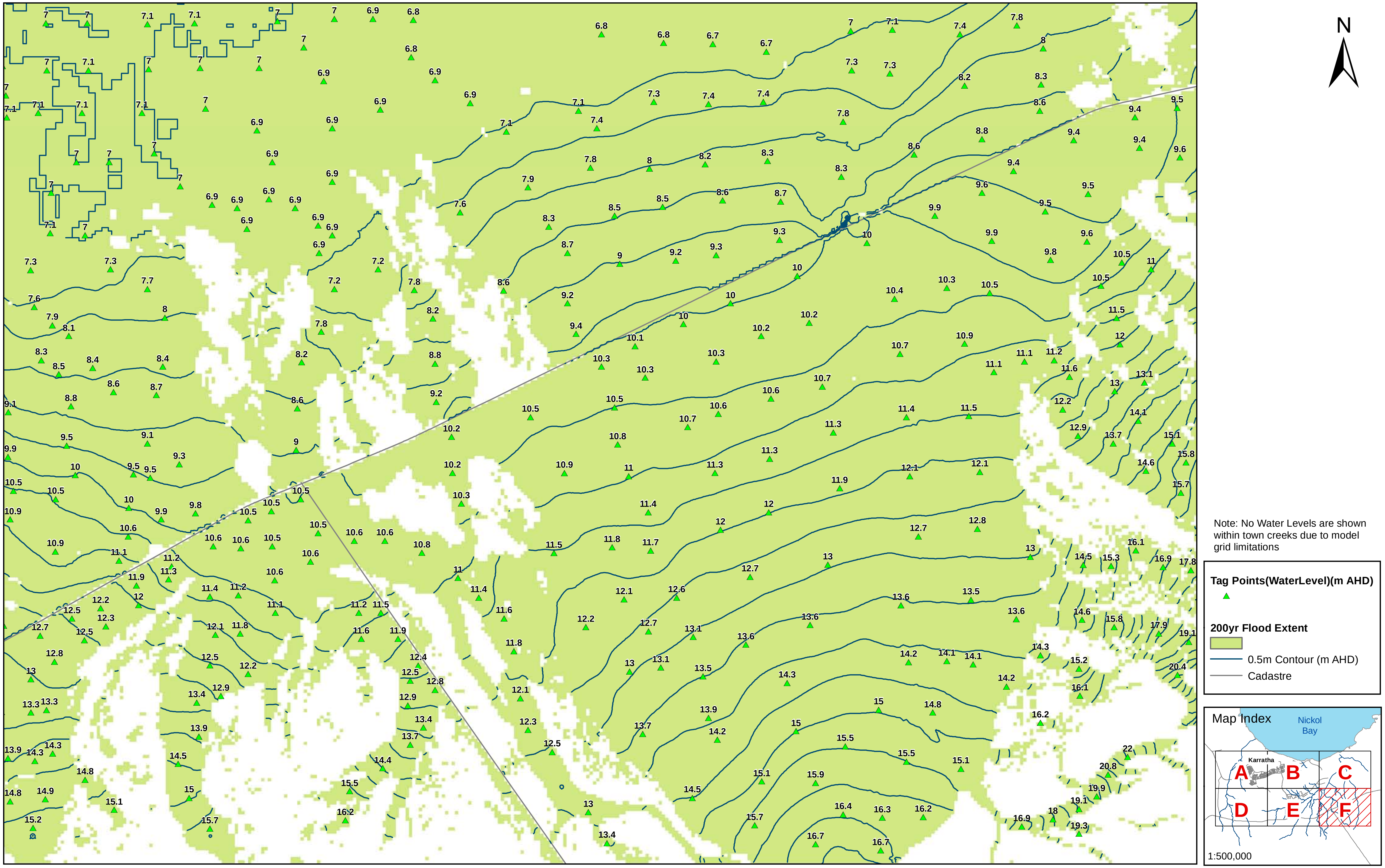
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

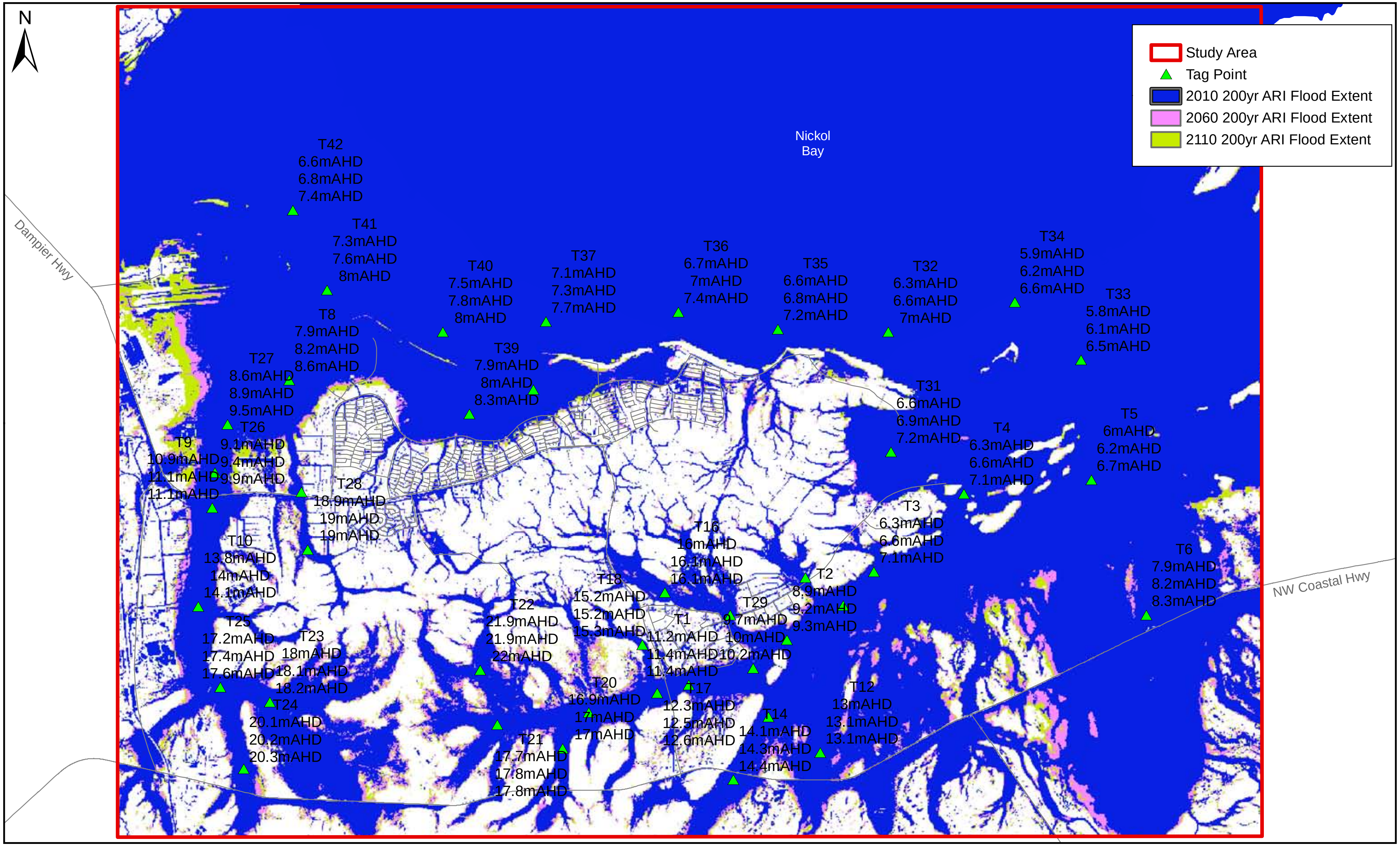
Figure C7E: 200yr ARI Flood Elevation - 2110 Climate Scenario - Sheet E



JDA

Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure C7F: 200yr ARI Flood Elevation - 2110 Climate Scenario - Sheet F



Data Source: GEMS Modelling and JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812
Scale:1:100,000

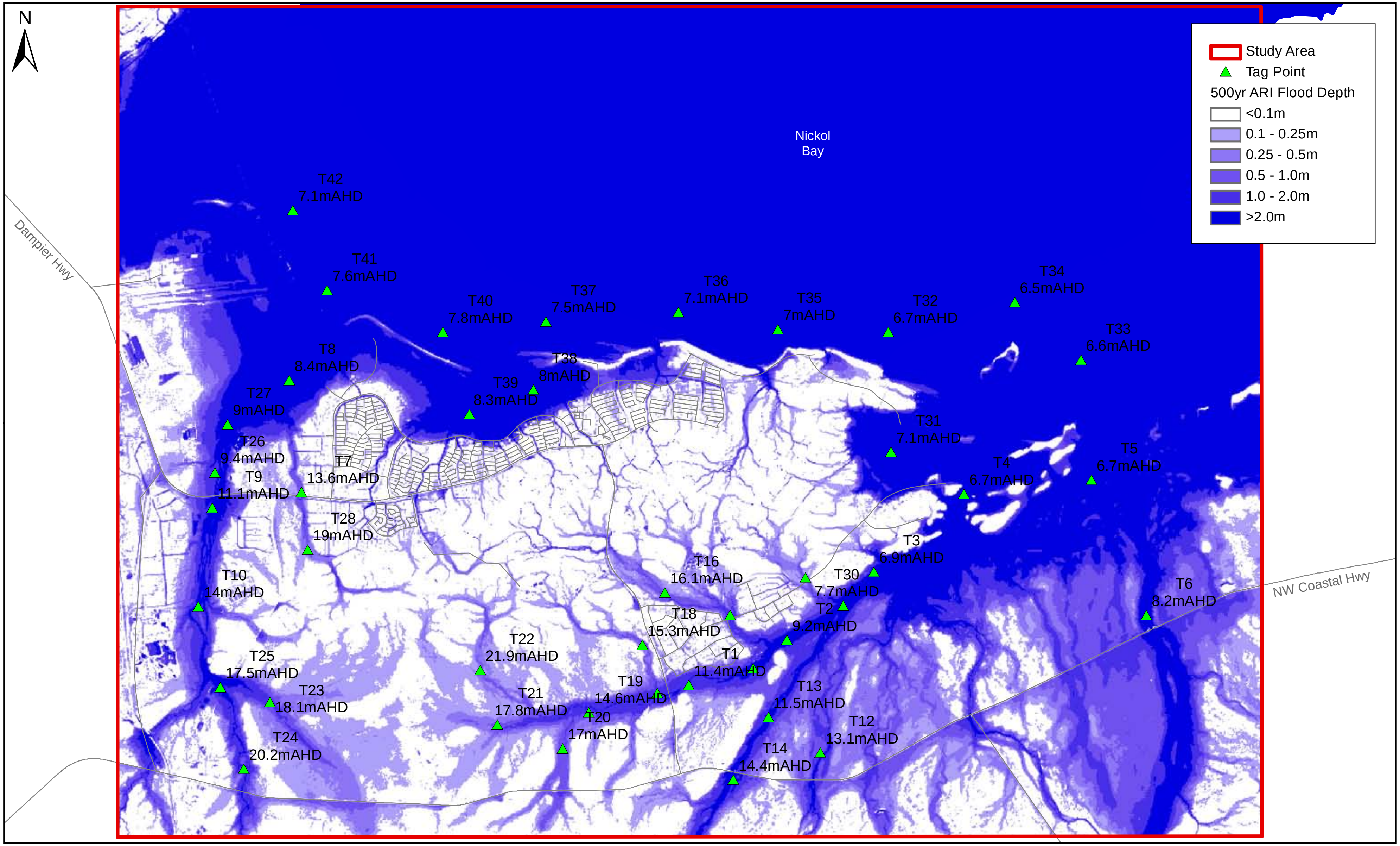
0 1.25 2.5 3.75 5 Kilometers

LandCorp
Karratha Coastal Vulnerability Study: Main Report

Figure C8 : Comparison of 200yr (2010), 200yr (2060) and 200yr (2110) Flood Extent

APPENDIX D

500yr ARI Flood Extent, Depth, Level and Flow Velocity for the 2010, 2060 & 2110 Climate Scenarios



Data Source: GEMS Modelling & JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

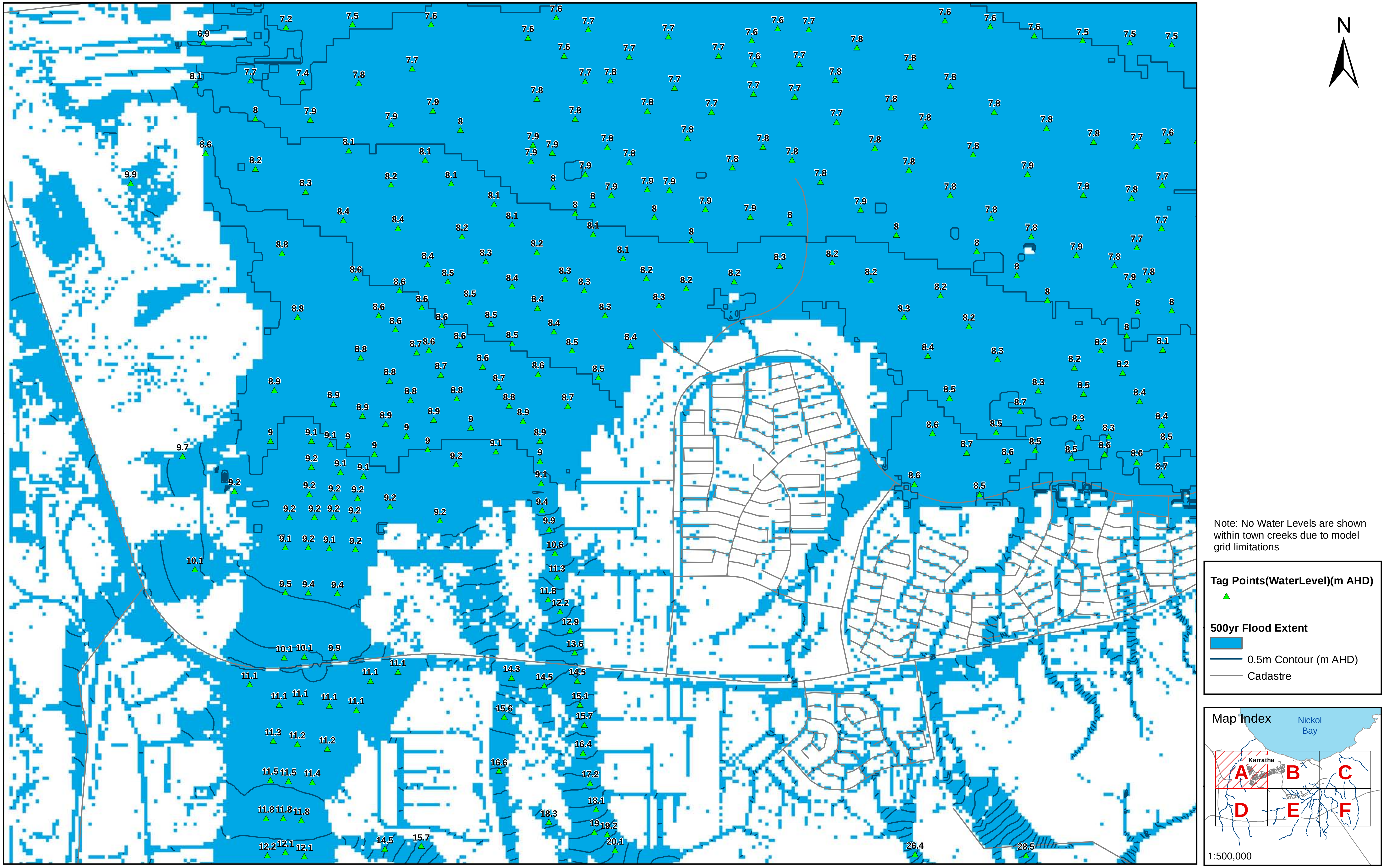
Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

LandCorp

Karratha Coastal Vulnerability Study: Main Report

Figure D1: 500yr ARI Flood Depth - 2010 Climate Scenario



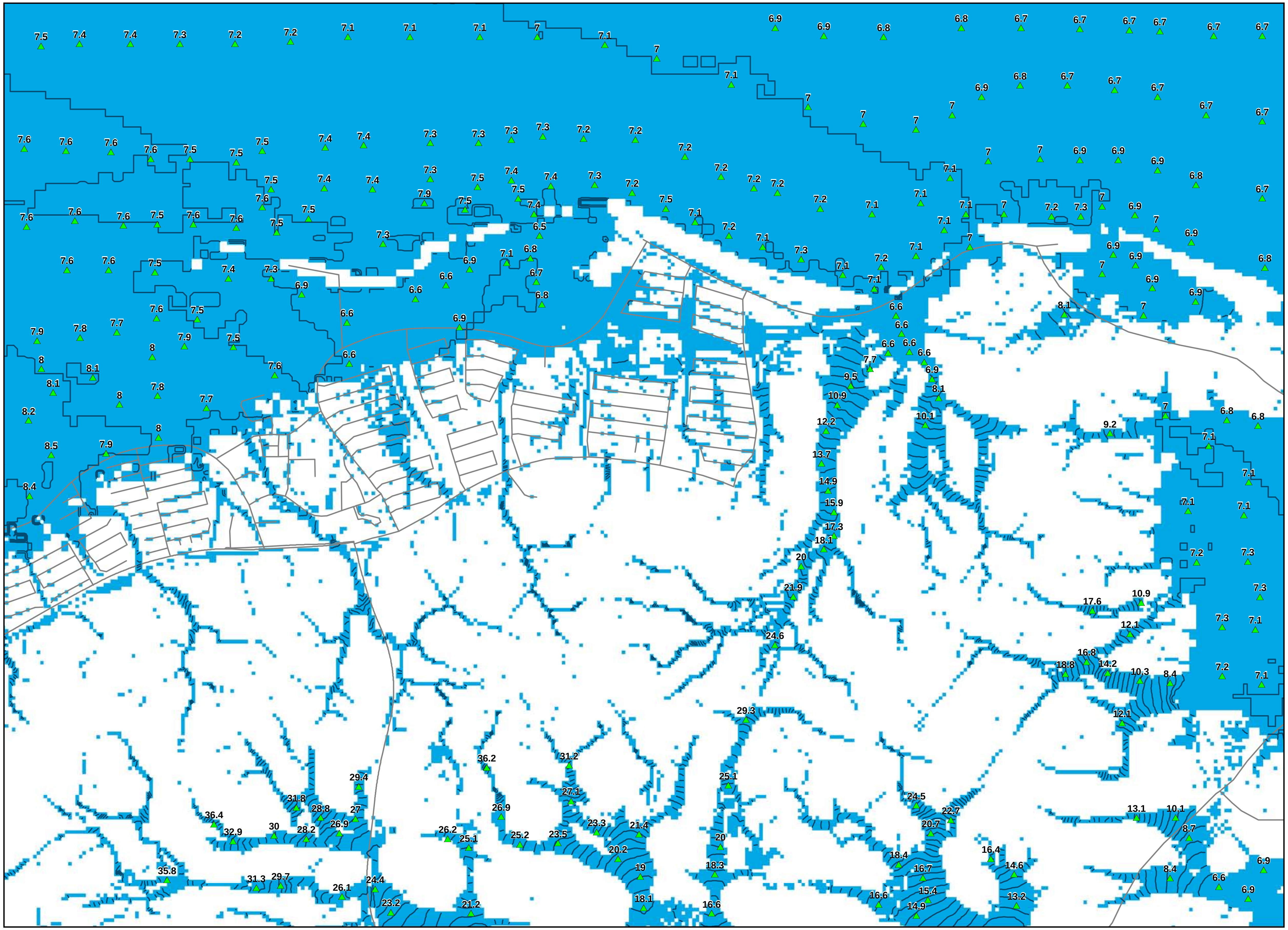
Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure D2A: 500yr ARI Flood Elevation - 2010 Climate Scenario - Sheet A



N

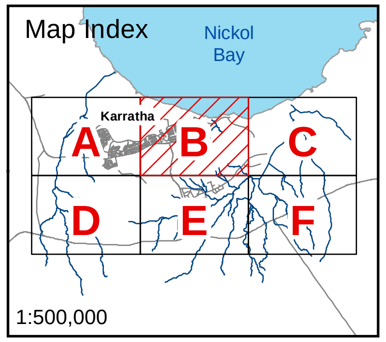
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

500yr Flood Extent

0.5m Contour (m AHD)

Cadastre

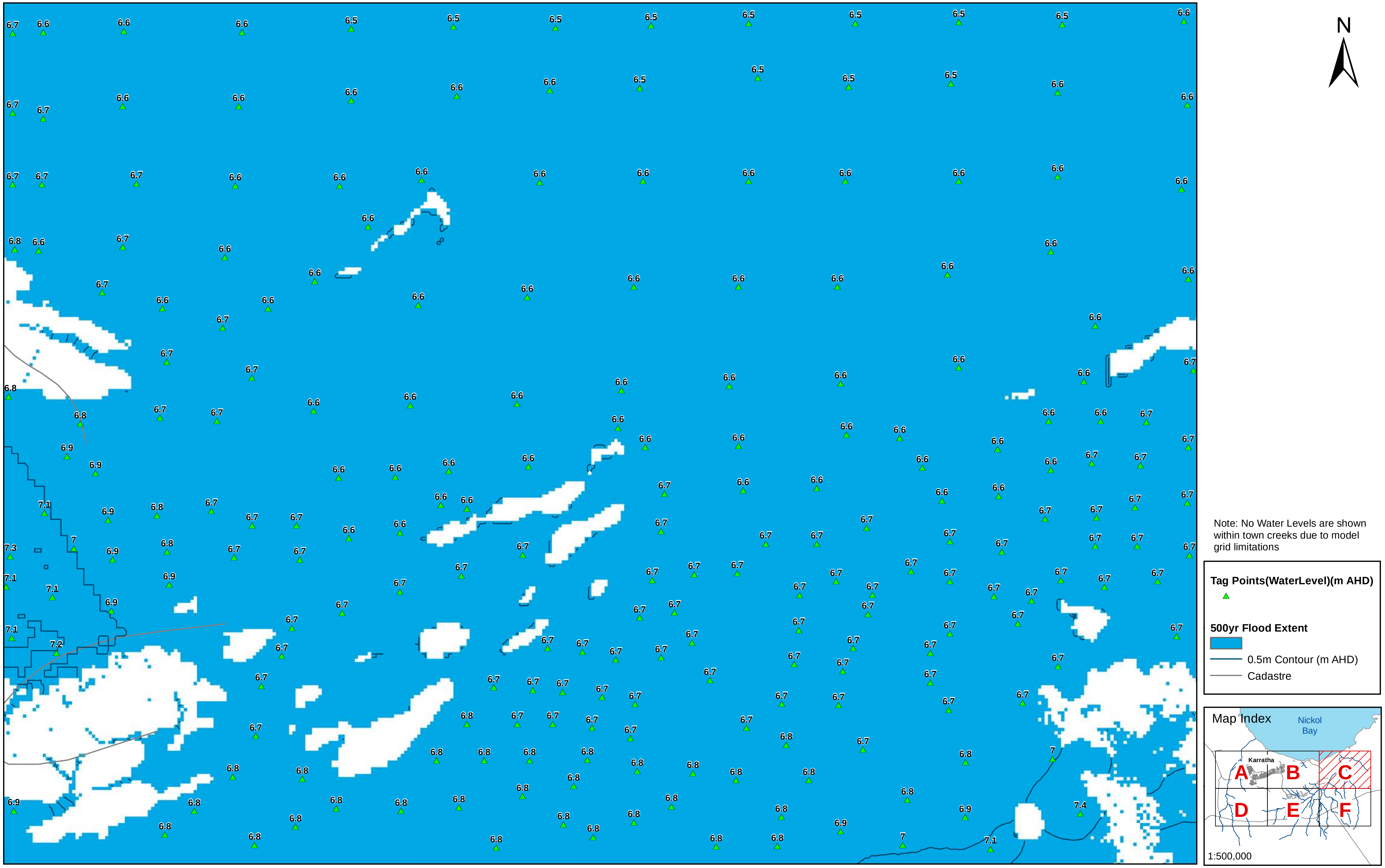


Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report

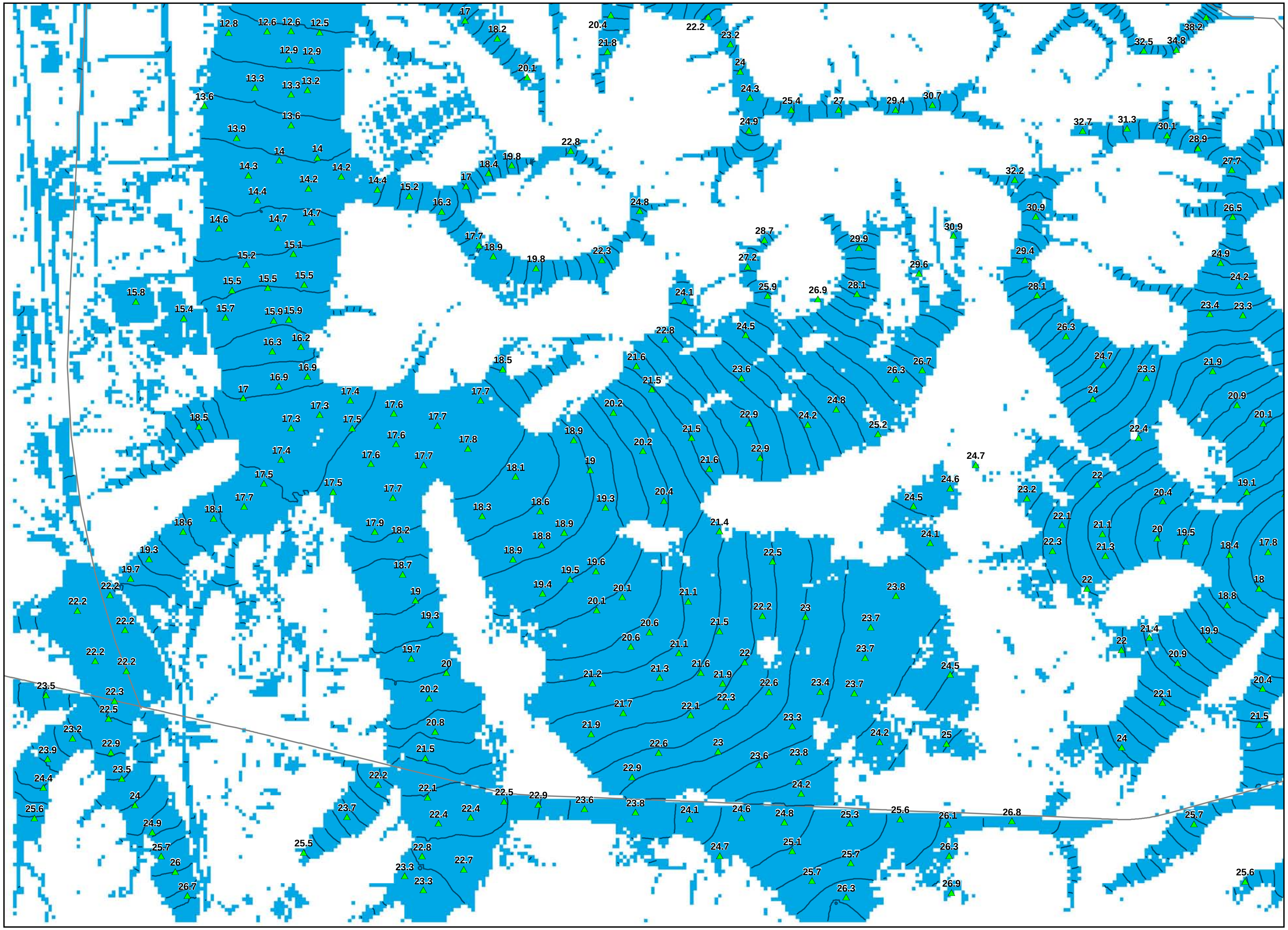
Figure D2B: 500yr ARI Flood Elevation - 2010 Climate Scenario - Sheet B



JDA

Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure D2C: 500yr ARI Flood Elevation - 2010 Climate Scenario - Sheet C



N

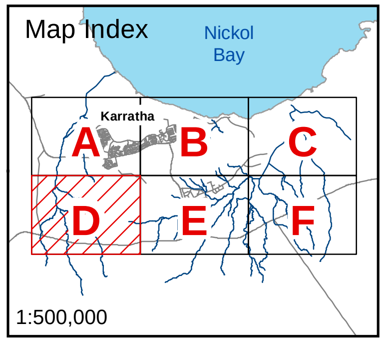
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

500yr Flood Extent

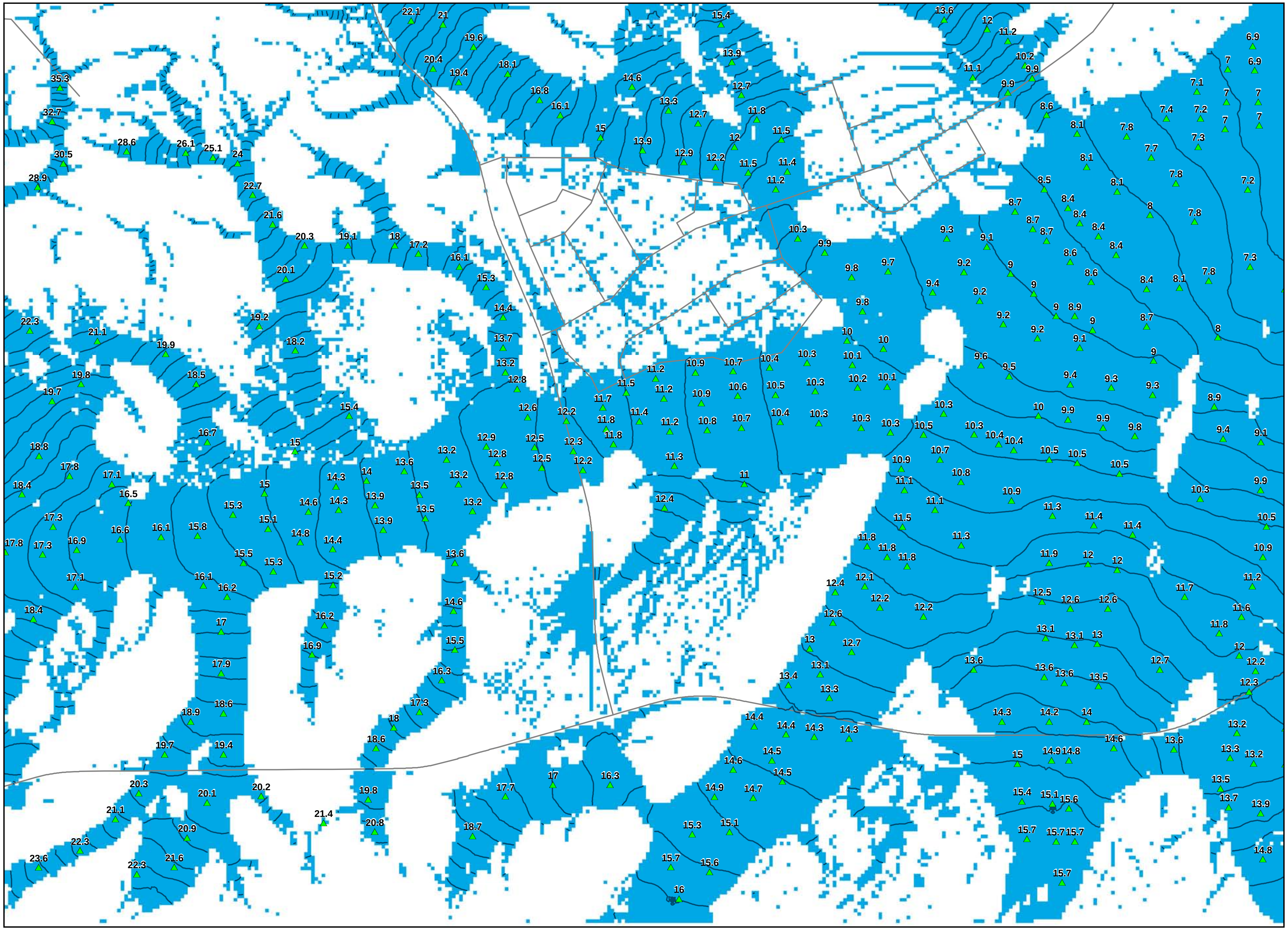
0.5m Contour (m AHD)

Cadastre



Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure D2D: 500yr ARI Flood Elevation - 2010 Climate Scenario - Sheet D



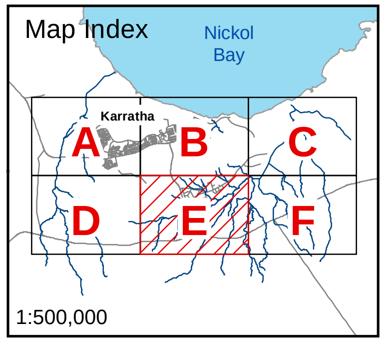
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

500yr Flood Extent

0.5m Contour (m AHD)

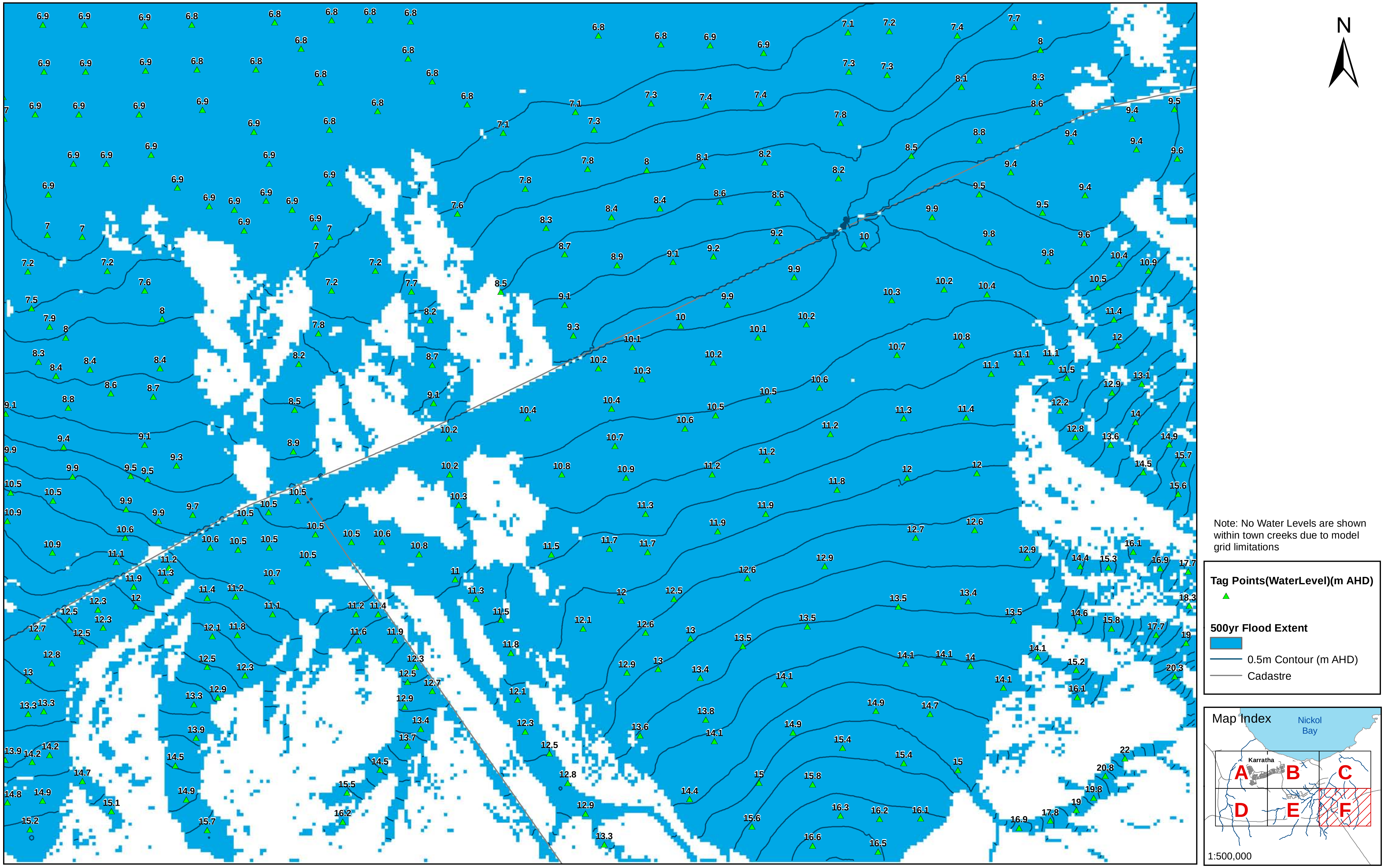
Cadastre



Job No. J4812
Scale:1:22,000

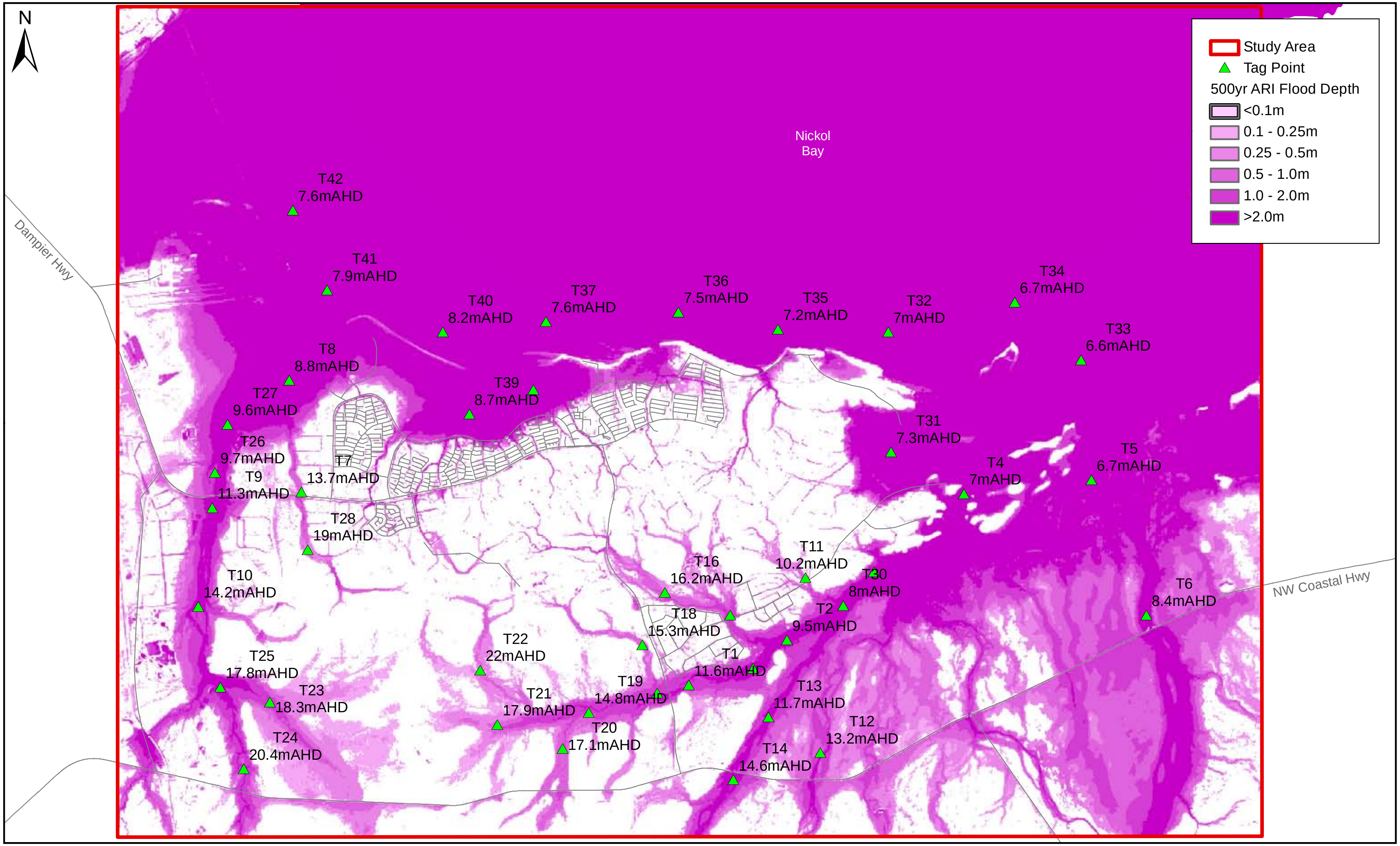
0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure D2E: 500yr ARI Flood Elevation - 2010 Climate Scenario - Sheet E



Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure D2F: 500yr ARI Flood Elevation - 2010 Climate Scenario - Sheet F



Data Source: GEMS Modelling & JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

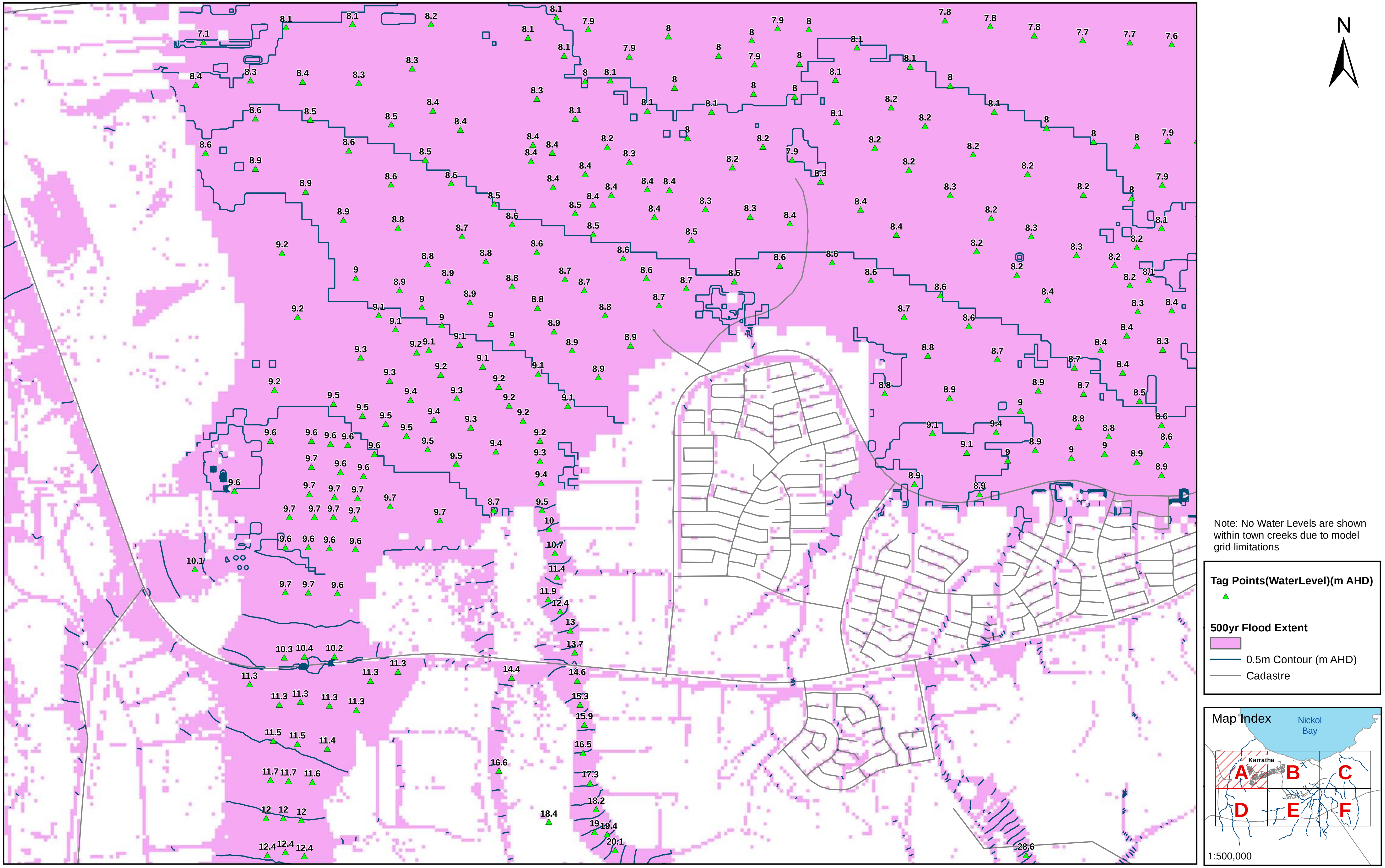
Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

LandCorp

Karratha Coastal Vulnerability Study: Main Report

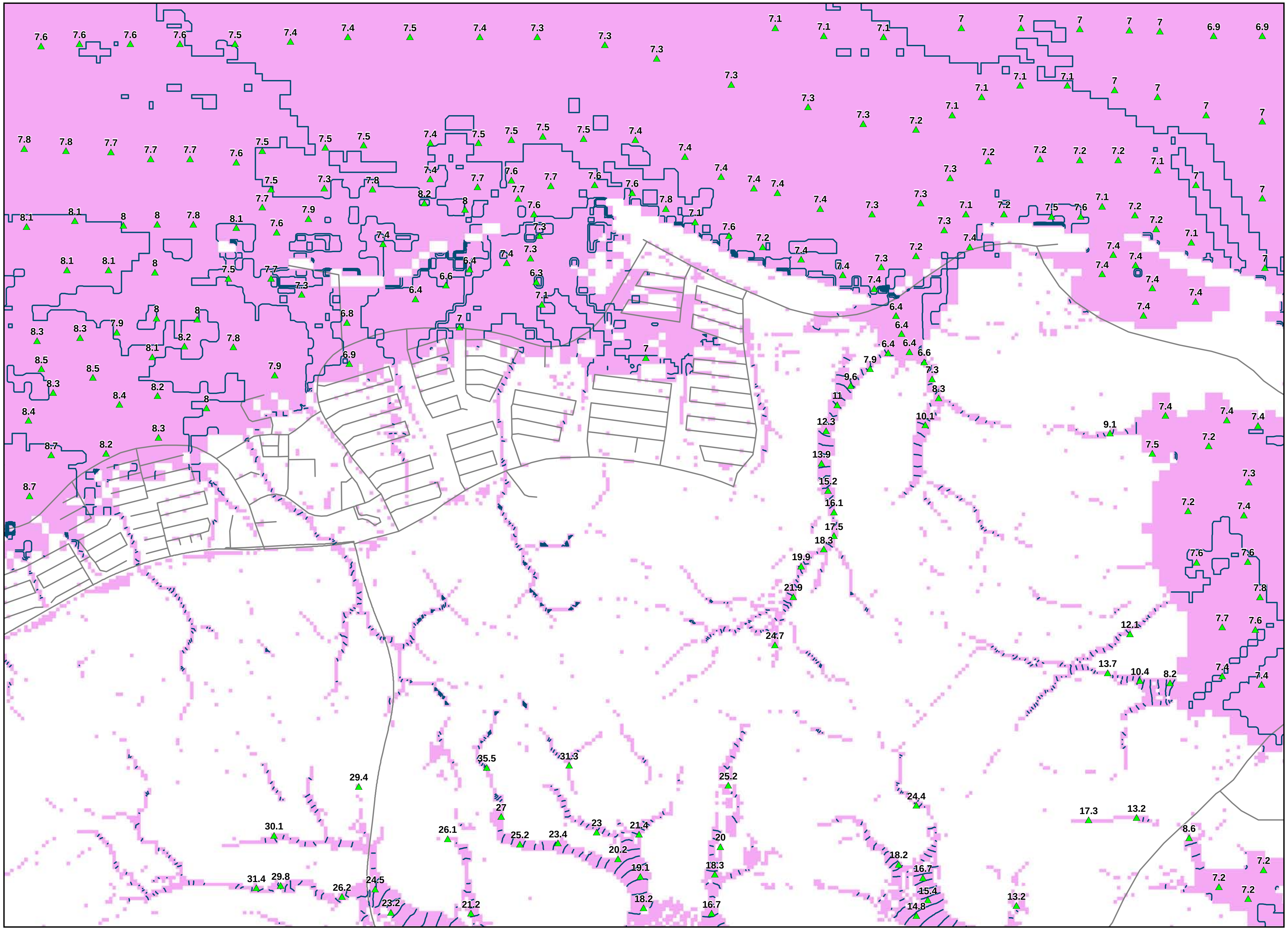
Figure D3: 500yr ARI Flood Depth - 2060 Climate Scenario



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure D4A: 500yr ARI Flood Elevation - 2060 Climate Scenario - Sheet A



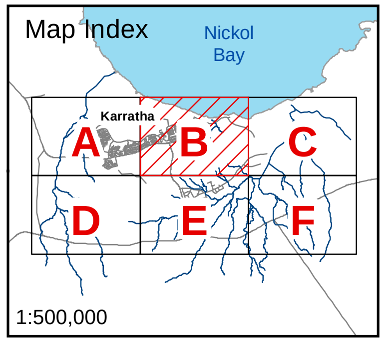
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

500yr Flood Extent

0.5m Contour (m AHD)

Cadastre



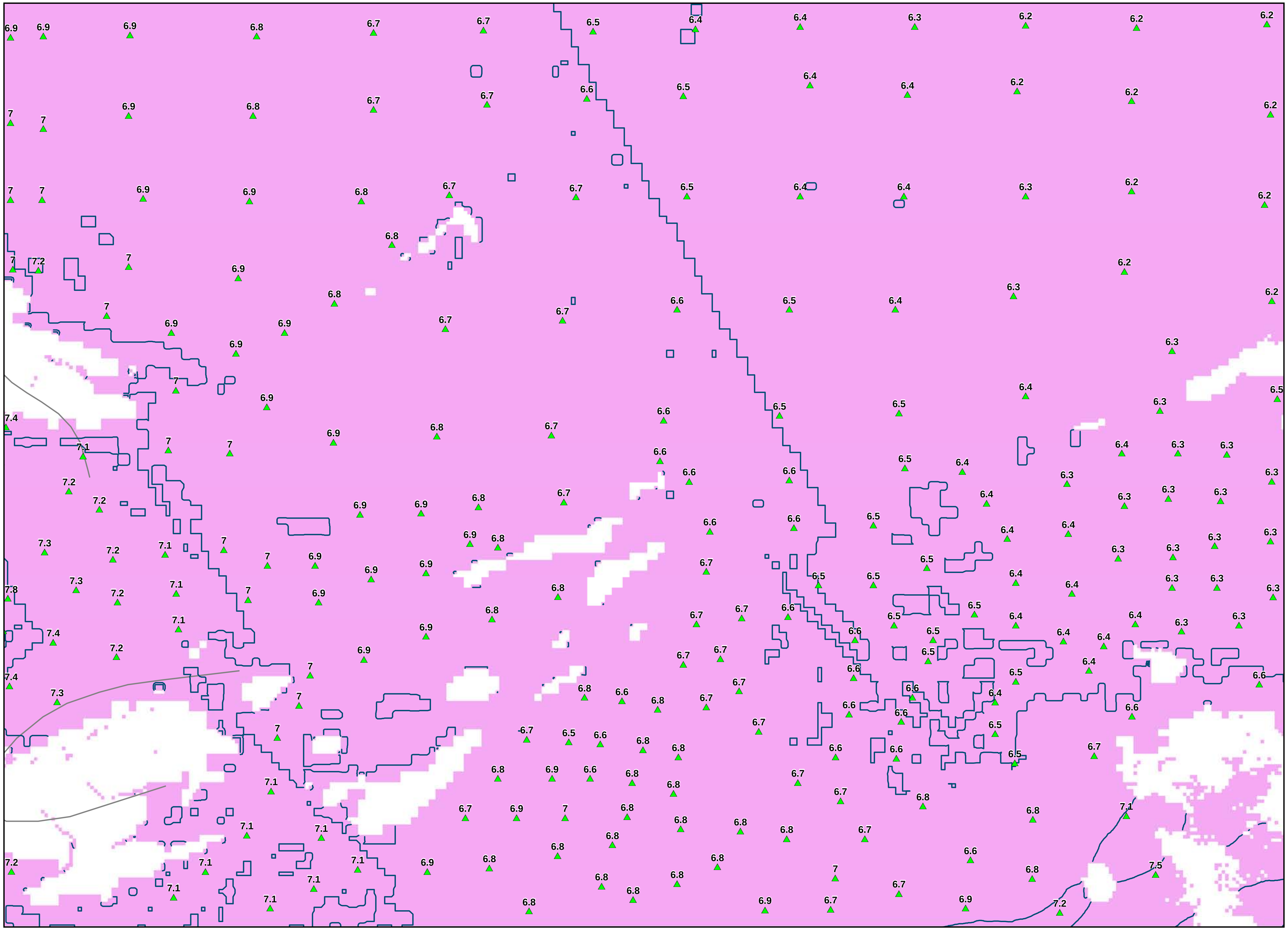
Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure D4B: 500yr ARI Flood Elevation - 2060 Climate Scenario - Sheet B



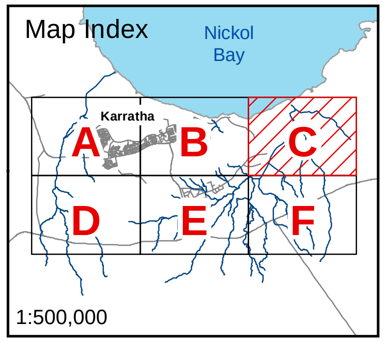
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

500yr Flood Extent

0.5m Contour (m AHD)

Cadastre



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

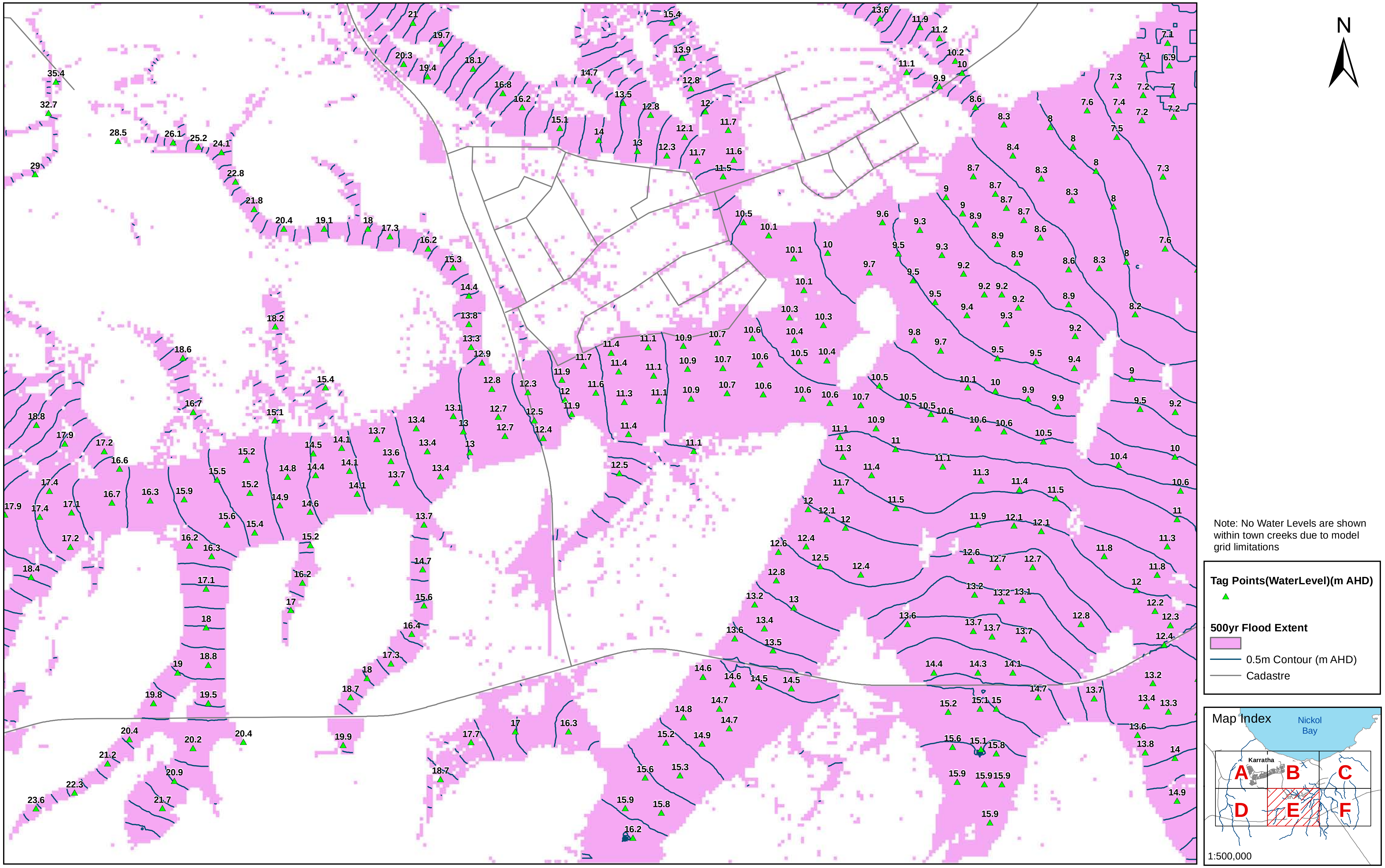
Karratha Coastal Vulnerability Study :Main Report

Figure D4C: 500yr ARI Flood Elevation - 2060 Climate Scenario - Sheet C

Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure D4D: 500yr ARI Flood Elevation - 2060 Climate Scenario - Sheet D



JDA

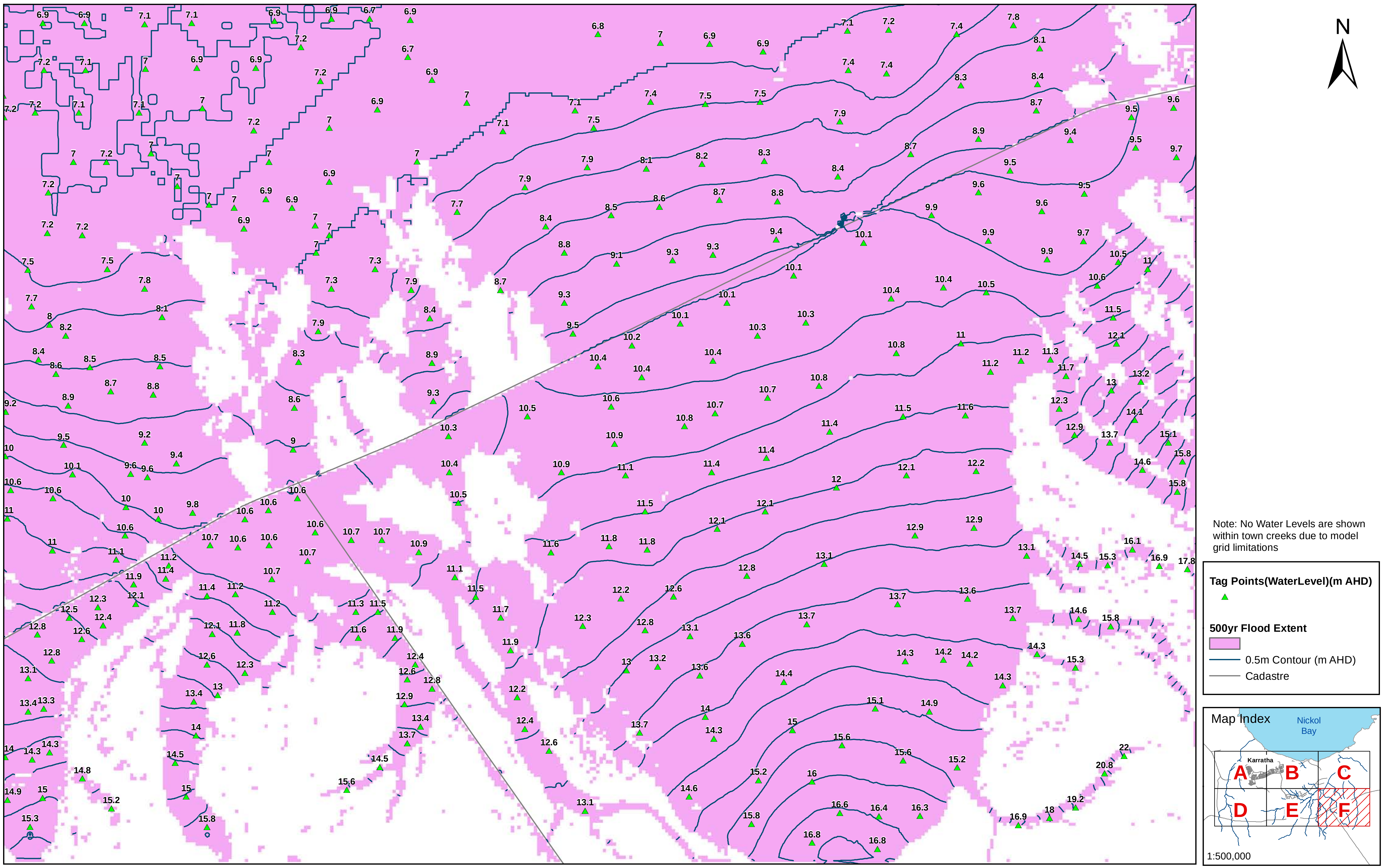
Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure D4E: 500yr ARI Flood Elevation - 2060 Climate Scenario - Sheet E



JDA

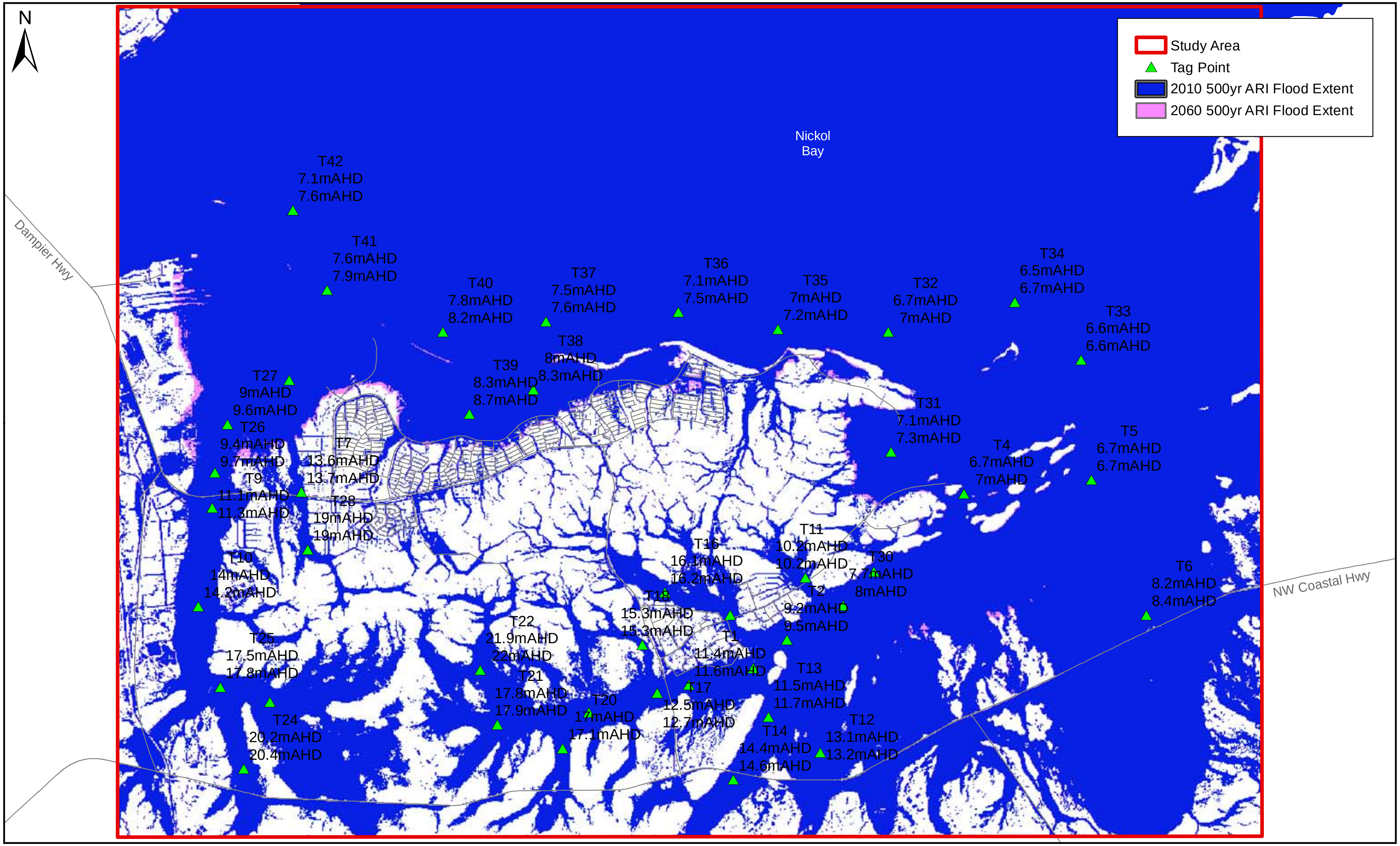
Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure D4F: 500yr ARI Flood Elevation - 2060 Climate Scenario - Sheet F



Data Source: GEMS Modelling and JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

LandCorp

Karratha Coastal Vulnerability Study: Main Report

Figure D5 : Comparison of 500yr (2010) and 500yr (2060) Flood Extent

Data Source: GEMS Modelling and JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

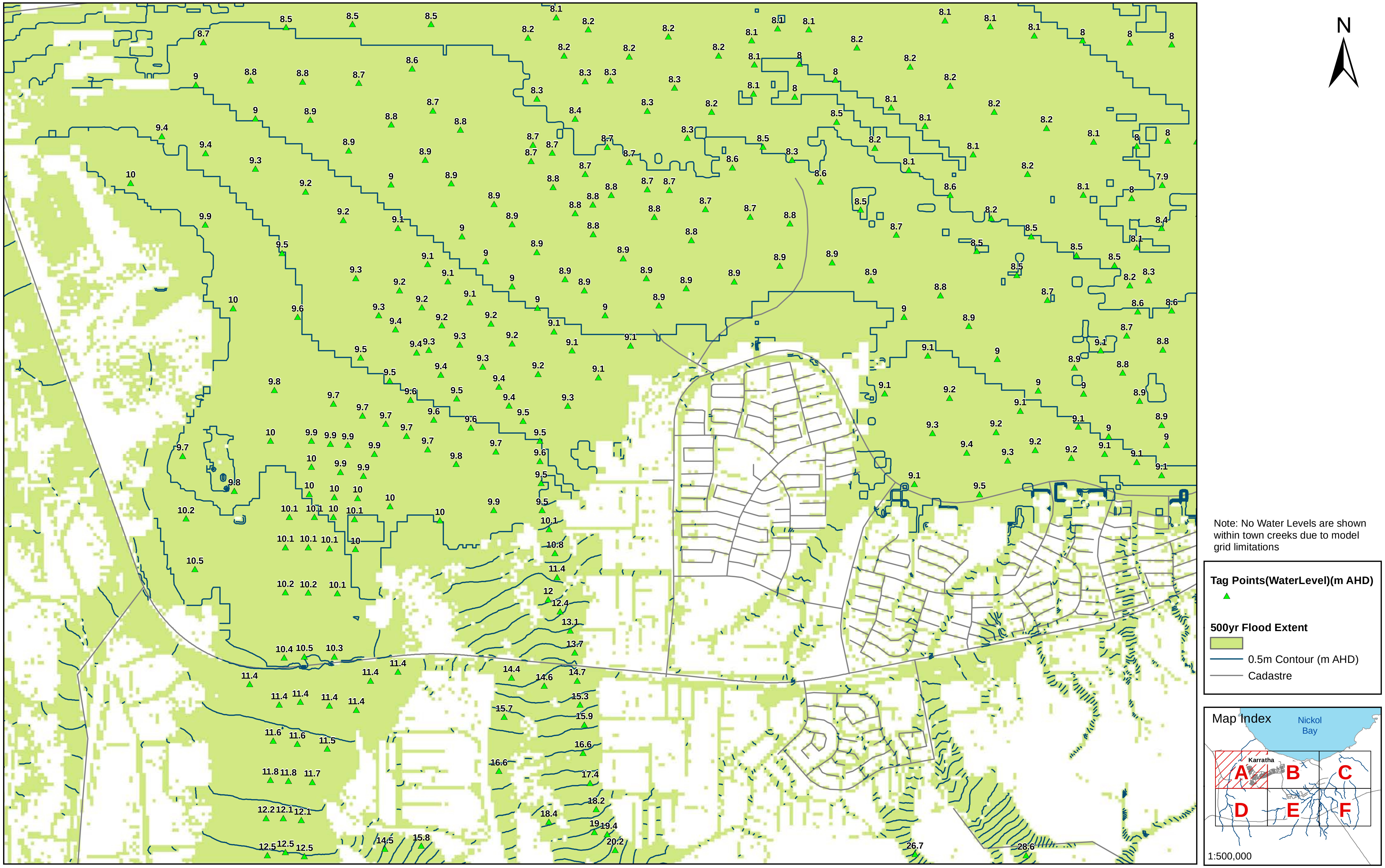
Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

LandCorp

Karratha Coastal Vulnerability Study: Main Report

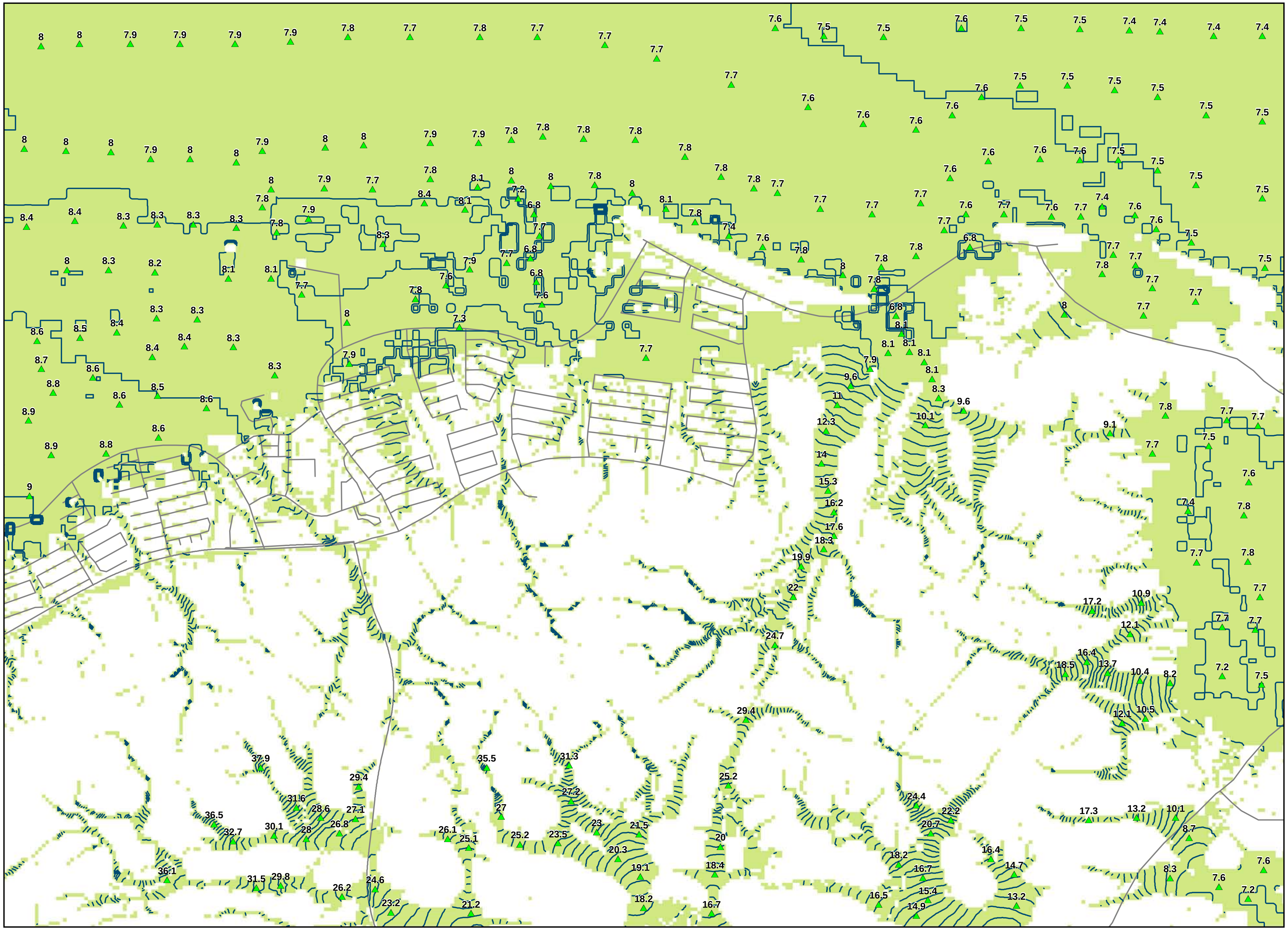
Figure D6: 500yr ARI Flood Depth - 2110 Climate Scenario



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure D7A: 500yr ARI Flood Elevation - 2110 Climate Scenario - Sheet A



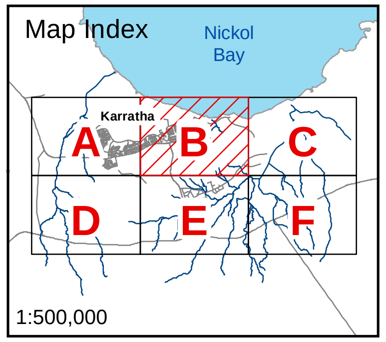
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

500yr Flood Extent

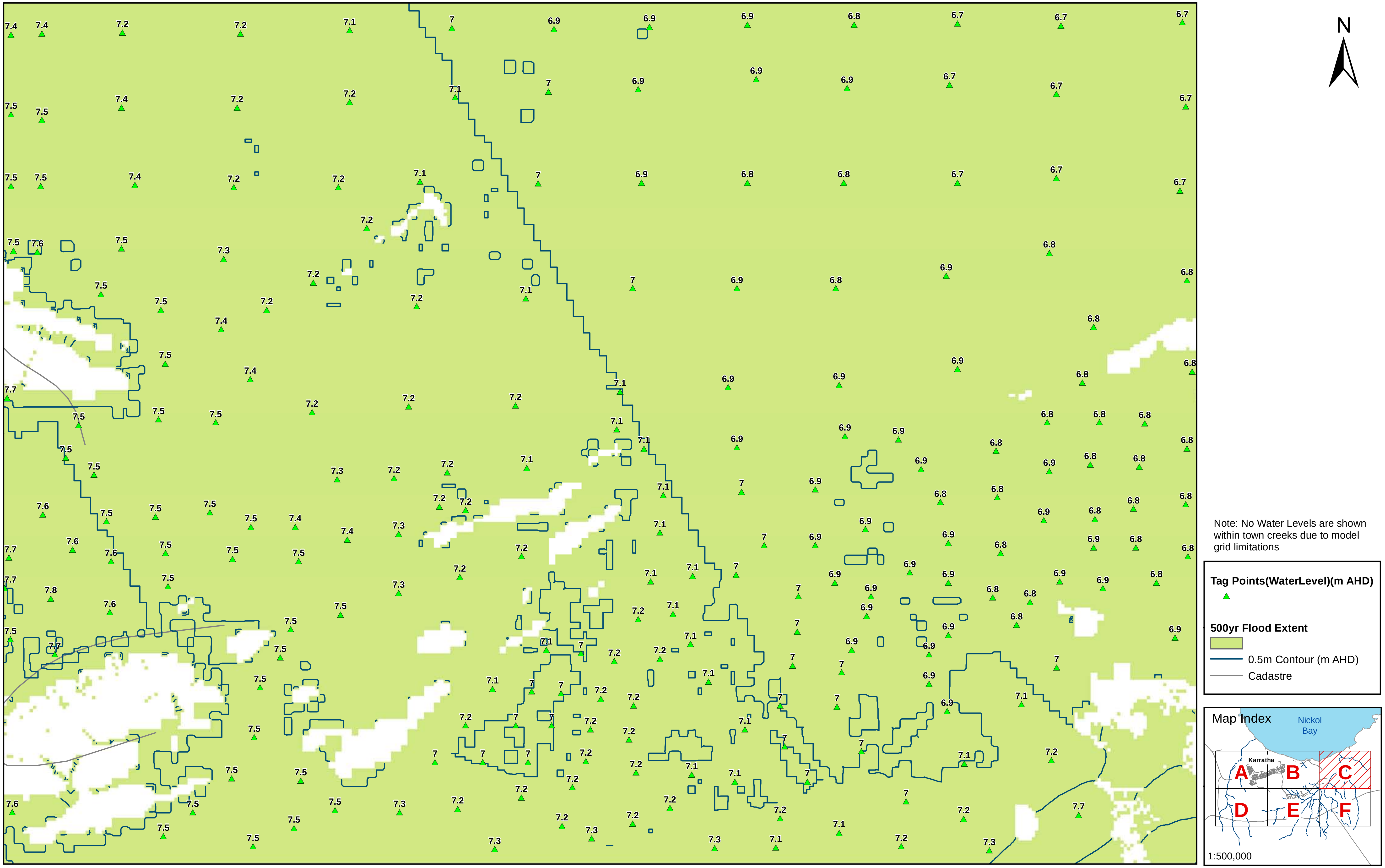
0.5m Contour (m AHD)

Cadastre



Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure D7B: 500yr ARI Flood Elevation - 2110 Climate Scenario - Sheet B



Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure D7C: 500yr ARI Flood Elevation - 2110 Climate Scenario - Sheet C

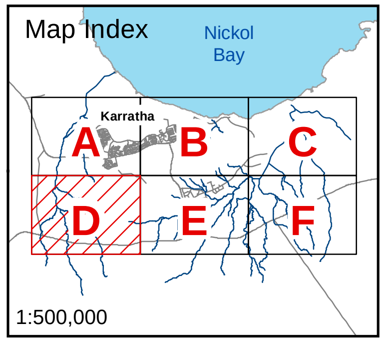
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

500yr Flood Extent

0.5m Contour (m AHD)

Cadastre



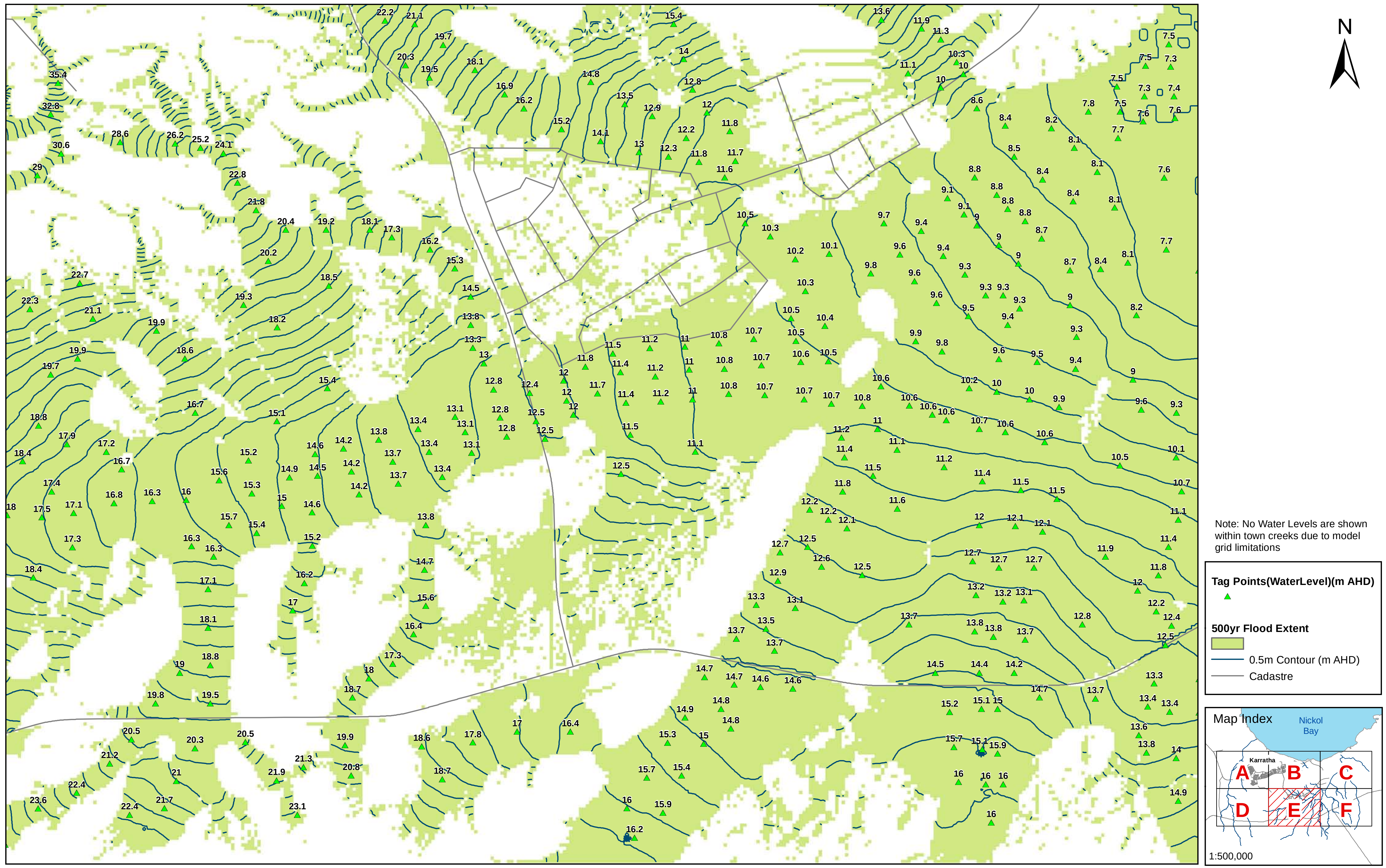
Job No. J4812
Scale:1:22,000

0 0.5 1 1.5 2 Kilometers

LandCorp

Karratha Coastal Vulnerability Study :Main Report

Figure D7D: 500yr ARI Flood Elevation - 2110 Climate Scenario - Sheet D



Job No. J4812
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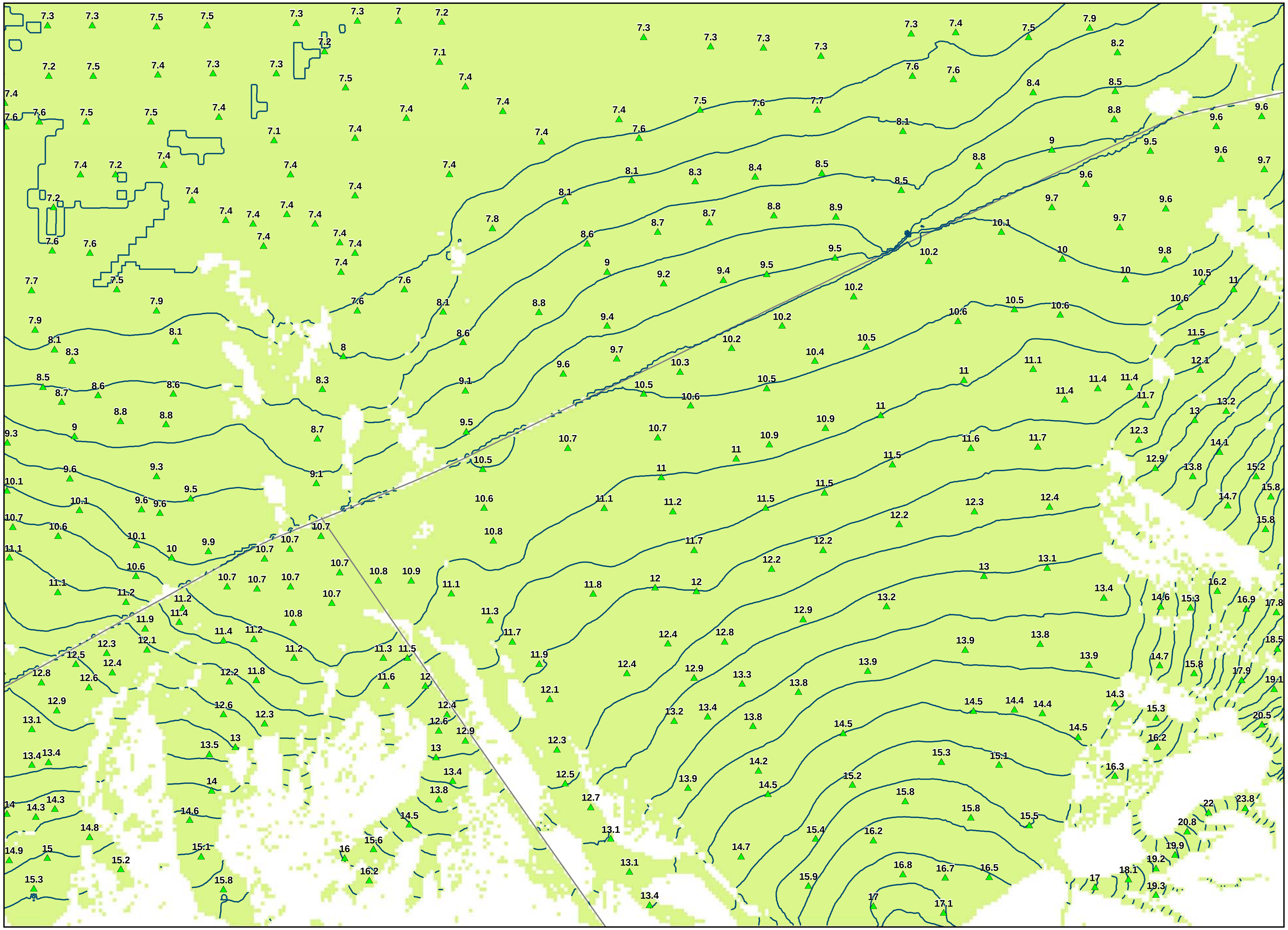
0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure D7E: 500yr ARI Flood Elevation - 2110 Climate Scenario - Sheet E



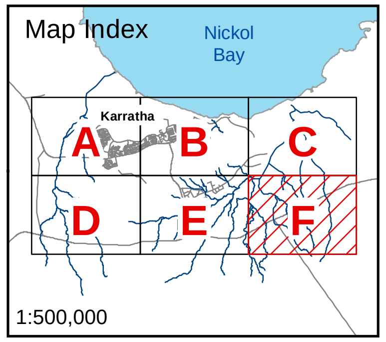
Note: No Water Levels are shown within town creeks due to model grid limitations

Tag Points(WaterLevel)(m AHD)

500yr Flood Extent

0.5m Contour (m AHD)

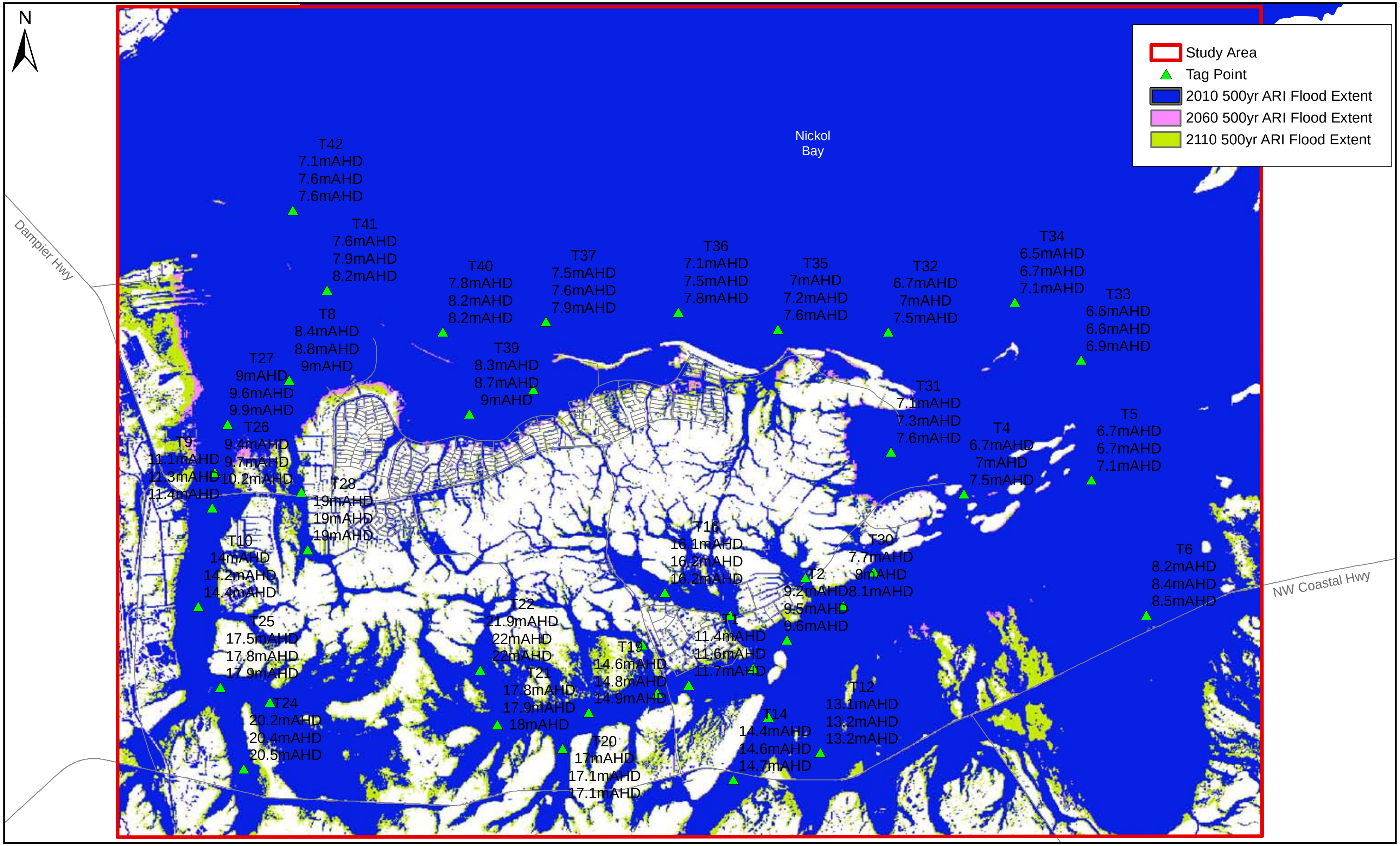
Cadastre



JDA

Job No. J4812
Scale:1:22,000
0 0.5 1 1.5 2 Kilometers

LandCorp
Karratha Coastal Vulnerability Study :Main Report
Figure D7F: 500yr ARI Flood Elevation - 2110 Climate Scenario - Sheet F



Data Source: GEMS Modelling and JDA Hydraulic Modelling 2011

JDA Consultant Hydrologists

Job No. J4812

Scale:1:100,000

0 1.25 2.5 3.75 5 Kilometers

LandCorp

Karratha Coastal Vulnerability Study: Main Report

Figure D8 : Comparison of 500yr (2010), 500yr (2060) and 500yr (2110) Flood Extent

APPENDIX E

Wave Run-Up for Karratha Townsite

Appendix E Wave Runup for Karratha Townsite

This technical note provides a summary of how wave runup may need to be considered for development within the Karratha area. Specifically, wave runup provides a small contribution to inundation across the existing floodplain, but is a significant factor for developments where inundation reaches retained fill.

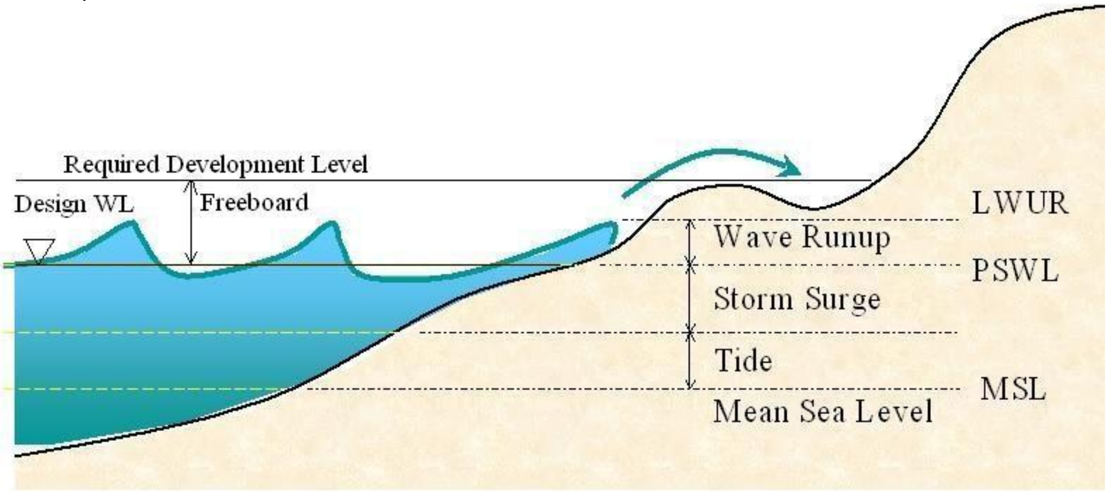


Figure 1: Coastal Inundation Terms

Wave runup is the upward vertical extent of water surface motion that can be attributed to waves, and therefore is identified as the maximum water-surface elevation above the still water level (Figure 1). The effect is brought about by the transfer of wave energy to potential energy (in the form of height) through the process of wave breaking at the shore. Runup is determined by incident wave conditions and the interaction of the waves with the coastal boundary. The latter dependence is significant for infrastructure planning, as selection of flood mitigation measures, such as a minimum floor level, will be affected by the associated shore treatment (e.g. beach or walling) and relative potential for exposure to wave action.

Methods for the calculation of wave runup are outlined in a range of coastal engineering texts[1,2,3,4,5], with general emphasis on calculations relevant to seawall design. The techniques describe a large number of parameters that influence wave runup, described schematically by Figure 2. These techniques are empirical in nature, generally based upon physical model testing. Initial descriptive analysis[6] undertaken was non-dimensionalised and described in terms of offshore wave conditions[7]. Further refinement of empirical relationships for beach run-up makes allowance for non-uniform waves[8]. Field observations suggest that this method may slightly exaggerate the run-up level.

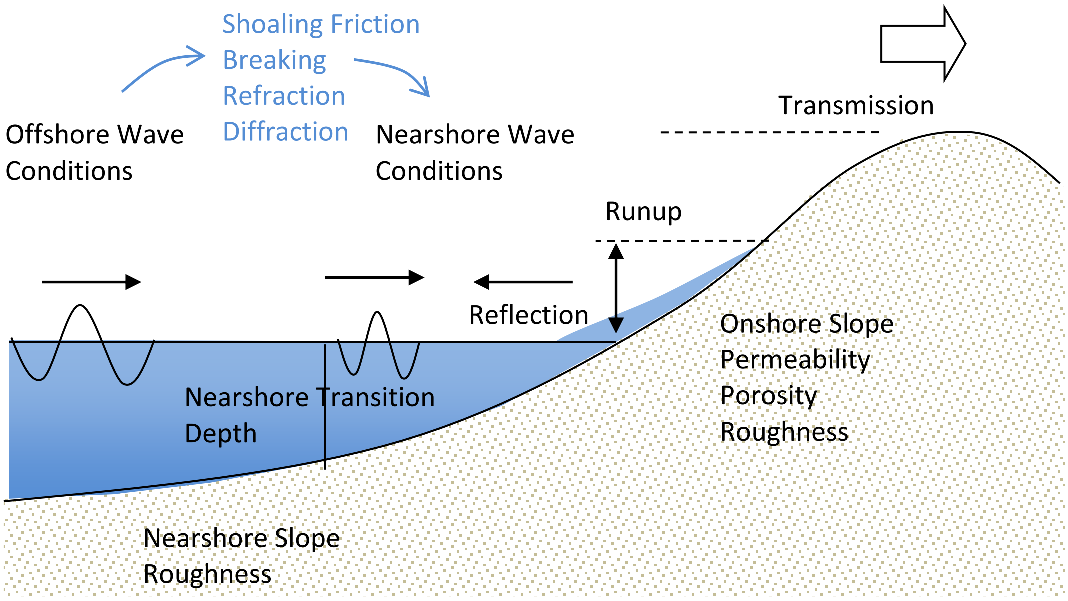


Figure 2: Factors Influencing Wave Runup

Of the factors affecting runup, the onshore and nearshore slope are the most significant, with the ratio of runup to wave height roughly proportional to the grade. This means runup is typically an order of magnitude less on a beach than on a coastal protection structure (Table 1). As a consequence, wave runup has much smaller influence upon gradually sloped sections of coast, such as occur at Karratha.

Table 1: Relative Influence of Structural Factors Affecting Runup
Ratios indicate range associated with each factor, highlighting significance of grade

Factor	Condition causing low runup	Relative Influence*	Condition causing high runup
Grade	Gently sloping beach	**1 - 10.0**	Typical revetment slope
Permeability	High permeability	1 - 1.6	Low permeability
Roughness	Rough surface	1 - 1.5	Smooth surface
Direction	Waves from side	1 - 1.4	Waves head-on
Depth	Shallow approach	1 - 1.3	Deep approach

* The relative influence indicates the difference between the R/Hs ratios as each factor varies. For example, the R/HS ratio for a gently sloping beach may be around 0.1, with the R/Hs for a revetment being around 1.0 under the same conditions. Therefore the relative influence of a steep grade may be in the order of 10x.

Runup is developed through the transfer of breaking wave energy to water elevation, and therefore is parameterised relative to the offshore wave height (Box 1). However, as a wave moves forward, it loses energy through other nearshore wave transformation processes, which do not contribute to elevation, including friction, turbulence, percolation, refraction and diffraction. Energy losses attributed to these processes need to be identified, such that runup can be estimated on the basis of *equivalent* offshore wave height, which decays as the wave progresses.

Box 1: Equation for Wave Runup

A general form for wave run-up is given by (USACE 2006)3:

$$\frac{R_{u\%}}{H_S} = \left(A\xi_o^B + C\right)\gamma_r\gamma_b\gamma_h\gamma_\beta$$

where A, B and C are coefficients determined by the slope structure, permeability and characteristic wave frequency

$R_{u\%}$ is the runup level exceeded by less than a nominated % of individual waves

H_S is significant wave height

$\xi_o = \tan\beta / (H_o/L_o)^{0.5}$ is the Irribarren number, indicating wave breaking type.

γ_r is a coefficient for roughness

γ_b is a coefficient for the presence of a berm on the slope

γ_h is a coefficient for wave distribution change due to shallow depths

γ_{β} is a coefficient for the angle of wave incidence

Frictional, turbulence and percolation losses vary significantly with water depth and the underlying surface, with an order of magnitude increase from 5m depth to 1m depth, or from the transition from muddy seabed through to flooding across sparsely vegetated low-relief land. Consequently, for overland flooding, the level of runup is strongly affected by the land immediately seaward of the still water level.

Along Karratha, coastal flooding cases considered by the KCVS are in the order of 6.0 to 9.0m AHD (peak steady water level) for 100 year to 500 year average recurrence intervals. Without structural modification, these levels correspond to the floodplain area located between Karratha townsite and the coastal dunes, with gradients in the range of 1 in 60 to 1 in 300. Waves approaching across the gradually sloping area are strongly damped by friction, with 80-90% loss, with a corresponding wave runup in the range of 0.1 to 0.3m. Further loss due to diffraction through the coastal dunes is likely to occur, although any destabilisation of the dunes may significantly increase transmitted wave energy and therefore increase wave runup.

The role of wave runup may be significantly enhanced if the existing structure is modified, particularly if earthworks are used to provide a higher fill level, abutting adjacent lower land (Figure 3). Runup is enhanced by increasing the steepness of the slope and by increasing the effective wave height at the structure. These effects should be assessed on a case-by-case basis, as the runup effect is determined by both the position and the nature of the retaining system. However, as an order of magnitude indication, runup associated with a typical revetment located 1.0m deeper than the peak steady water level may be 2.0-3.0m. Runup of nearly four times the incident wave height is possible if the depth at the toe of the structure corresponds to the equivalent offshore wave height, due to shoaling. Where runup may be amplified through earthworks and walling, it is not usually practical to build to this height, but to accommodate a suitable quantity of overtopping through structural design and development setbacks.

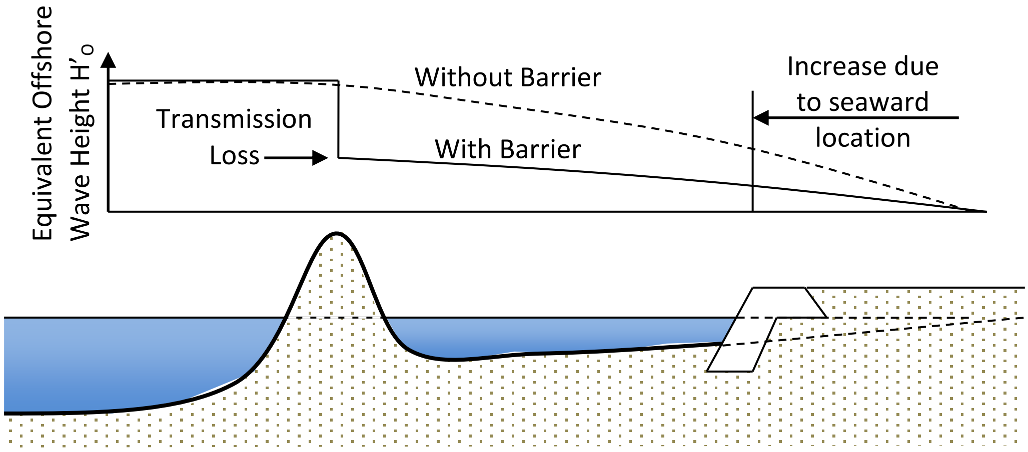


Figure 3: Wave height increase associated with infilling

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ROYALTIES FOR REGIONS

LANDCORP

KARRATHA COASTAL VULNERABILITY STUDY

ATTACHMENT II: Hydrological Assessment

August 2012

Prepared by:

JDA Consultant Hydrologists

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Executive Summary

JDA Consultant Hydrologists was commissioned by Landcorp to prepare the Karratha and Dampier Coastal Vulnerability Study. Task 2 of this Study was the hydrological assessment of catchments impacting on the Study Area. The assessment included the estimation of design flows at key locations within the Study Area, for Average Recurrence Intervals (ARI) of 2, 10, 100, 200 and 500 years.

A second objective of the hydrologic assessment was to provide design runoff hydrographs for catchments discharging to the hydraulic model area. Hydrographs were provided for the 2yr, 10yr, 100yr, 200yr and 500yr ARI for durations between 0.5 hours and 72 hours.

Flow estimations have been calculated for thee climate change scenarios, based on the current climate, 50 years hence and 100 years hence. These are referred to as 2010, 2060 and 2110 respectively. Changes from the existing climate for the 2060 and 2110 scenarios are based on increased rainfall intensities of 20% and 30% respectively (derived from Attachment Report I).

Peak flow estimations have been based on the following techniques:

- Rational Method (regional method from Australian Rainfall & Runoff);
- Index Flood Method (regional method from Australian Rainfall & Runoff);
- RORB model (hydrologic catchment model, using regional data from Australian Rainfall & Runoff);
- XP-Storm model (hydrologic catchment model, using regional data from Australian Rainfall & Runoff); and
- Flood Frequency Analysis (from nearby gauged catchments, as no streamflow gauges within the Study Area).

Peak flow estimates for the three primary catchments are shown below.

Catchment	Area (km^2)	Method	ARI				
			2yr	10yr	100yr	200yr	500yr
7 Mile Creek to Dampier Hwy	60	RORB	56	250	700	880	1180
		XP-Storm	12	218	710	920	1260
		Rational	48	220	1040	-	-
		Index Flood	40	140	700	-	-
Nickol River to North West Coastal Hwy	126	RORB	11	680	2200	3100	4100
		XP-Storm	32	760	2400	3200	4440
		Rational	130	670	5090	-	-
		Index Flood	120	430	2200	-	-
Nickol River Western Tributaries	277	RORB	9	470	1300	1700	2260
		XP-Storm	20	400	1320	1730	2360
		Rational	98	450	2190	-	-
		Index Flood	67	240	1200	-	-

Climate change is predicted to increase rainfall intensities. The Index Flood Method estimates peak flows based on annual rainfall rather than intensities. Annual rainfall will not necessarily increase. With the Rational Method, peak flows are directly proportional to rainfall intensity, so a 20 or 30% increase in rainfall will result in 20 or 30% increase in estimated peak flows. The loss models in RORB and XP-Storm are absolute losses, rather than proportional, so increasing rainfall intensity by 20% will result in peak flows with greater than 20% increase.

The methodology adopted was discussed with Department of Water to ensure acceptability.

Glossary

Average Recurrence Interval (ARI)	The average return period or frequency of an event.
Catchment	The area of land that is drained by a river and its tributaries.
Computerised Design IFD Rainfall System (CDIRS)	The Intensity Frequency Duration system developed by the Bureau of Meteorology that produces IFD graphs, data and coefficients for any location in Australia.
Flood Frequency Analysis	Statistical method of analysis to estimate the probability, return period or average recurrence interval of a flow or flood event based on historical data.
Hydrograph	A graph of discharge in a river throughout a period of time.
Hydrology	The study of the movement, distribution, quality and properties of water of the Earth, including the hydrologic cycle and water resources.
Intensity Frequency Duration (IFD)	The intensity of rainfall for a particular ARI storm event of a particular duration.
Index Flood Method	A regionalisation technique for estimating peak flow of a catchment for design floods in ungauged catchments or catchments with limited data.
Peak Flow	The highest level of discharge that occurs from a river during a storm event. This is represented by the highest point on the hydrograph.
Rational Method	A method for estimating peak flow of a catchment for design floods in ungauged catchments or catchments with limited data based on rainfall intensity and runoff coefficient.
RORB	RORB is a runoff and stream flow routing program used to calculate flood hydrographs from rainfall and other channel inputs. It calculates runoff as rainfall excess by subtracting losses from rainfall. The rainfall excess is then routed through catchment storage to produce hydrographs.
Topography	The Earth's surface shape, relief, landforms and features.
Tributary	A stream or river that flows into a larger river.

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1. INTRODUCTION

The Hydrological Assessment component of the Karratha Coastal Vulnerability Study investigates runoff generation from catchments discharging through the Study Area (Figure 1).

Major catchments include the Nickol River in the Eastern section of the Study Area and 7 Mile Creek in the Western section of the Study Area. Three main catchments have been chosen for assessment. These include 7 Mile Creek to Dampier Highway, Nickol River to North West Coastal Highway and the Western Tributaries of Nickol River (Figure 2).

For these catchments, the 2yr, 10yr, 100yr, 200yr and 500yr ARI peak flows were estimated. These estimates were based on the following techniques:

- Flood frequency analysis – no gauging station data was available with the Study Area, however regional data was assessed.
- Regional methods from Australian Rainfall & Runoff (IEAust, 1997) – the Rational and Index Flood Methods were assessed for each catchment.
- Hydrologic catchment modelling – the RORB and XP-Storm models were used to generate runoff hydrographs and estimate peak flows for each catchment.

No historic flows have been recorded in the Study Area so a hydraulic assessment of these was not possible.

In addition to the hydrologic assessment, design flood hydrographs were required for the hydraulic modelling component of the Study (Attachment V). Eleven catchments to the south of the hydraulic model were assessed for the 2yr, 10yr, 100yr, 200yr and 500yr ARI events for durations between 0.5hr and 72hr and hydrographs generated as input to the hydraulic model.

The change in climate for 2060 and 2110 was considered with regard to impact on peak flow estimates. The climate change component of the Study (Attachment I) recommends the following changes to rainfall intensities:

- 2060 – 20% increase in rainfall intensities; and
- 2110 – 30% increase in rainfall intensities.

These increases have been incorporated into the hydrologic modelling.

2. CATCHMENT DESCRIPTION

There are two main catchments which drain towards the Karratha Study Area. These are the Nickol River and 7 Mile Creek catchments. Both of these have subcatchments contributing to flow into the Study Area. There are also 19 small creeks catchments which convey flow through the Karratha town site.

There are a number of environmental conditions that influences the flooding response. This section describes the environmental context of the catchments and their subcatchments.

2.1 Location

The Study Area catchments are located approximately 10 to 22km south of Karratha town site and have a total area of approximately 43,450ha (Figure 2). The catchments consist of tributaries that extend to Mount Regal to the west, Mount Prinsep to the south and the Nickol River catchment to the east.

2.2 Climate & Rainfall

Karratha has an arid climate characterized by hot summers with periodic heavy rain and mild winters with occasional rainfall.

The Pilbara coast experiences more cyclones than any other part of Australia. Since 1910, there have been 48 cyclones that have caused damaging wind gusts in excess of 90km/h in the Karratha, Dampier and Roebourne region. On average this equates to about one every two years. About half of these cyclones have an impact equivalent to a category one cyclone. Ten of these: 1925, 1939, 1945, 1954, Shirley 1966, Sheila-Sophia 1971, Trixie 1975, Chloe 1984, Orson 1989 and John 1999 have caused very destructive wind gusts in excess of 170km/h (BoM 2010).

The average annual rainfall for Karratha is 280mm per year (Figure 3), with a maximum recorded annual rainfall of 855mm based on records taken between 1974 and 2009 at Karratha airport (BoM 2011). Most of the recorded precipitation is received during the wet season, as a result of tropical cyclones and local thunderstorms. Along the central Pilbara coast, the cyclone season runs from mid-December to April peaking in February.

The average annual pan evaporation is approximately 3,590mm (Luke et al, 1988).

2.3 Topography

The topography of the catchment areas is variable across the site (Figure 4). In some areas it is moderately steep, characterized by a number of hills in the western and southern areas. The elevation of these hills varies between 90mAHD and 180mAHD. In other areas topography is very flat, with these plains occurring through the central section of the catchment area between the southern hills and the Karratha Hills.

Within the Karratha Town Centre, the land is gently sloping towards the coast. Immediately south of the Karratha Town Centre are the Karratha Hills. The elevation of these hills varies between 45mAHD and 115mAHD.

The channel for Nickol River is well defined and incised, with the bed level at approximately 0mAHD east of the Study Area.

2.4 Soils & Vegetation

The catchments are covered by floodplain deposits of red-brown silty sand (Figure 5), which has been partially reworked by wind action over much of the catchment. The sand may contain nodules or lenses of calcrete below the surface, and scattered pebbles.

The river and creek channels consist of alluvium; sand and gravel. Within the floodplain, the channels consist of clay, silt and sand.

In general the soils have a low permeability, with little infiltration capacity. This limits losses to groundwater during rainfall events.

Undeveloped regions of the catchment feature hummock grassland, low tussock, spinifex grass vegetation and acacia forest and woodland (Figure 5).

2.5 Surface Drainage

The major surface drainage feature is Nickol River (Figure 6). This catchment has a total area of 539km^2 to the mouth of the river and an area of 277km^2 to North West Coastal Highway. The catchment extends to approximately 22km south of Karratha town site. The channel width in Nickol River is approximately 200-600m in the main channel.

There are a number of tributaries for the Nickol River to the south of the Karratha Hills and west of the main Nickol River. These include Turnoff Creek, Lulu Creek, Hilux Creek and several unnamed creeks. These drain the southern areas of the Karratha Hills. The Light Industrial Area is located within these subcatchments. These subcatchments have a combined area of 127km^2.

The 7 Mile Creek catchment to the west of the Karratha town site is a secondary drainage feature (compared to the Nickol River catchment). It has a total area of 78km^2 to the mouth of the river and an area of 60km^2 to Dampier Road. The catchment extends south of North West Coastal Highway. The catchment also includes Madigan Creek.

The range of hills south of Karratha town site (Karratha Hills) act as a water shed boundary and water drains from the northern portion of the hills through the Karratha town site. There are approximately 19 catchments (GHD, 2010) and creek lines which discharge flow towards Nickol bay.

2.6 Groundwater

Groundwater occurs within a single aquifer known as the Pilbara Fractured Rock Aquifer.

Although there are no long term groundwater monitoring bores known to exist within the Karratha Area, the watertable is expected to be 5-10m below surface and may vary seasonally in depth by 2-3m in response to heavy rainfall. The groundwater is expected to be slightly brackish to saline, in the range 2,500 – 10,000mg/L Total Dissolved Solids, but there may be more saline groundwater in localized areas of low permeability.

2.7 Land Use

Land use in Karratha as a regional centre for the west Pilbara contains a mix of developed and undeveloped areas. The majority of the Study Area features the main Karratha town site and surrounding areas include the Karratha airport, the Seven Mile railway workshop facility, residential developments Baynton West and Nickol, the Karratha Light Industrial Area, a sewerage treatment plant and an explosive reserve. An aerial photograph of the Study Area is shown in Figure 6.

Significant infrastructure includes part of the Dampier Paraburdoo railway line, Dampier Highway on the main land and a stretch of North West Coastal Highway that is between Dampier Paraburdoo railway line and Roebourne townsite.

Undeveloped areas feature sparse native vegetation consisting of low tussock and spinifex grass, and areas of rock outcrop in the hill regions.

The majority of the catchment areas, particularly the Nickol River catchment, consists of undeveloped areas.

3. REVIEW OF PREVIOUS STUDIES

3.1 Surface Hydrology of the Pilbara Region (WRC, 2000)

Water & Rivers Commission described the surface hydrology of the Pilbara region, which includes the overview of the drainage basins, rainfall, stream flow and water quality and flooding for the major rivers of region , such as the Ashburton, De Grey, Fortescue, Maitland, Cane and Harding Rivers.

The major flood observed was 1975, when Cyclone Joan crossed the Pilbara coast and resulted in rainfall of up to 600mm. The rivers experienced major flooding from the event.

The peak flows for five selected rivers in the region were estimated using Log Person Type III and GEV. The 100yr ARI peak estimated flow for Harding River (1,056km^2 catchment area) was 6,314m^3/s.

3.2 Maitland Industrial Estate Hydrology Study (JDA, 2009)

A hydrological investigation for Maitland Industrial Estate, Karratha was performed by JDA in 2009 to estimate the 100yr ARI flow using the available record for Maitland River and other rivers in the region. Frequency curves were fitted to the historical data, using Log person III.

The investigation indicated that higher rainfall have been occurred over the Maitland River catchment since 2004.

The 100yr ARI estimated flow in Harding River upstream of the Cooya Pooya was 5,700m^3/s.

3.3 Seven Mile Creek Flood Study (GHD, 2009)

GHD produced a report investigating flood levels in 7 Mile Creek upstream of Dampier Hwy as part of an assessment for the Karratha Support Industry Estate.

The catchment for 7 Mile Creek was estimated to be 60km^2. GHD used the Urban B MIKE11 hydrology sub model to simulate the overland flow from the catchment for the 10yr and 100yr ARI storm events.

The model was calibrated using a calibrated Rational Method approach, based on local gauged catchments. Calibration was used to set initial and continuing losses for the runoff model.

The 10yr and 100yr ARI flood peak flows immediately upstream of Dampier Hwy was estimated to be 217m^3/s and 627m^3/s respectively for existing conditions.

3.4 Madigan Creek Flood Study (JDA, 2010)

In 2010 JDA assessed flood levels in Madigan Creek (a tributary of 7 Mile Creek) as part of the investigation for the Madigan Development. This is located between Madigan Rd and the existing Baynton West development, upstream of Dampier Hwy.

Runoff from the catchment was estimated using RORB modelling, with validation using the Rational and Index Flood Methods. The loss model adopted was that of the GHD (2009) study for the overall 7 Mile Creek catchment. Peak flows generated from the RORB model were similar to those from the Rational Method, with a 100yr ARI peak flow of 125m^3/s.

Design storm hydrographs generated by RORB were used within a MIKE11 hydraulic model to estimate flood levels for the proposed development.

3.5 Karratha Drainage Management Plan (GHD, 2010)

This GHD study examined the existing stormwater drainage network within the Karratha Town Site (north of the Karratha Hills) and proposed drainage management plan. The document reviewed water sensitive urban design in Karratha and general drainage design principles for the Pilbara region.

Nineteen drain systems were identified and a site investigation defined drain type, cross section description and vegetation for each.

The ILSAX model in DRAINS was used to estimate peak flow from each catchment. Various land uses were applied, each having their own loss model and roughness. Impervious areas such as paved surfaces, roofs, driveways, carparks and rock areas were modelled using a 1mm initial loss and flow path roughness of 0.015. Pervious areas such as grass or soil areas were modelled using a 5mm initial loss and a flow path roughness of 0.035.

The 100yr ARI peak flows from the catchments varied between 2.5m^3/s (catchment 4: 5.8ha) to 56.2m^3/s (catchment 9a: 158.5ha).

4. HYDROLOGIC DATA

4.1 Methodology

Hydrologic analysis of the contributing catchments was performed to estimate peak flows and design hydrographs for the various design ARI storm events. Techniques include:

- Flood frequency analysis,
- Regional methods from Australian Rainfall and Runoff (IEAust, 1997) such as the Rational Method and Index Flood Method,
- Hydrologic catchment modelling.

Hydrograph generation was an important requirement of the Hydrologic Assessment as the Hydraulic Modelling Assessment incorporates flow from the catchments to the south of the Study Area and routes runoff through the Study Area.

Therefore two hydrologic catchment models were assessed. These were the RORB and XP-Storm software models. These models were compared and validated against peak flows estimates from Rational and Index Flood Methods and regional stream flow gauging data analysis.

Although two hydrograph methods were assessed only one was required for generating the hydraulic model input. The XP-Storm model was selected as this model allowed greater control of hydrograph time step data.

Details of the catchment hydrologic analyses are presented below.

4.2 Catchment Areas

There are three catchment systems within the Study Area (Figure 6). In the western section there is 7 Mile Creek which extends to the south and west of the Study Area. In the northern central section there are the Karratha Town creeks which drain water from the town site and the Karratha Hills immediately south of the town. In the southern central and eastern sections there is the Nickol River catchment. This is a significant catchment which extends south and east of the Study Area.

In this Study, the tributaries within the southern central section have been assessed in addition to the main Nickol River. The 7 Mile catchment has been assessed to Dampier Hwy. These catchment areas are also shown on Figure 6. The Karratha town catchments have not been included in the analysis due to their small size. Catchment details have been included in Table 1.

In addition to these primary hydrologic assessment catchments, the hydraulic model subcatchments have been assessed. These catchments are subcatchments of the primary catchments with the northern boundary of these subcatchments at 7,699,000 mN, which is the southern extent of the hydraulic model (Figure 7). Details of these catchments have also been included in Table 1. The subcatchments have been assigned a letter – A1-4 (7Mile Creek), B, C (Turnoff Creek), D (Lulu Creek), E, F, G, and Nickol River (Figure 3).

TABLE 1: CATCHMENT AREAS

Hydrologic Assessment Catchments		Area (km^2)
7 Mile Creek to Dampier Hwy		60.0
Nickol River to North West Coastal Highway		277.2
Nickol River Western Tributaries		126.5
Hydraulic Model Input Catchments		**Area (km^2)**
A1	7 Mile Creek Tributary 1	5.0
A2	7 Mile Creek Tributary 2	3.3
A3	7 Mile Creek Tributary 3	16.7
A4	7 Mile Creek Tributary 4	3.6
B	Unnamed Creek 1	3.8
C	Turnoff Creek	27.6
D	Lulu creek	29.1
E	Unnamed Creek 2	5.5
F	Unnamed Creek 3	1.6
G	Hilux Creek	4.1
Nickol River	Nickol River	267.0

4.3 Design Rainfall

Rainfall input for the modelling of design storms was based on procedures from Australian Rainfall and Runoff (AR&R) (IEAust, 1997). This includes rainfall intensities and temporal patterns for design storm durations between 30 minutes and 72 hours, and ARI's between 2yr and 500yr for Karratha (Figure 8).

The rainfall pattern was assumed to be spatially uniform across the catchments.

Table 2 presents Rainfall Intensity Frequency Duration (IFD) data for Karratha (CDIRS, BoM, 2009) up to 100yr ARI. The 200 and 500yr ARI Rainfall Intensity was estimated by extrapolating the 100yr ARI IFD data using the AR&R recommended Algebraic Method (Table 2).

Figure 3 shows the 1yr to 500yr ARI IFD for Karratha.

It is estimated from climate models that rainfall intensity will increase in time. Attachment 5 of this Study assessed the projected change in climate. It is estimated that by 2060, rainfall intensities will increase 20% from current intensities. By 2110, it is estimated that a 30% increase will occur from current intensities. These changes have been incorporated to estimate future hydrograph information.

TABLE 2: INTENSITY FREQUENCY DURATION (IFD) FOR KARRATHA (mm/hr)

Duration	2yr ARI	10yr ARI	50yr ARI	100yr ARI	200yr ARI	500yr ARI
0.5hr	49.1	93.3	148.0	174.0	199.6	238.2
1hr	32.6	63.7	103.0	122.0	139.9	167.9
3hr	14.9	31.1	52.0	62.4	74.2	90.4
6hr	8.81	19.2	32.9	39.9	48.4	59.7
12hr	5.30	11.9	20.9	25.4	31.3	38.8
24hr	3.32	7.52	13.2	16.1	20.0	24.8
48hr	2.09	4.67	8.17	10.0	12.3	15.2
72hr	1.52	3.39	5.94	7.24	8.94	11.1

During this Study, Cyclone Bianca impacted on Karratha on 27th January 2011. The 96mm of rainfall that fell occurred within a 16hr period (average rate of 6.0mm/hr). This was equivalent to between a 2yr to 5yr ARI rainfall event (Figure 8).

5. HYDROLOGIC MODELLING

As discussed previously, there are no historical flow records available within the Study Area. Flood frequency analysis was based on regional data. Other regional methods such as the Rational and Index Flood Methods were also assessed to aid validation of models. Hydrologic catchment models were based on regional parameters. The different methods were compared and assessed.

5.1 Regional Flood Frequency Analysis

Regional flood frequency analysis was performed using streamflow data from gauging stations located in adjacent catchments. Three Department of Water (DoW) gauging stations were analysed. The locations and catchments of the stations are presented in Figure 9. These four gauging station have areas with a similar range to the catchments in present Study.

Catchment area and the length of record of measured flows available for each station are presented in Table 3.

Flood frequency analysis was performed based on an annual maximum series with a Log Pearson Type III distribution consistent with AR&R (IEAust, 1997). Harding River gauging stations 709002 & 709007 flow data was combined for analysis as advice by Simon Rodgers (DoW).

Flood frequency graphs with confidence limits for each station are presented in Figures 10 to 12.

A 100yr ARI runoff coefficient for these three gauging sites was estimated based on the Rational Method equation from AR&R. It was assumed that rainfall is uniformly distributed throughout the whole catchment. The 100yr ARI runoff coefficient (C_{100}) was estimated for each catchment as the peak flow is known (from the LP III analysis), catchment area is known, and the rainfall intensity can be calculated. These estimated 100yr ARI runoff coefficients range between 0.41 and 0.67 as shown in Table 3. This runoff coefficient is related to peak flow estimation rather than total flow volume.

TABLE 3: DOW GAUGING STATIONS DETAILS

Station		Catchment Area (km^2)	Period of Record		Time of Concentration (hr)	Recorded Peak Flow (m^3/s)	Estimated Runoff Coefficient, C_{100}
Number	Name		Date	Years			
709002	Harding River at Marmurrina Pool D/S	49.5	1967	1987	2.5	138	0.41 [1]
709007	Harding River at Marmurrina Pool U/S	49.3	1974	1999	2.5	317	
709006	Tanberry Creek at Blue Dog Pool	128	1974	2001	3.7	400	0.61
709010	Turner River at Pincunah	885	1985	2010	7.4	1300	0.32

Note: 1.Harding River gauging stations 709002 & 709007 record was combined for analysis

The 10yr, 50yr, 100yr and 500yr ARI flows determined from these graphs for the station are shown in Table 4.

TABLE 4: 2010 DOW GAUGING STATIONS ESTIMATED PEAK FLOWS USING LPIII

Station		Estimated Peak Flow (m^3/s)					
Number	Name	2yr	5yr	10yr	50yr	100yr	500yr
709002 & 709007	Harding River at Marmurrina Pool D/S & U/S	40	90	140	300	400	600
709006	Tanberry Creek at Blue Dog Pool	60	210	140	370	1100	1750
709010	Turner River at Pincunah	190	560	1000	2300	3200	5500

GHD (2009) used the flow data of these same gauging stations to calibrate their model of 7 Mile Creek in Karratha. JDA understands that the approach used was to calculate a calibrated Cy/C2 parameter for the 10 and 100yr ARI events, which was then used to calculate peak flows for the 10 and 100 year events. Loss parameters in a runoff model were then calibrated to match the estimated peak flows. The study found that using a 5mm Initial Loss (IL) and 2mm Continuing Loss (CL) for a 100 yr ARI storm event of 186mm rainfall provided the best calibration for 7 Mile Creek. This was for storm duration of approximately 3 hours.

The same method was used to provide a guide for the current Study. The LPIII analysis was used to estimate the 2yr, 5yr, 10yr, 50yr and 100yr ARI flows for the three catchments. The Rational Method is described as:

$$Q_y = 0.278\ C_2\ (C_y / C_2)\ I_{Tc}\ A = 0.278\ C_y\ I_{Tc}\ A \qquad T_c = 0.58\ A^{0.38}$$

Where Q_y = Peak flow at ARI of y years (m^3/s)

I_{Tc} = rainfall intensity at time of concentration (mm/hr)

T_c = time of concentration (hr)

A = catchment area (km^2)

C_y = runoff coefficient for ARI of y years

For each ARI the runoff coefficient, C_y, was calculated. The (C_y/C_2) parameter was then calculated for each catchment (Table 5). These parameters were then averaged over the three catchments. This average was then used to describe a "calibrated" Rational Method for the North West. The C_2 parameter could be calculated for catchments within the Study Area.

TABLE 5: CALIBRATED C_Y/C_2 RATIONAL METHOD RUNOFF COEFFICIENTS

Station		C_2/C_2	C_5/C_2	C_{10}/C_2	C_{50}/C_2	C_{100}/C_2
Number	Name					
709002 & 709007	Harding River at Marmurrina Pool D/S & U/S	1.00	1.48	1.70	2.24	2.48
709006	Tanberry Creek at Blue Dog Pool	1.00	2.06	2.79	3.82	4.12
709010	Turner River at Pincunah	1.00	1.77	2.33	3.25	3.59
Average		1.00	1.77	2.28	3.11	3.40

This was done for the Nickol River catchment to North West Coastal Highway. It was found that the 100yr ARI event calibrated best to a 50mm initial loss and a 5mm/hr continuing loss model (using XP-Storm). The 10yr ARI event calibrated best to a 30mm initial loss and a 5mm/hr continuing loss model. This is similar to the recommended loss model for the Pilbara from AR&R which prescribes an initial loss of 40mm and 5mm/hr continuing loss.

5.2 Rational Method

5.2.1 Rational and Index Flood Methods

The Rational Method uses regionalisation techniques for estimating peak flows in catchments where there are ungauged sites or sites with limited streamflow data (Water & Rivers Commission, 1999). Equations adopted for validation of the catchment are from relationships derived from gauged catchments in the North West region of Western Australia (IEAust, 1997).

Note that the estimated peak flow for the 100yr ARI event is extrapolated as the Rational Method only provides peak flow estimates up to the 50yr ARI event.

The Rational Method equation is described as:

$$Q_y = 0.278\ C_2\ (C_y/C_2)\ I_{Tc}\ A$$

with $C_2 = 0.301\ L^{-0.2}$

and $T_c = 0.58\ A^{0.38}$

Where Q_y = Peak flow at ARI of y years (m^3/s)

I_{Tc} = rainfall intensity at time of concentration (mm/hr)

T_c = time of concentration (hr)

A = catchment area (km^2)

C_y/C_2 = runoff coefficient for ARI of y years, with values provided in AR&R (IEAust, 1997)

The Rational Method runoff coefficients ranged between 0.18 for the 2yr ARI event to 1.0 for the 100yr ARI event.

Table 6 and Figures 13 to 18 show the peak flow estimates for the three hydrologic assessment catchments and the eleven hydraulic model input catchments.

5.3 Index Flood

Similar to the Rational Method, the Index Flood Method also uses regionalisation techniques for estimating peak flows in catchments where there are ungauged sites or sites with limited streamflow data. Equations adopted for validation of the catchment are from relationships derived from gauged catchments in the North West region of Western Australia (IEAust, 1997).

Note that the estimated peak flow for the 100yr ARI event is extrapolated as the Index Flood Method only provides peak flow estimates up to the 50yr ARI event.

The equation for the Index Flood Method is described as:

$Q_y = Q_5 (C_y/C_5)$

With $Q_5 = 6.73x10^{-4} . A^{0.72} . P^{1.51}$

Where Q_y = Peak flow at ARI of y years (m^3/s)

A = Catchment area (km^2)

P = Annual precipitation (mm)

C_y/C_5 = runoff coefficient for ARI of y years, with values provided in AR&R (IEAust, 1997)

An annual rainfall of 300mm was used for the calculation of peak flows. Results of flow estimates are shown in Table 6 and Figures 13 to 18.

TABLE 6: 2010 ESTIMATED RATIONAL AND INDEX FLOOD METHODS PEAK FLOWS (m^3/s)

Catchment		ARI							
		2yr		10yr		50yr		100yr	
		RM	IFM	RM	IFM	RM	IFM	RM	IFM
7 Mile Ck to Dampier Hwy		48	40	222	137	867	442	1039	700
Nickol River to NWCH		131	116	667	430	3772	1549	5086	2200
Nickol River West Tribs		98	67	452	242	1791	848	2190	1200
A1	7 Mile Creek T1	8	5	33	15	88	38	120	45
A2	7 Mile Creek T2	7	4	29	13	75	34	100	40
A3	7 Mile Creek T3	25	14	110	46	360	130	440	170
A4	7 Mile Creek T4	8	4	34	13	85	34	100	40
B	Unnamed Creek	8	4	34	13	81	32	96	37
C	Turnoff Creek	30	21	140	69	520	210	610	250
D	Lulu Creek	30	21	140	71	530	210	630	260
E	Unnamed Creek	12	7	53	20	160	55	180	65
F	Unnamed Creek	4	3	19	9	50	22	59	28
G	Hilux Creek	9	5	36	15	90	39	110	44
Nickol River	Nickol River	130	100	670	380	3800	1400	4900	1800

Note: RM : Rational Method IFM: Index Flood Method

5.4 RORB Modelling

5.4.1 Model Background

Hydrologic modelling for all catchments external to the model area was performed using the runoff routing model RORB. RORB is a general runoff and stream flow routing program used to calculate flood hydrographs from rainfall and other channel inputs. It calculates runoff as rainfall excess by subtracting losses from rainfall. The rainfall excess is then routed through catchment storage to produce hydrographs.

The model is areally distributed, nonlinear, and applicable to both rural and urban catchments. It has the capacity to model temporal and spatial variability in rainfall, as well as storage reservoirs and culverts. Reach storage is the main way in which RORB represents hydrologic processes. Reach storages are assumed to have storage-discharge relations of the form:

$$S = 3600\ k\ Q^{m}$$

where S is the storage (m^3), Q is the outflow discharge (m^3/s), m is a dimensionless exponent, and k is a dimensional empirical coefficient that is comprised of the product of k_r and k_c, where k_r is a dimensionless ratio called the relative delay time, and k_c is an empirical coefficient characterising the entire catchment and stream network. It is important to note that k_c can only be generally compared between models that have the same catchment sub-divisions and stream network, though some rough comparison can be made if the catchment is sub-divided differently.

Calibration of storm event runoff hydrographs (where available) in RORB is predominantly achieved by adjusting the m and k_c values to achieve the best fit, as well as the runoff coefficient R_c which is the runoff volume as a proportion of rainfall volume.

5.4.2 Parameters k_c and m

RORB parameters k_c and m are either estimated by best fit of estimated and/or observed stream flow hydrographs or based on existing published data.

As there is no hydrograph data available for these catchments, k_c value was calculated from the regional relationship derived by Flavell and Belstead (1983) as the recommended procedure by AR&R (IEAust, 1997). The relationship applicable to the study area is for the Pilbara as follows:

$$k_c = 1.06\ L^{0.87}\ S^{-0.46}$$

Where L = the mainstream channel length (km).

The mainstream channel lengths and calculated k_c values for all catchments are given in Table 7.

For the dimensionless exponent m, a value of 0.85 was adopted consistent with other similar studies, considered appropriate for west Western Australian conditions (IEAust, 1997).

5.4.3 RORB Model Peak Flow Estimate

The RORB model was run based on the above parameters for the study area catchments to generate peak flows for the 2yr, 10yr, 50yr, 100yr, 200yr and 500yr ARI rainfall events. These peak flows are presented in Table 8 and Figures 13 to 18.

TABLE 7: RORB MODELLING PARAMETERS

Catchment ID		Main stream length, L (km)	Slope, S (m/km)	K_c
7 Mile Creek to Dampier Hwy		10	4	4.15
Nickol River to NWCH		19	2.5	4.87
Nickol River West Tributaries		12	4	9.01
A1	7 Mile Creek Trib 1	2	5.5	0.88
A2	7 Mile Creek Trib 2	2	5.0	0.92
A3	7 Mile Creek Trib 3	5.8	4.3	2.50
A4	7 Mile Creek Trib 4	1.3	8.8	0.47
B	Unnamed Creek 1	2	7.5	0.77
C	Turnoff Creek	8	3.4	3.71
D	Lulu creek	9	4.2	3.70
E	Unnamed Creek 2	3	8.3	1.04
F	Unnamed Creek 3	1.9	5.3	0.86
G	Hilux Creek	1.5	2	1.10
Nickol River	Nickol River	18	2.7	8.27

TABLE 8: 2010 ESTIMATED RORB MODEL PEAK FLOWS (m^3/s)

External Catchments		ARI					
		2yr	10yr	50yr	100yr	200yr	500yr
7 Mile to Dampier Hwy		5.5 (18)	250 (18)	530 (6)	700 (6)	880 (6)	1180(6)
Nickol River to NWCH		11 (18)	680 (36)	1640 (6)	2200 (6)	3100 (6)	4100 (6)
Nickol River West Tributaries		9.2 (18)	470 (18)	980 (6)	1300 (6)	1700 (6)	2260 (6)
A1	7 Mile Creek T1	1 (6)	32 (6)	62 (12)	82 (12)	110 (1)	140 (1)
A2	7 Mile Creek T2	1 (6)	27 (6)	52 (12)	68 (12)	88 (1)	120 (1)
A3	7 Mile Creek T3	2 (18)	84 (6)	180 (6)	230 (6)	300 (6)	380 (6)
A4	7 Mile Creek T4	1 (6)	32 (6)	60 (1)	75 (1)	110 (1)	140 (6)
B	Unnamed Creek	1 (6)	27 (6)	54 (1)	72 (1)	93 (1)	120 (1)
C	Turnoff Creek	3 (6)	140 (6)	280 (6)	370 (6)	470 (6)	620 (6)
D	Lulu Creek	3 (18)	120 (6)	260 (6)	340 (6)	430 (6)	580 (6)
E	Unnamed Creek	1.5 (6)	47 (6)	92 (1)	120 (1)	160 (1)	210 (1)
F	Unnamed Creek	1 9 (6)	15 (6)	28 (1)	37 (1)	49 (1)	64 (1)
G	Hilux Creek	1 (6)	36 (6)	72 (12)	90 (12)	130 (12)	160 (1)
Nickol River	Nickol River	11 (18)	690 (36)	1600 (6)	2100 (6)	2800 (6)	3600 (6)

5.5 XP-Storm Modelling

XP-Storm is a modelling package for the dynamic simulation of river and stormwater systems. It simulates the natural rainfall runoff processes and flow in natural and engineered channels.

In the hydrology (runoff) module, a rainfall loss model is applied. On impermeable surfaces, all rainfall is converted to runoff. For permeable surfaces, losses can be estimated using infiltration excess based on a variety of options. These can range between simple proportional loss, or an initial and continuing loss model, or an infiltration model to calculate excess. Runoff is then routed to the outlet based on several potential options.

Rainfall is applied based on rainfall distributions and intensity frequency duration procedures as described in AR&R (IEAust, 1997). These design storms produce hydrographs for each storm duration between 0.5hr and 72hr. The critical duration will result in a hydrograph with the largest peak flow.

5.5.1 Loss Model & Routing Method

For the XP-Storm modelling, an initial and continuing loss model was chosen. Australian Rainfall & Runoff (IEAust, 1997) provides regional data on appropriate losses around Australia. For Karratha, AR&R suggests using an initial loss of 40mm and a continuing loss of 5mm/hr. This was used as a starting point for the model, with the intention that these losses may be modified if peak flows were significantly different from the other peak flow estimation methods.

The Laurenson routing procedure was chosen to estimate the peak flows hydrographs.

5.5.2 XP-Storm Model Peak Flow Estimation

The XP-Storm model was run based on the above methods for the Study Area catchments to estimate peak flows for the 2yr, 10yr, 50yr, 100yr, 200yr and 500yr ARI events. These peak flows are shown in Table 9 and Figures 13 to 18.

TABLE 9: 2010 ESTIMATED XP-STORM MODEL PEAK FLOWS (m^3/s)

Catchment		ARI					
		2yr	10yr	50yr	100yr	200yr	500yr
7 Mile to Dampier Hwy		11.9 (12)	218 (24)	528 (3)	707 (3)	917 (3)	1264 (24)
Nickol River to NWCH		32.3 (12)	761 (24)	1868 (12)	2398 (3)	3205 (3)	4444 (3)
Nickol River West Tributaries		20.2 (12)	404 (24)	934 (3)	1316 (3)	1729 (3)	2360 (3)
A1	7 Mile Creek	2.7 (12)	35 (24)	68 (24)	78 (24)	110 (1)	140 (1)
A2	7 Mile Creek	2.5 (12)	32 (24)	68 (24)	73 (24)	97 (1)	130 (1)
A3	7 Mile Creek	7 (12)	93 (24)	210 (24)	300 (24)	400 (24)	530 (24)
A4	7 Mile Creek	2.5 (12)	33 (24)	60 (24)	73 (24)	95 (1)	130 (1)
B	Unnamed Creek	2.5 (12)	31 (24)	55 (24)	70 (24)	91 (1)	130 (1)
C	Turnoff Creek	8 (12)	130 (72)	290 (3)	380 (6)	550 (24)	750 (24)
D	Lulu Creek	8 (12)	130 (72)	300 (3)	390 (6	540 (24)	760 (24)
E	Unnamed Creek	3.8 (12)	50 (24)	97 (24)	130 (24)	160 (24)	210 (1)
F	Unnamed Creek	1.3 (12)	17 (24)	32 (24)	42 (24)	52 (24)	70 (24)
G	Hilux Creek	2 (12)	25.5 (24)	53 (24)	72 (24)	92 (24)	119 (1)
Nickol River	Nickol River	35(12)	746 (24)	1800 (3)	2300 (3)	3200 (3)	4300 (3)

Note: Critical duration (hr) shown in brackets

5.6 Model Validation

Calibration of hydrographs and peak flow estimates generated from the RORB and XP-Storm model could not be performed due to the absence of gauging station data within the catchment. Validation of the RORB and XP-storm peak flows based on comparison with alternative flood estimation methods (Rational and Index Flood Methods) was performed instead.

The comparison of the estimates of 2yr, 10yr, 50yr, 100yr, 200yr and 500yr ARI peak flows using four methods, RORB, XP-Storm, Rational and Index Flood Methods are given in Figures 13 to 18.

It can be seen that the RORB and XP-Storm peak flow estimates are similar for each catchment. For the 50yr and 100yr ARI events, RORB and XP-Storm are close to the Index Flood Method, but much lower than the Rational Method estimate. For the 10yr ARI, the RORB and XP-Storm flow estimates are close to (but slightly less than) the Rational Method, and much greater than the Index Flood Method.

The results in general indicate that the two hydrograph generation models provide results within estimates from the regional methods. The results also show that the adopted loss model for XP-Storm provides results similar to RORB and therefore is acceptable for future simulations.

6. HYDRAULIC MODEL INPUT DATA

As described in Section 4.2, as well the primary hydrologic assessment catchments, subcatchments to the South of the hydraulic model needed to be assessed and data (flow hydrographs) required for the hydraulic model. These subcatchments are outside of the hydraulic model area, but flow from these areas needs to be included as part of the assessment as they will have an impact on flood levels.

The hydraulic model input catchments will also need to take into account changes to climate, for the 2060 and 2110 simulations.

It was decided to use XP-Storm to generate the hydrographs for all ARI events. Peak flows and hydrographs from XP-Storm were similar to RORB, but greater control of hydrograph time step was possible with XP-Storm, which allowed for easier input of the data into the MIKE FLOOD hydraulic model.

6.1 Future Climate Scenarios

The likelihood of changes to rainfall and runoff statistics, due to climate change, has been considered as part of the overall vulnerability study and reported on by CZM (see Attachment I).

In summary the recommended changes are to rainfall IFD as follows:

- 2060 – 20% increase in rainfall intensities
- 2110 – 30% increase in rainfall intensities

These increases have been incorporated into the XP-Storm Model described in Section 4.3 above.

6.2 Design Flood Hydrographs Estimation

A series of XP-Storm simulations were performed to generate design hydrographs for the 2yr, 10yr, 100yr, 200yr and 500yr ARI rainfall events, with durations ranging from 0.5hr to 72hr. The critical duration was selected based on the highest peak of the flow hydrographs generated. For each hydraulic model simulation, the appropriate ARI and duration design hydrograph was used.

The resulting design flows for 2010, 2060 and 2110 are presented in Table 10 and Figures 19 to 23. Critical durations are different for each catchment due to catchment area results in different time of concentrations. While only peak flows relating to critical durations are presented in Table 10 and Figures 19 to 23, hydrographs for each duration have been generated for each catchment and ARI, so that, for example, the 100yr ARI 3hr duration hydraulic model simulation utilises the 100yr ARI 3hr duration inflow hydrographs from the external catchments.

It can be seen that the increase in rainfall results in increases in runoff. For example the 100yr ARI peak flow from the Nickol River for 2010 is 2,300m^3/s which increases to 3,200m^3/s (39% increase) in 2060 and 3,650m^3/s (59% increase) in 2110. By comparison, total runoff volume for the Nickol River catchment increases from 65 Mm^3 in 2010 to 85 Mm^3 (31% increase) in 2060 and 95 Mm^3 (46% increase) in 2110. The greater increase in peak flow rates compared to total runoff is due to the loss model parameters being absolute, rather than proportional.

TABLE 10: 2010, 2060, 2110 ESTIMATED XP-STORM MODEL PEAK FLOWS (m^3/s)

Catchment		Yr	ARI				
			2yr	10yr	100yr	200yr	500yr
A1	7 Mile Creek	2010	2.7	35	78	110	140
		2060	6.3	51	112	144	185
		2110	7.4	59	128	164	217
A2	7 Mile Creek	2010	2.5	32	73	97	130
		2060	5.6	45.3	99	126	170
		2110	6.6	51.5	130	145	190
A3	7 Mile Creek	2010	7	93	300	400	530
		2060	19.3	147	390	510	660
		2110	23	175	440	560	730
A4	7 Mile Creek	2010	2.5	33	73	95	130
		2060	5.57	45	99	126	168
		2110	6.5	51	113	144	189
B	Unnamed Creek 1	2010	2.5	31	70	91	130
		2060	5.4	43	95	122	163
		2110	6.3	49	109	139	183
C	Turnoff Creek	2010	8	130	380	550	750
		2060	23.5	184	530	710	990
		2110	28	218	600	800	110
D	Lulu Creek	2010	8	130	390	540	760
		2060	23.9	187	540	720	1010
		2110	28.5	220.8	610	819	1130
E	Unnamed Creek 2	2010	3.8	50	130	160	210
		2060	9.2	74	160	205	275
		2110	10.8	88	185	233	310
F	Unnamed Creek 3	2010	1.3	17	42	52	70
		2060	2.98	24	52	66	90
		2110	3.49	27.5	60	75	101
G	Hilux Creek	2010	2	25.5	72	92	119
		2060	5	40	92	114	147
		2110	5.9	46	102	125	165
Nickol River	Nickol River	2010	35	746	2300	3200	4300
		2060	95	1110	3200	4300	5300
		2110	114	1280	3650	4700	6400

7. CONCLUSIONS

- Three primary catchment areas were chosen for hydrologic assessment. These were the Nickol River to North West Highway, 7 Mile Creek to Dampier Hwy and the western tributaries of Nickol River. In addition the eleven hydraulic model input catchments were also assessed.
- Hydrological assessment was performed to estimate 2yr, 10yr, 50yr, 100yr, 200yr and 500yr ARI peak flows.
- Four methods – the Rational Method, Index flood Method, RoRB and XP-Storm models were applied to estimate, compare and validate the hydrological modelling assessment.
- Regional flood frequency analysis was performed using stream flow data from gauging stations located in adjacent catchments. These three gauging station have catchment areas with in a similar range to the catchments in present Study. Flood frequency analysis was performed based on an annual maximum series with a Log Pearson Type III distribution consistent with AR&R (IEAust, 1997).
- The loss model used in the RORB and XP-Storm models was based on the Design Loss Rates procedure for North West Western Australia as presented in AR&R (IEAust, 1997). An initial loss of 40mm and continuing loss of 5mm/hr was included in the model for all ARI and durations, in consultation with Department of Water (DoW).
- The modelling indicates that the RORB and XP-Storm estimated peak flows were consistent. It was decided to use the XP-Storm generated hydrographs for the hydraulic model input catchments as this model allowed for greater control of hydrograph timesteps, which may for greater ease of input to the hydraulic model.
- As a result of climate change, rainfall intensities are expected to increase by 20% in 2060 and 30% in 2110. This results in increased runoff
- The likelihood of changes to rainfall and runoff statistics, due to climate change rainfall IFD were increase rainfall intensities by 20% in 2060 and 30% in 2110. The increased rainfall intensities results in increased runoff, which can be greater than the percentage increase in rainfall due to the loss model being absolute rather than proportional.

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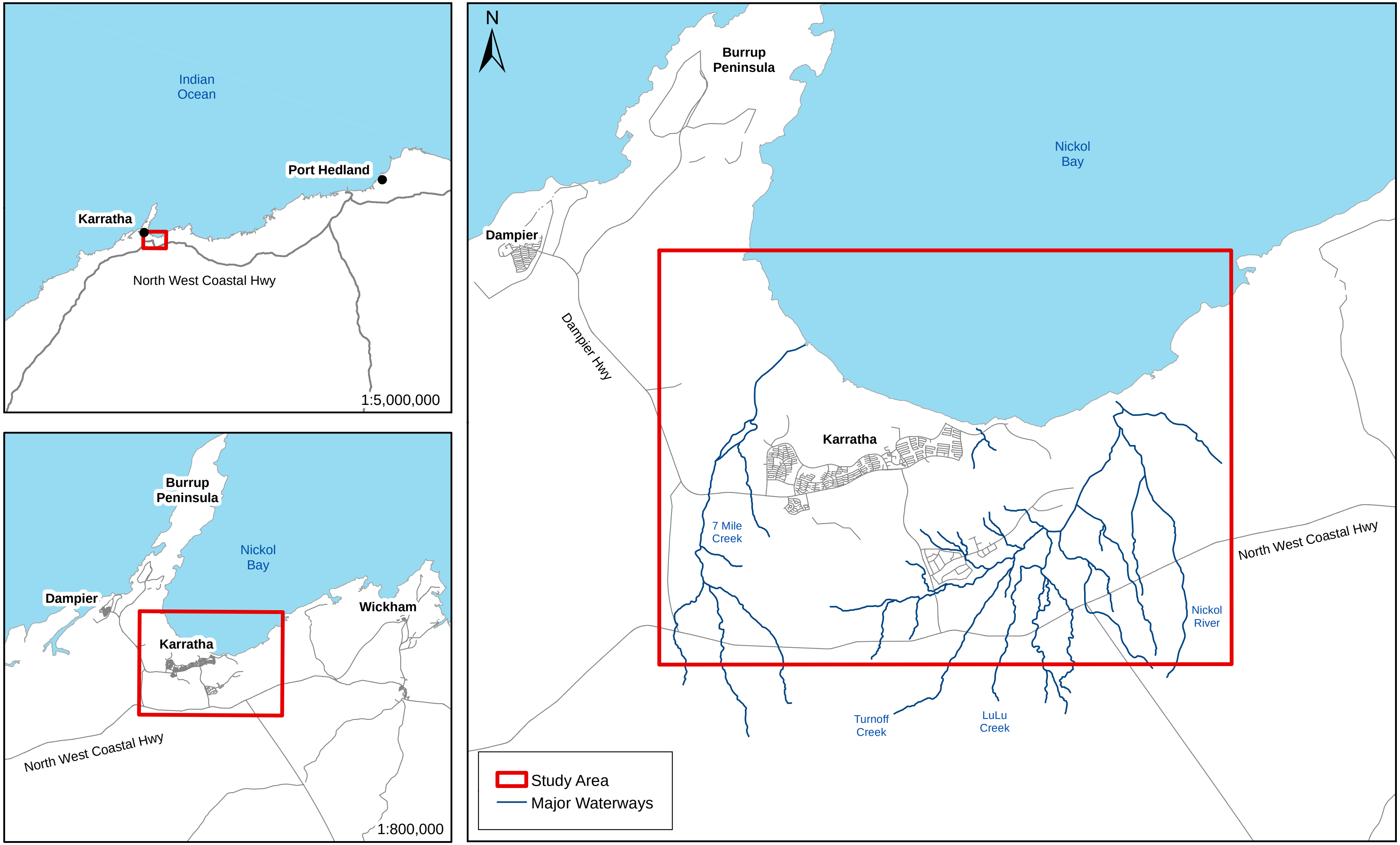
FIGURES



Data Source: Main Roads 2010

Job No. J4812

Scale: 1:200,000

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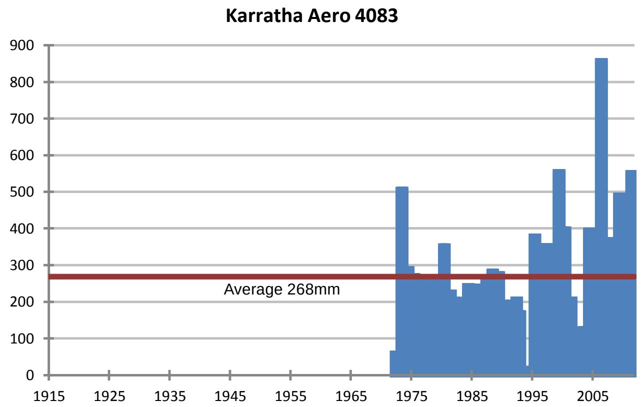
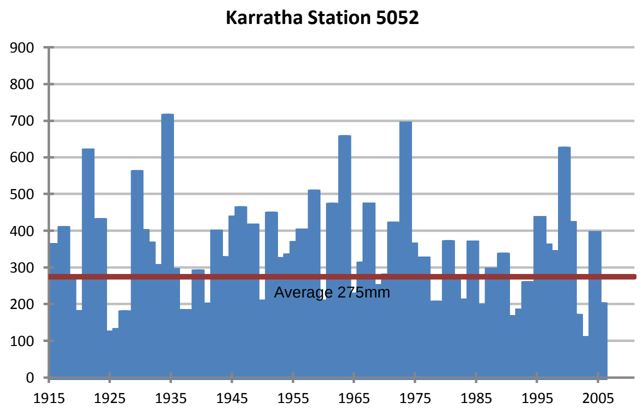
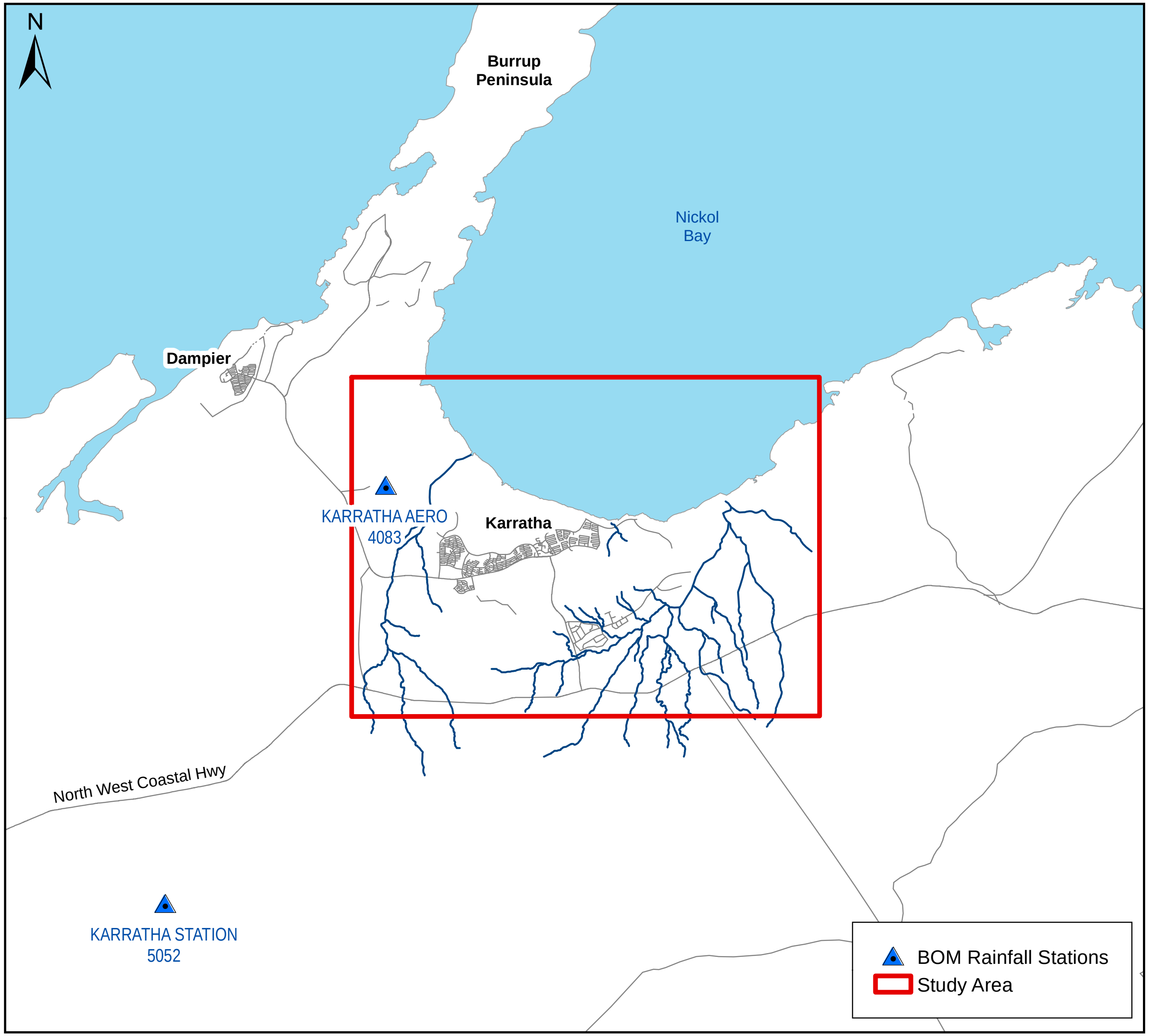
Karratha Coastal Vulnerability Study Report II: Hydrological Assessment

Figure 1: Location Plan







Data Source: Bureau of Meteorology 2011

Job No. J4812

Scale: 1:300,000

0 5 10 15 20 Kilometers

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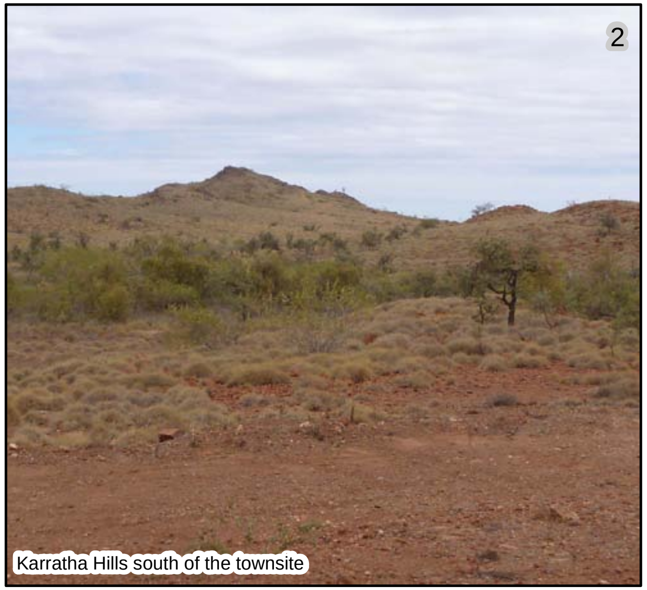
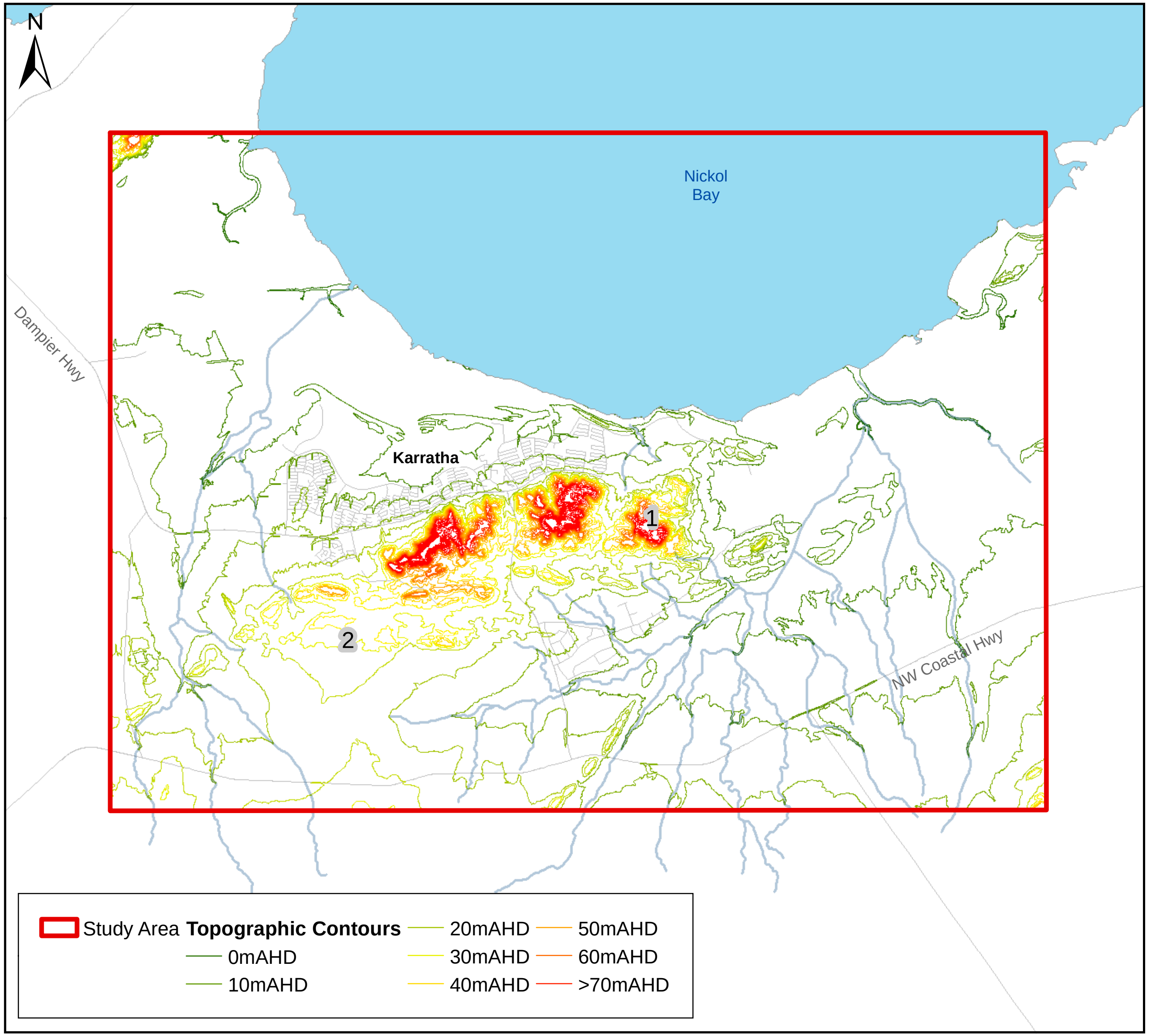
Figure 2: Annual Rainfall Data

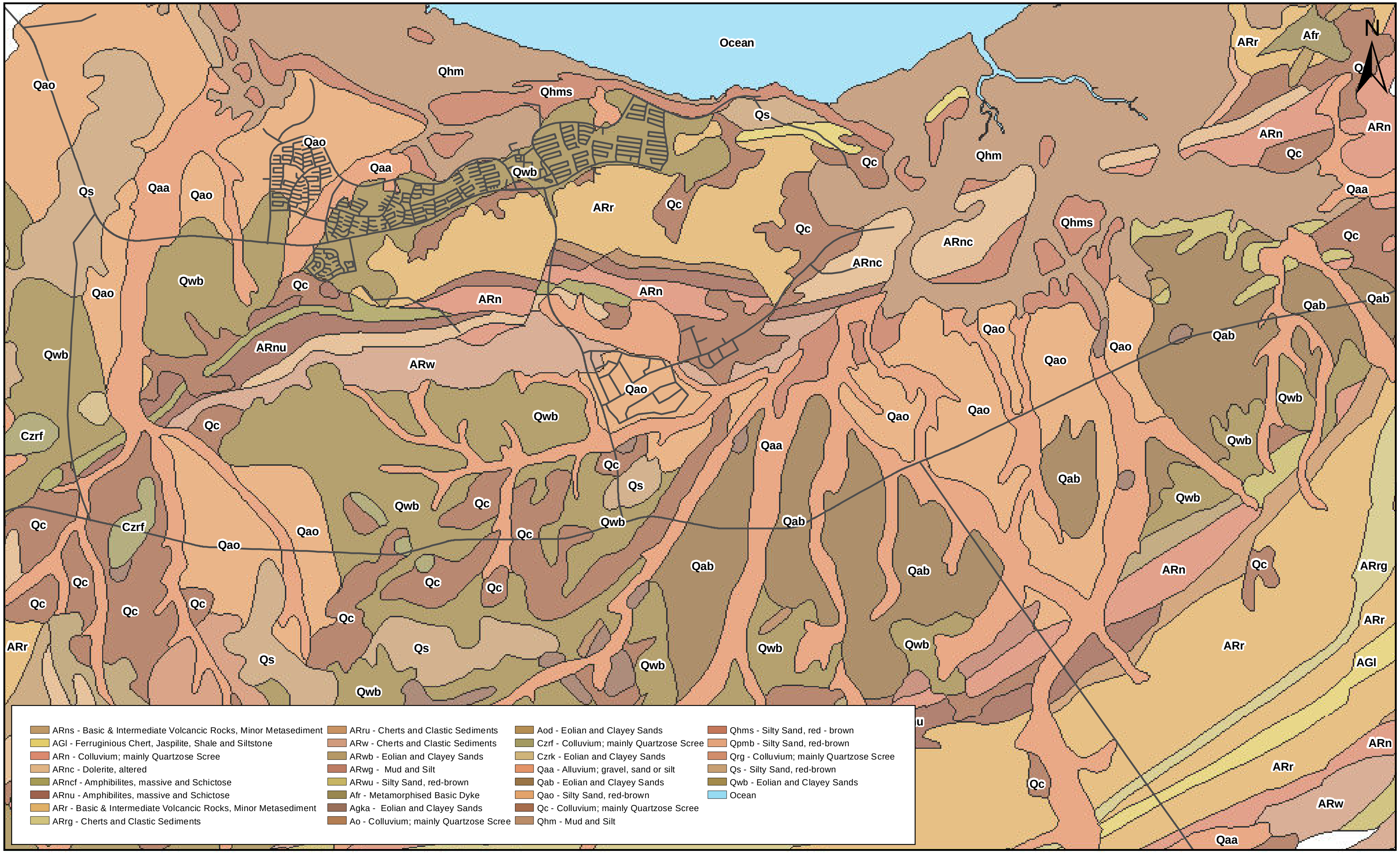


Data Source: NearMap 2011



Job No. J4812
Scale: 1:150,000
0 2.5 5 7.5 10 Kilometers

LandCorp
Karratha Coastal Vulnerability Study Report II: Hydrological Assessment
Figure 3: Topography



Data Source: GSWA 1:250,000 Dampier-Barrow Island Sheet

Job No. J4812

Scale: 1:100,000

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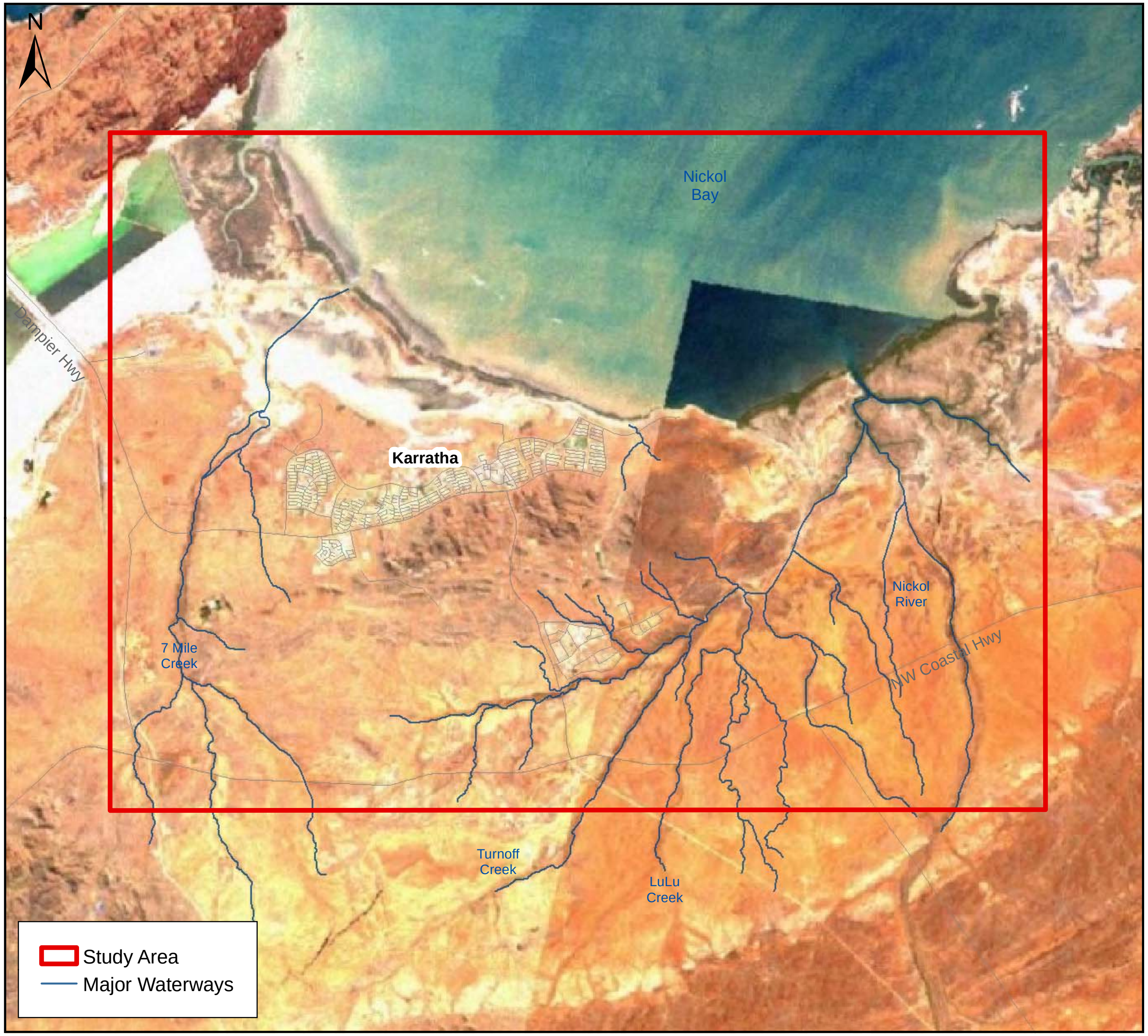
Landcorp

Karratha Coastal Vulnerability Study Report II: Hydrological Assessment

Figure 4 : Regional Surface Geology



Data Source: NearMap 2011

Job No. J4812
Scale: 1:150,000
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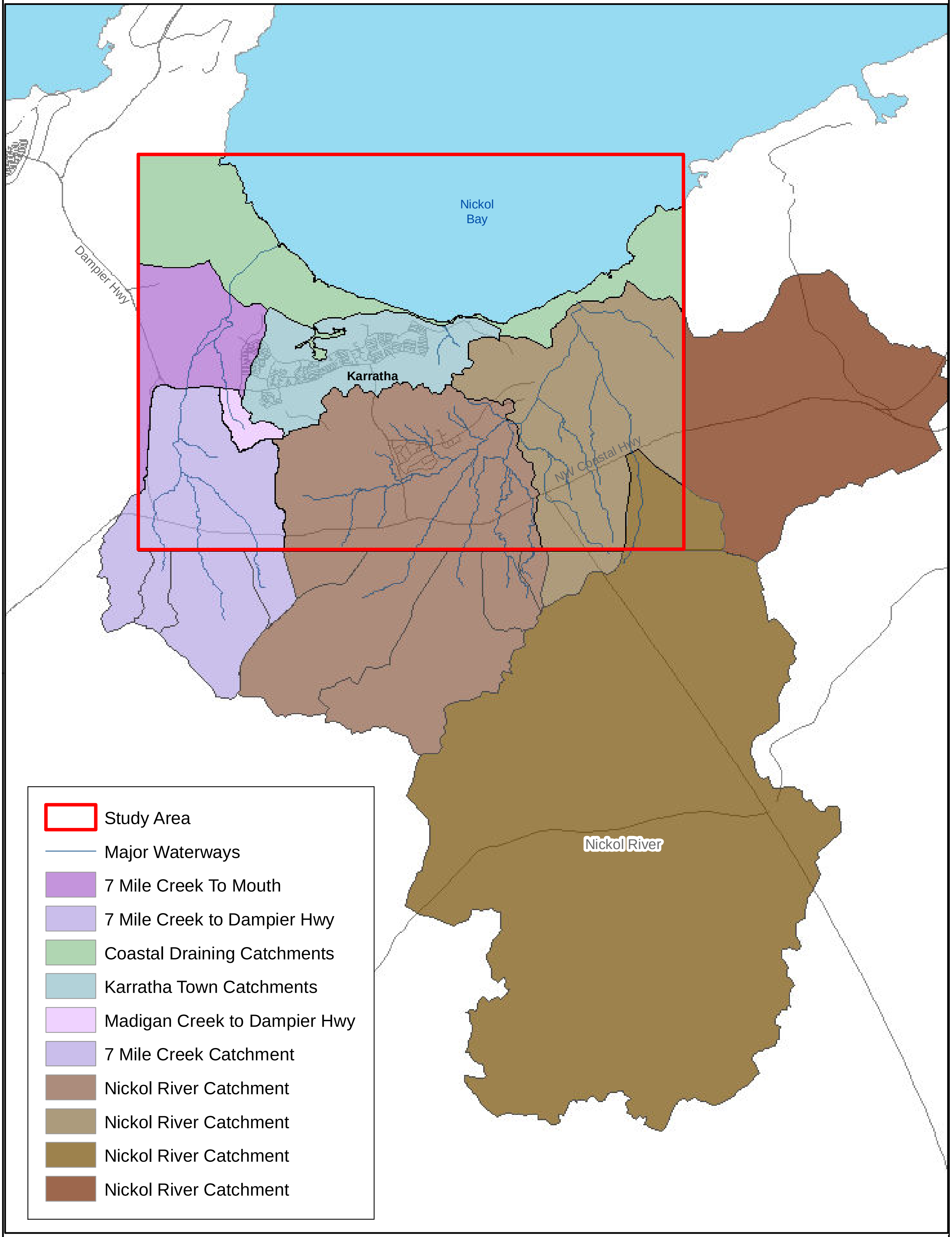
LandCorp
Karratha Coastal Vulnerability Study Report II: Hydrological Assessment
Figure 5: Aerial Photography



Data Source: JDA Hydrological Modelling 2011

JDA Consultant Hydrologists

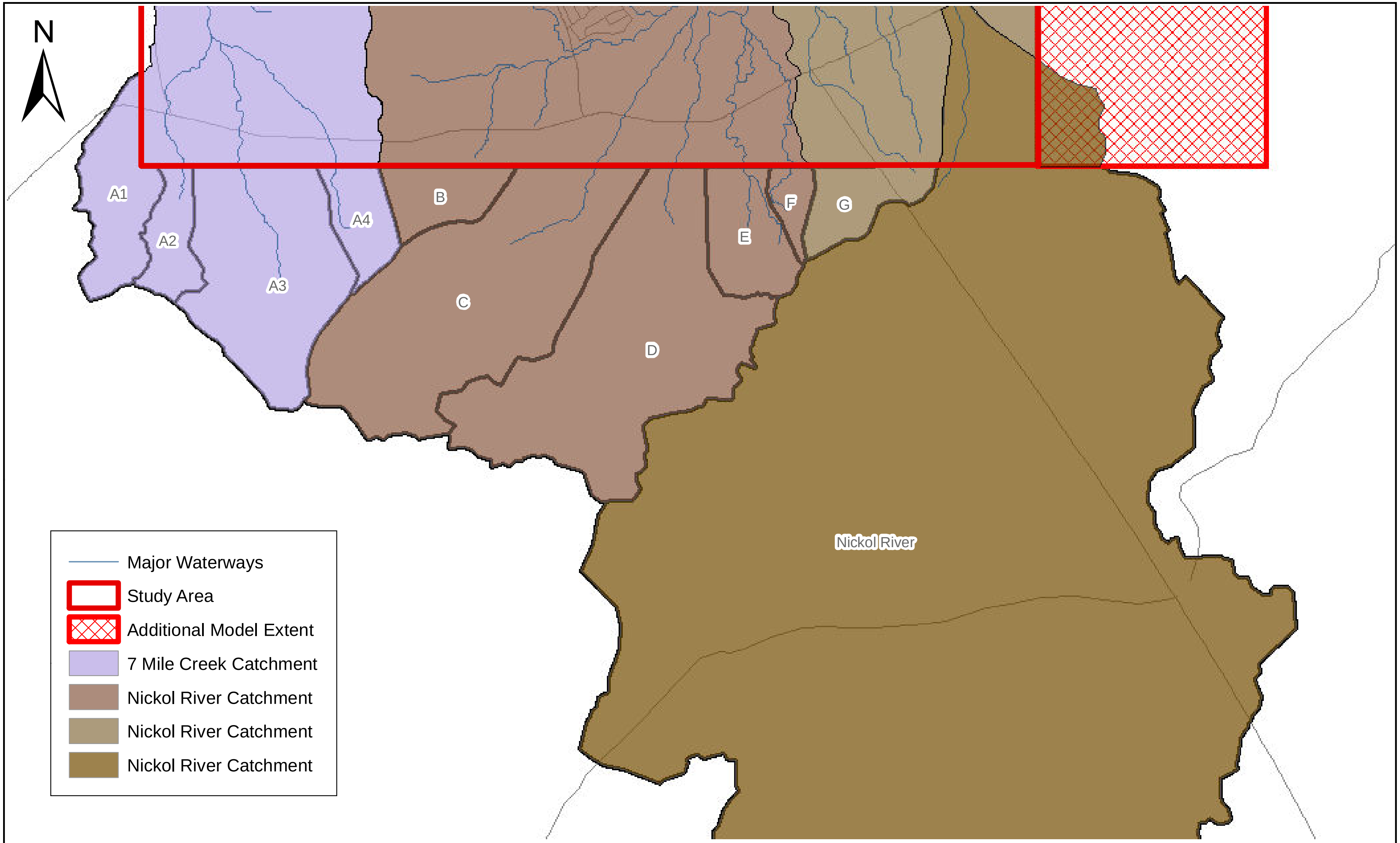
Job No. J4812

Scale: 1:200,000

LandCorp

Karratha Coastal Vulnerability Study Report V: Hydrology

Figure 6: Catchment Mapping



Data Source: JDA Hydrological Modelling 2011

JDA Consultant Hydrologists

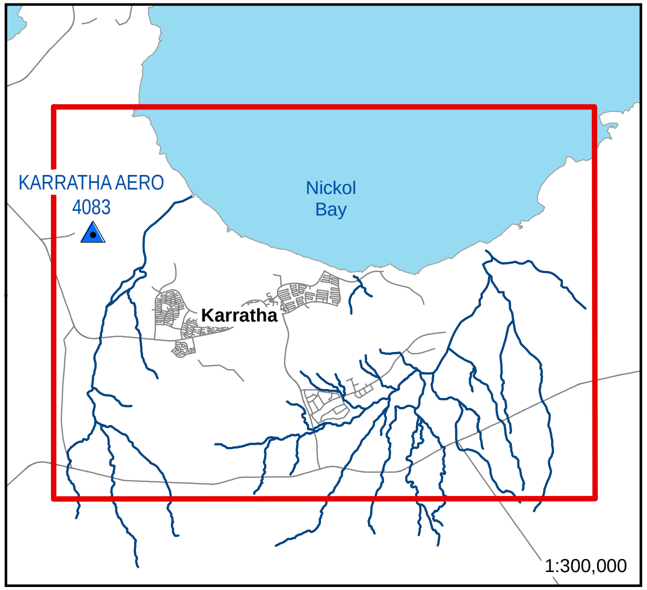
Job No. J4812
Scale: 1:125,000

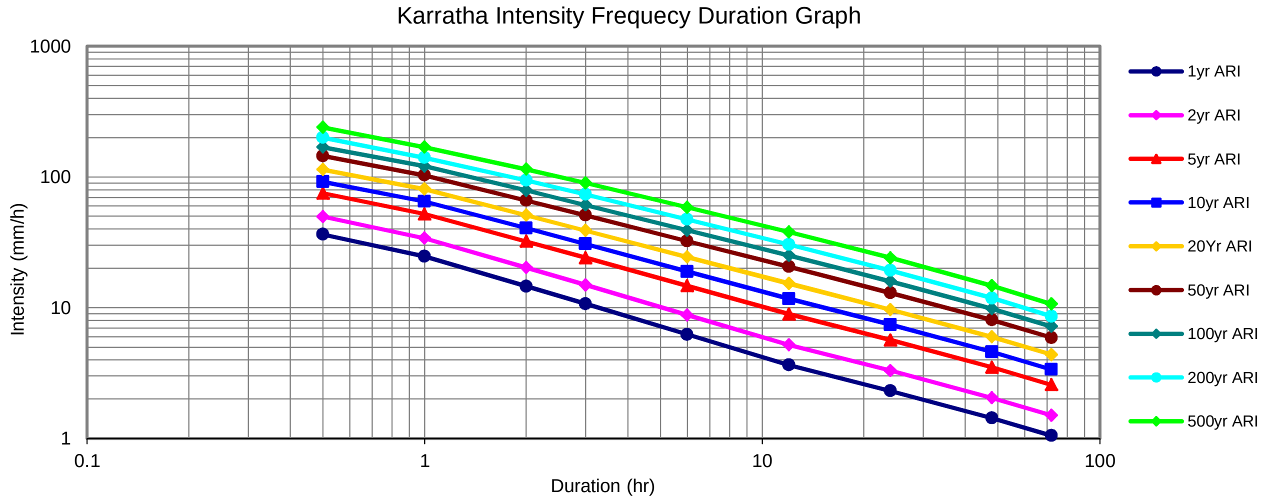
0 5 10 Kilometers

LandCorp

Karratha Coastal Vulnerability Study Report V: Hydrology

Figure 7: Hydraulic Model Input Catchments





Cyclone Bianca (2-5yr ARI): Flooding over the NW Coastal Hwy

Data Source: Shire of Roebourne 2011

Karratha Intensity Frequecy Duration Table

Duration	1 Year	2 years	5 years	10 years	20 years	50 years	100 years
5Mins	78.6	106	157	190	231	289	336
6Mins	73.2	99.1	146	177	216	271	314
10Mins	59.8	81.2	121	147	181	227	264
20Mins	44.1	60.2	91	112	138	175	204
30Mins	35.9	49.1	74.9	92.4	114	146	171
1Hr	23.7	32.7	50.7	63.2	78.8	101	119
2Hrs	14.6	20.3	32.2	40.6	51.3	66.5	79.2
3Hrs	10.7	15	24.2	30.8	39.2	51.3	61.3
6Hrs	6.26	8.83	14.7	19	24.4	32.4	39.2
12Hrs	3.73	5.31	9.01	11.8	15.2	20.4	24.8
24Hrs	2.32	3.3	5.62	7.34	9.53	12.8	15.6
48Hrs	1.45	2.06	3.46	4.49	5.8	7.73	9.37
72Hrs	1.05	1.49	2.5	3.24	4.17	5.57	6.73

Data Source: Bureau of Meteorology 2011

JDA

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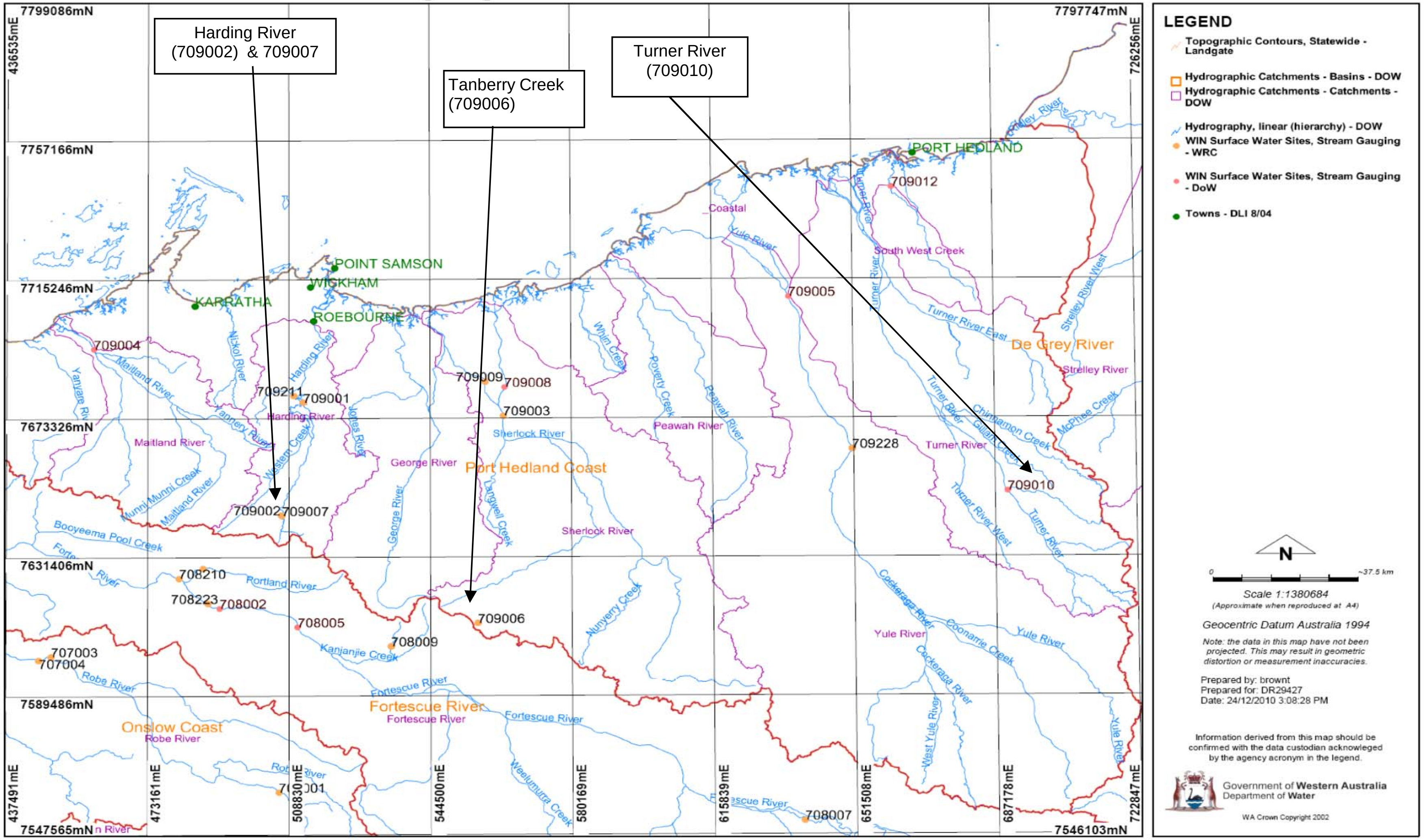
Karratha Coastal Vulnerability Study Report II: Hydrological Assessment
Figure 8: Karratha IFD

Stream gauges Port Hedland Coast



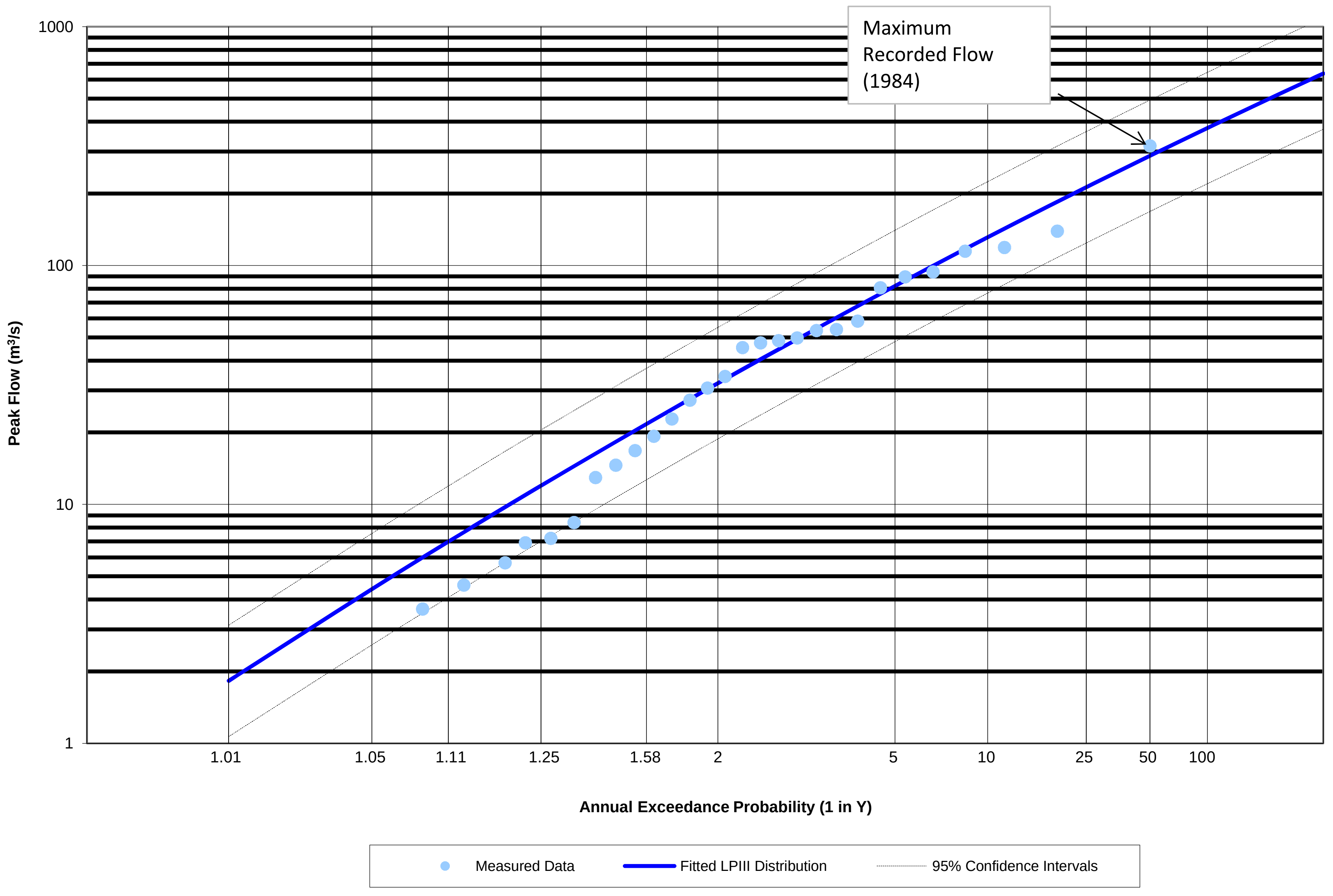
Data Source: Department of Water (DoW) Western Australia

Job No: J4812

LandCorp

Karratha Coastal Vulnerability Study Report II: Hydrological Assessment

Figure 9: DoW Gauging Stations Location



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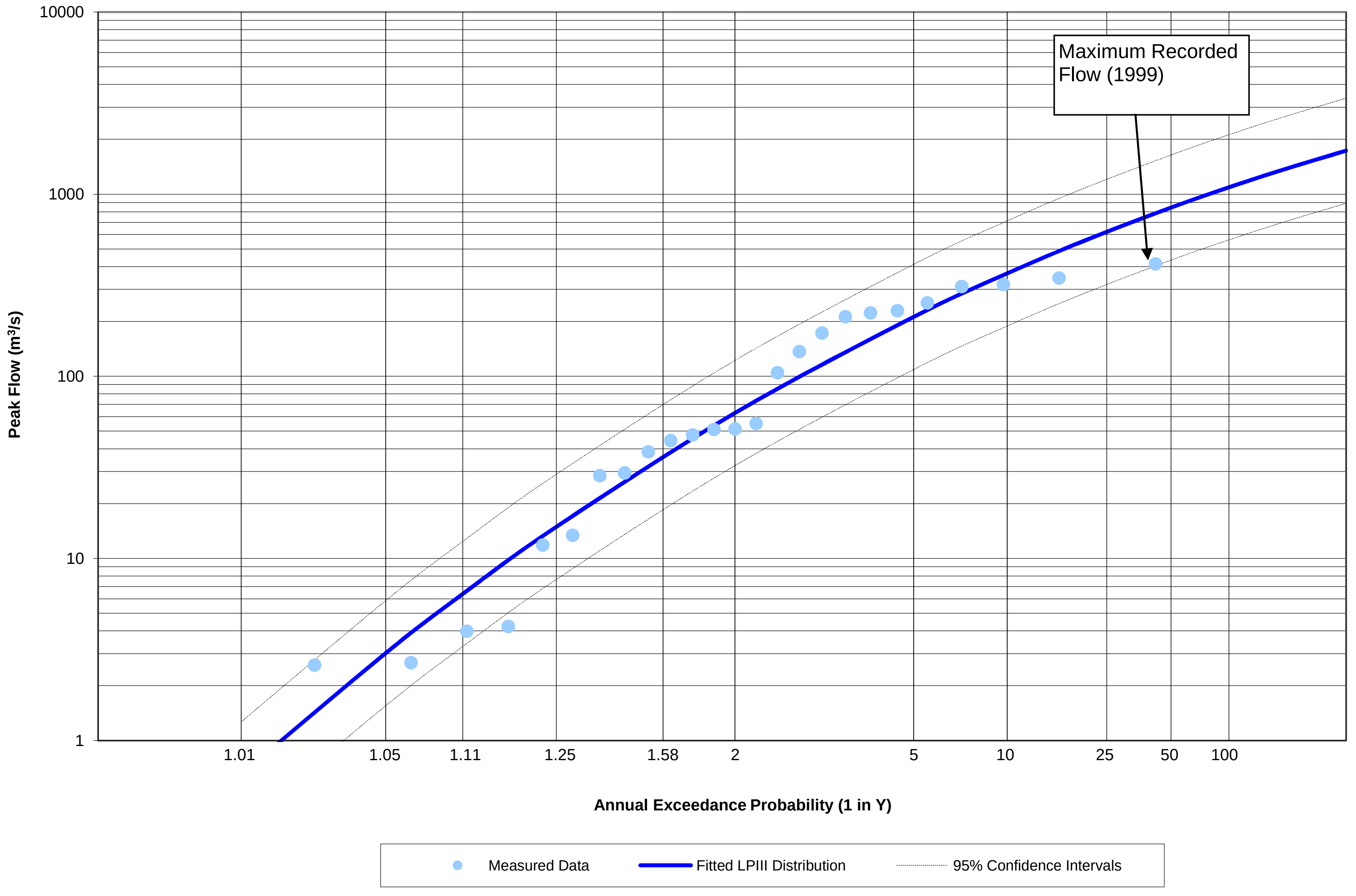
Karratha: Coastal Vulnerability Scope: 2010

Figure 10: Annual Series Flood Frequency for Harding River 709002 & 7090007



Job No. J4812

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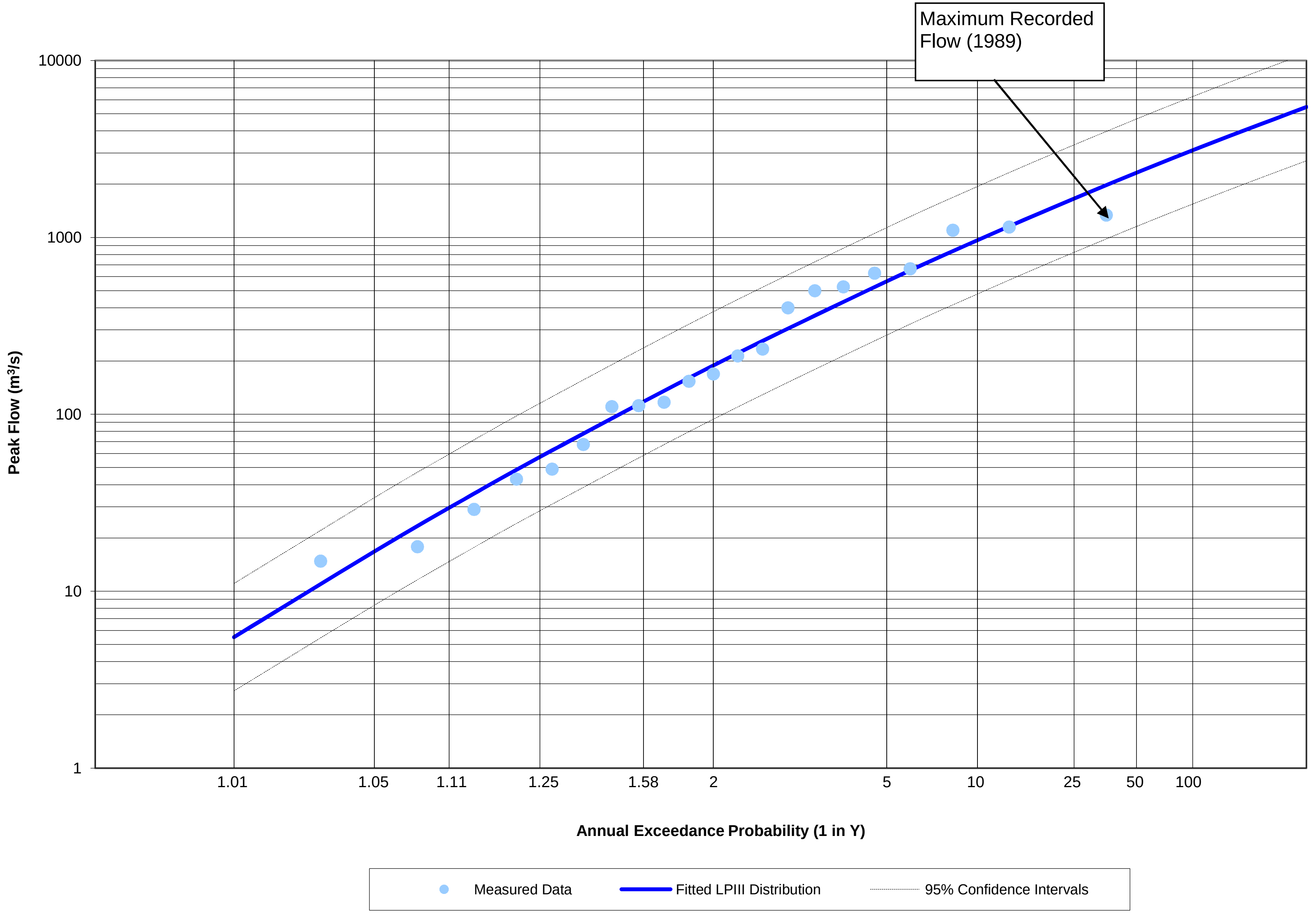
Karratha Coastal Vulnerability Study Report II: Hydrological Assessment

Figure 11: Annual Series Flood Frequency for Tanberry Creek at Blue Dog Pool (709006)



Job No. J4812

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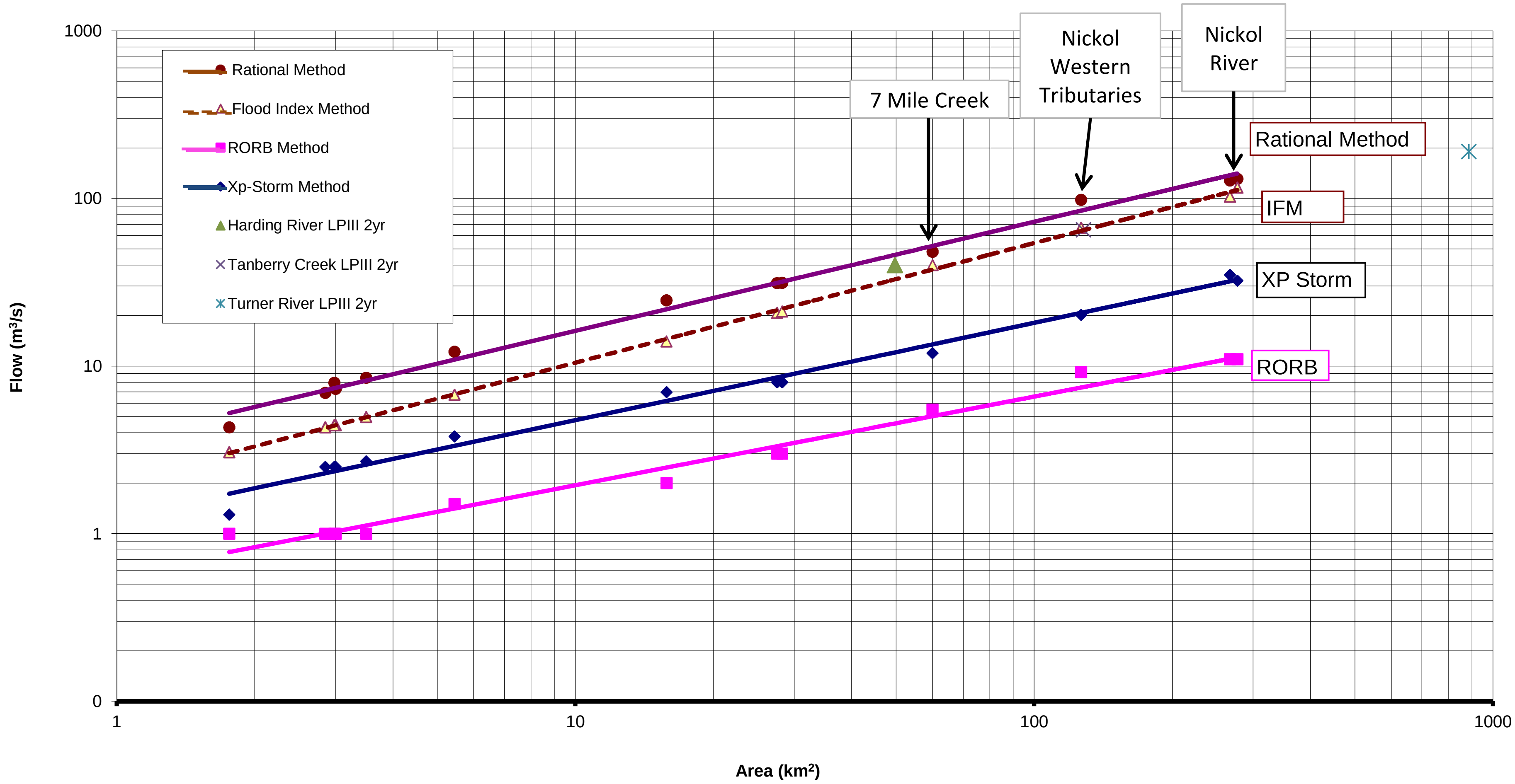
Karratha Coastal Vulnerability Study Report II: Hydrological Assessment

Figure 12: Annual Series Flood Frequency for Turner River at Pincunah (709010)



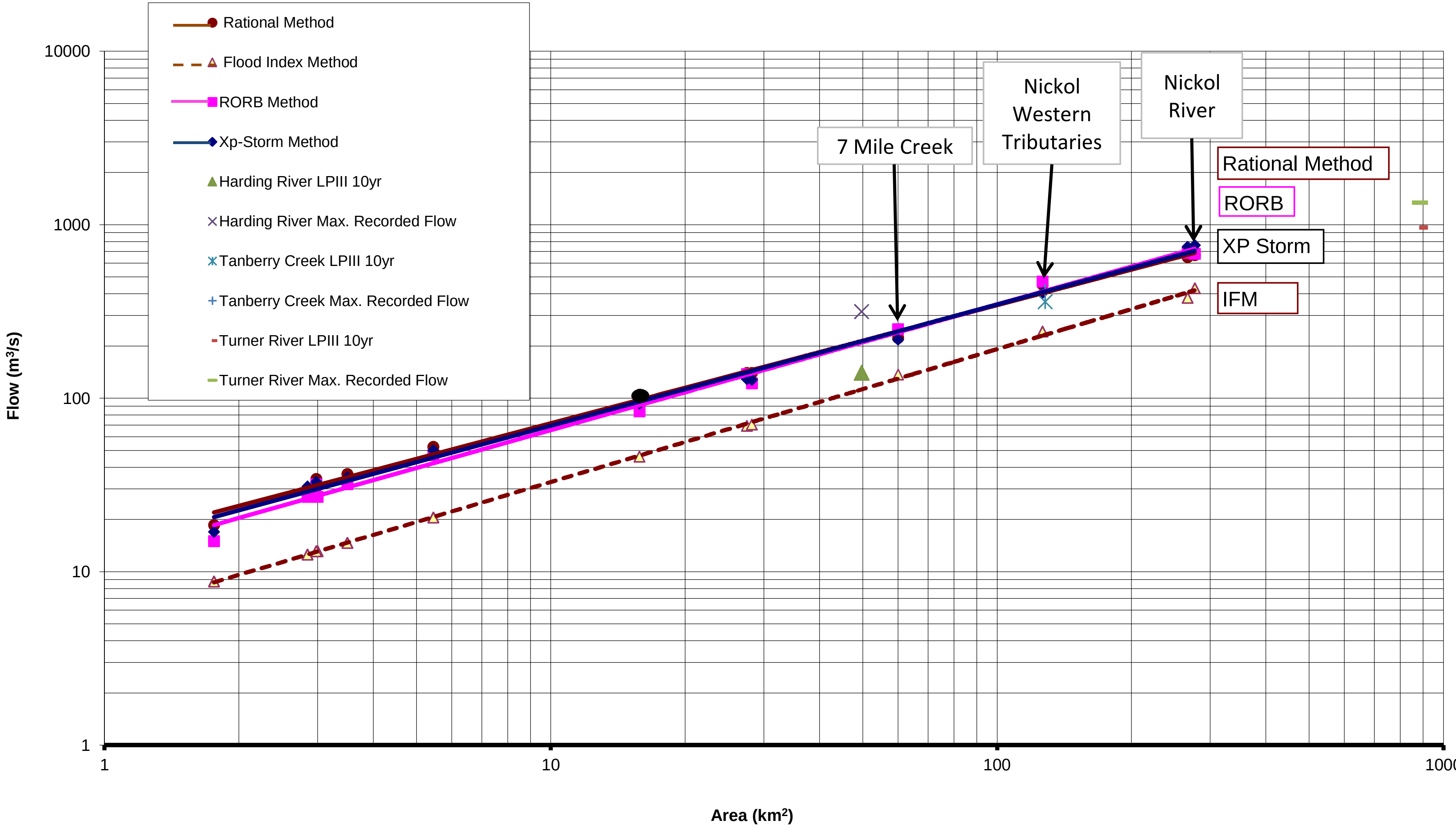
Data Source: AR&R

Job No: J4812

LandCorp

Karratha Coastal Vulnerability Study Report II: Hydrological Assessment

Figure 13: Comparison of Estimated 2yr ARI flows using Rational Method, Index Flood Method, XP-Storm and RORB



Data Source: AR&R

JDA

Job No: J4812

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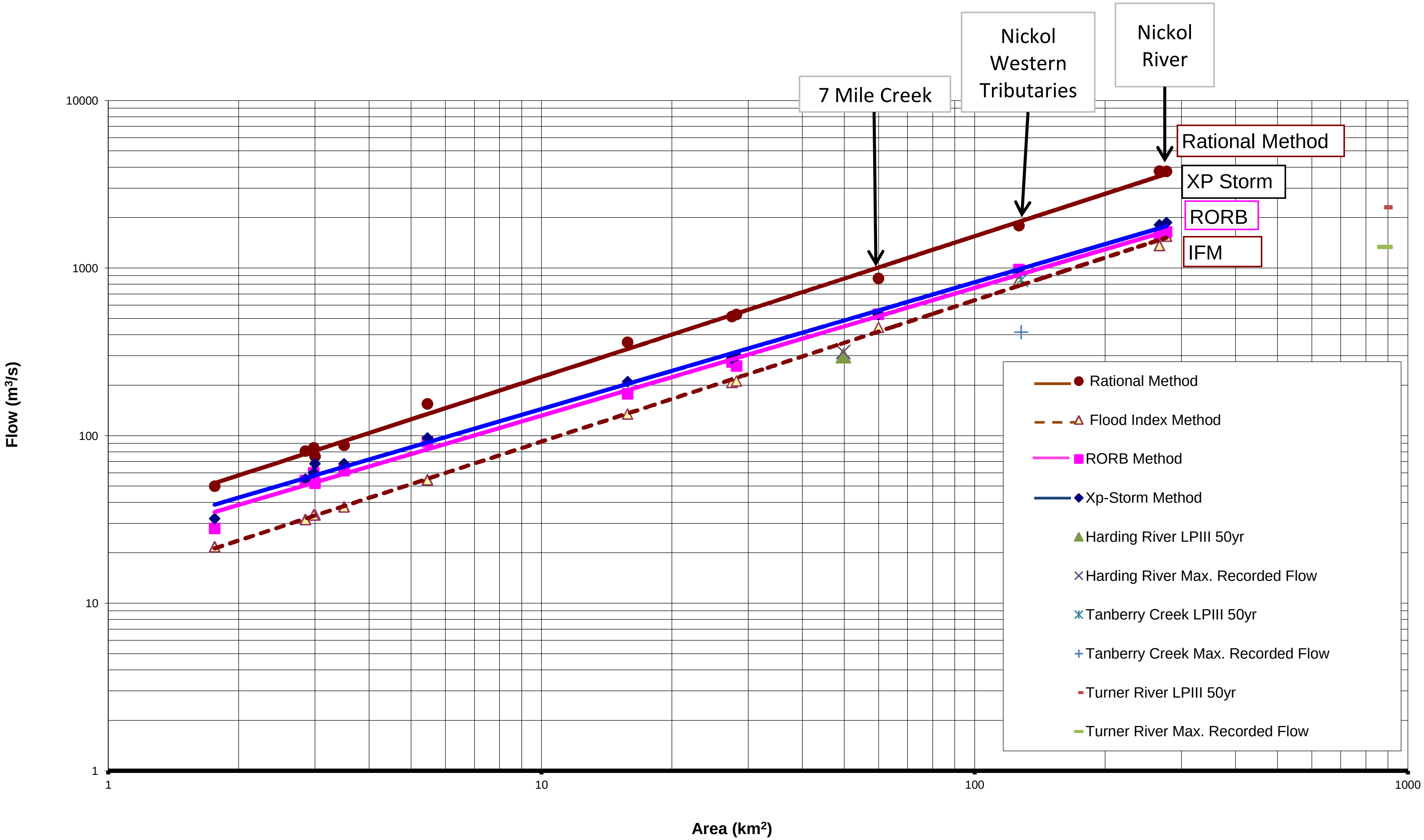
Karratha Coastal Vulnerability Study Report II: Hydrological Assessment

Figure 14: Comparison of Estimated 10yr ARI flows using Rational Method, Index Flood Method, XP Storm and RORB



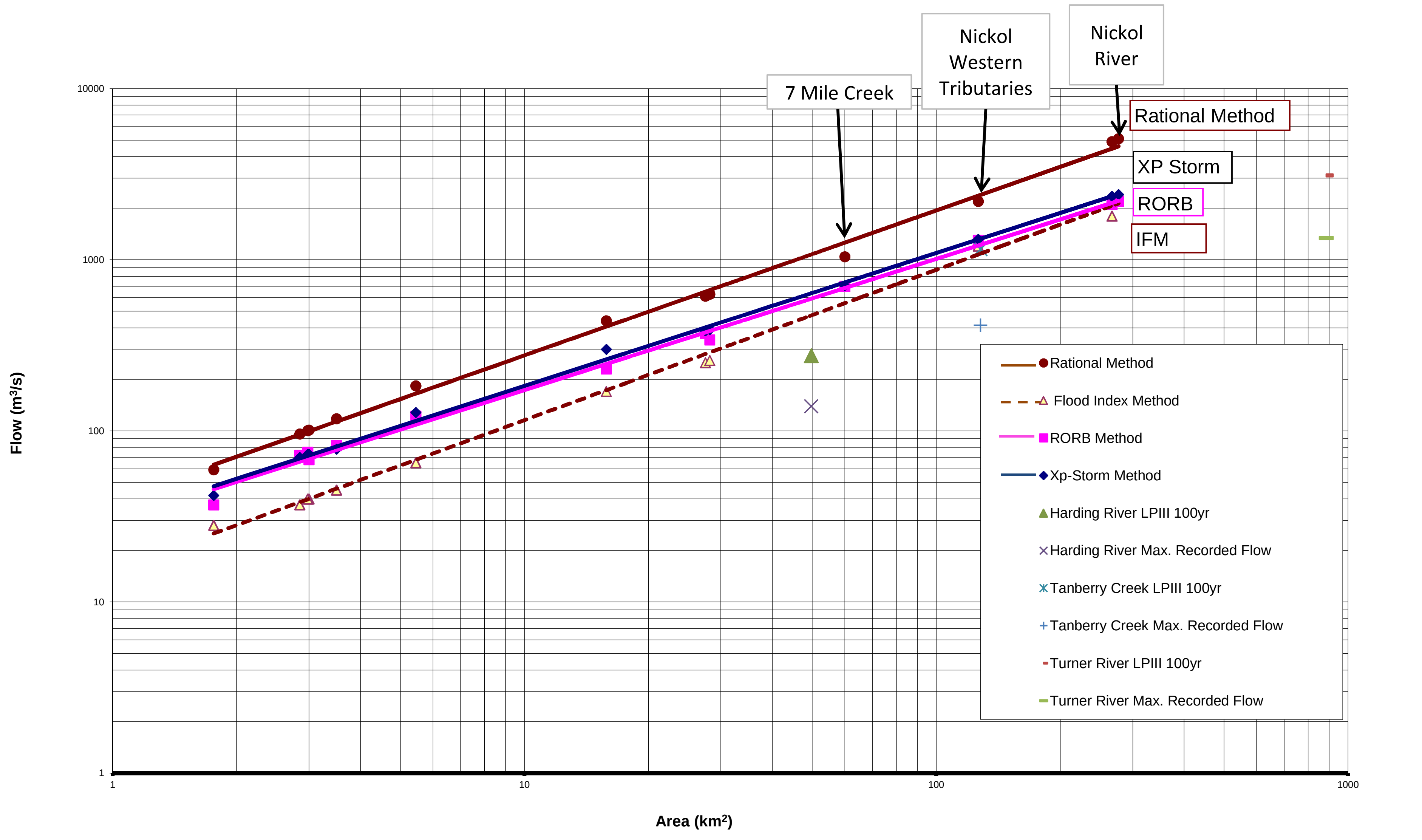
Data Source: AR&R

Job No: J4812

LandCorp

Karratha Coastal Vulnerability Study Report II: Hydrological Assessment

Figure 15: Comparison of Estimated 50yr ARI flows using Rational Method, Index Flood Method, XP Storm and RORB



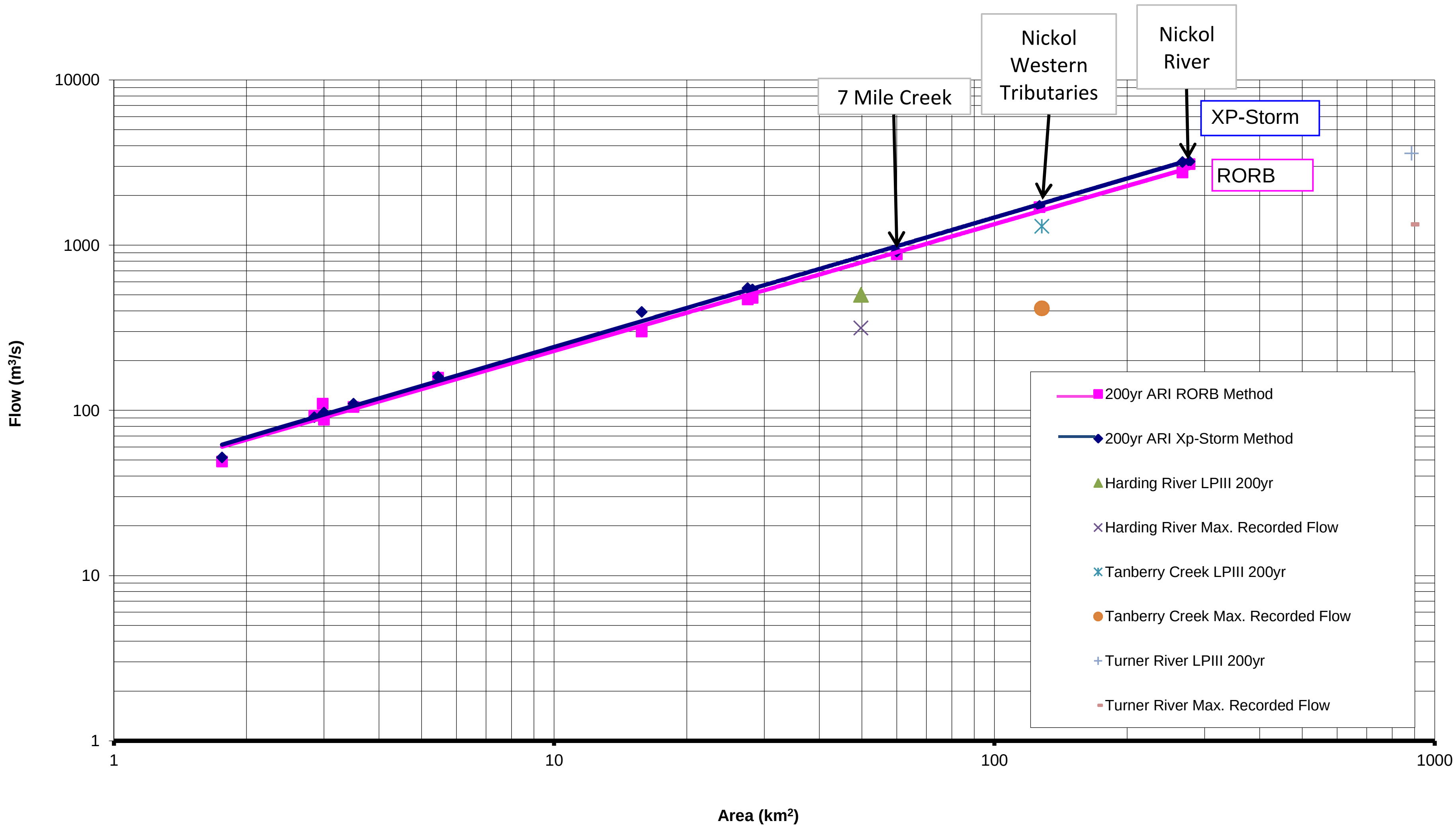
Data Source: AR&R

Job No: J4812

LandCorp

Karratha Coastal Vulnerability Study Report II: Hydrological Assessment

Figure 16: Comparison of Estimated 100yr ARI flows using Rational Method, Index Flood Method, XP Storm and RORB



Note: AR&R recommends that design flows derived from the Rational Method and IFM cannot be extrapolated for events >100yr ARI.

Data Source: AR&R

JDA Consultant Hydrologists

Job No: J4812

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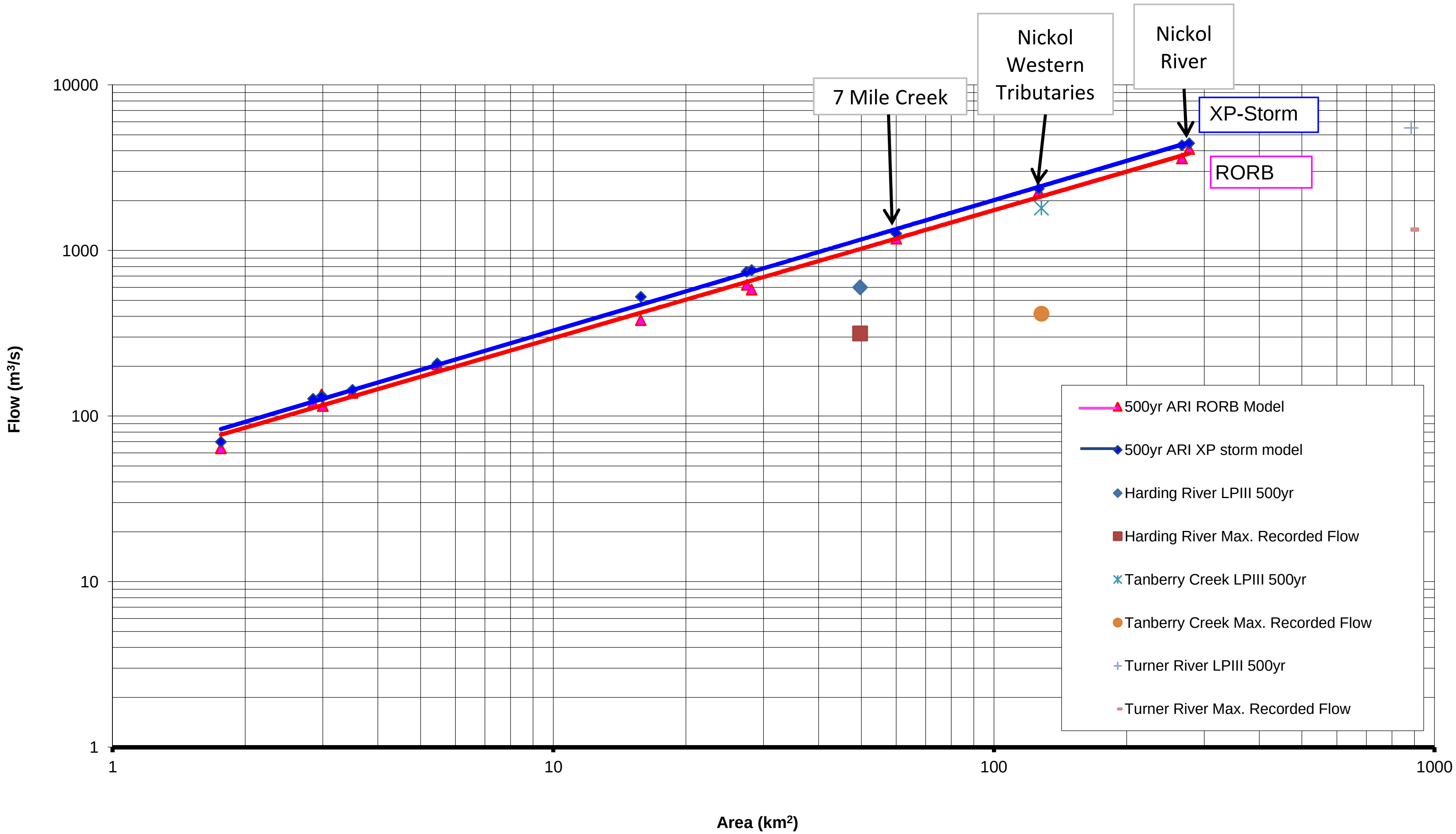
Karratha Coastal Vulnerability Study Report II: Hydrological Assessment

Figure 17: Comparison of Estimated 200yr ARI flows using XP-Storm and RORB Model



Note: AR&R recommends that design flows derived from the Rational Method and IFM cannot be extrapolated for events >100yr ARI.

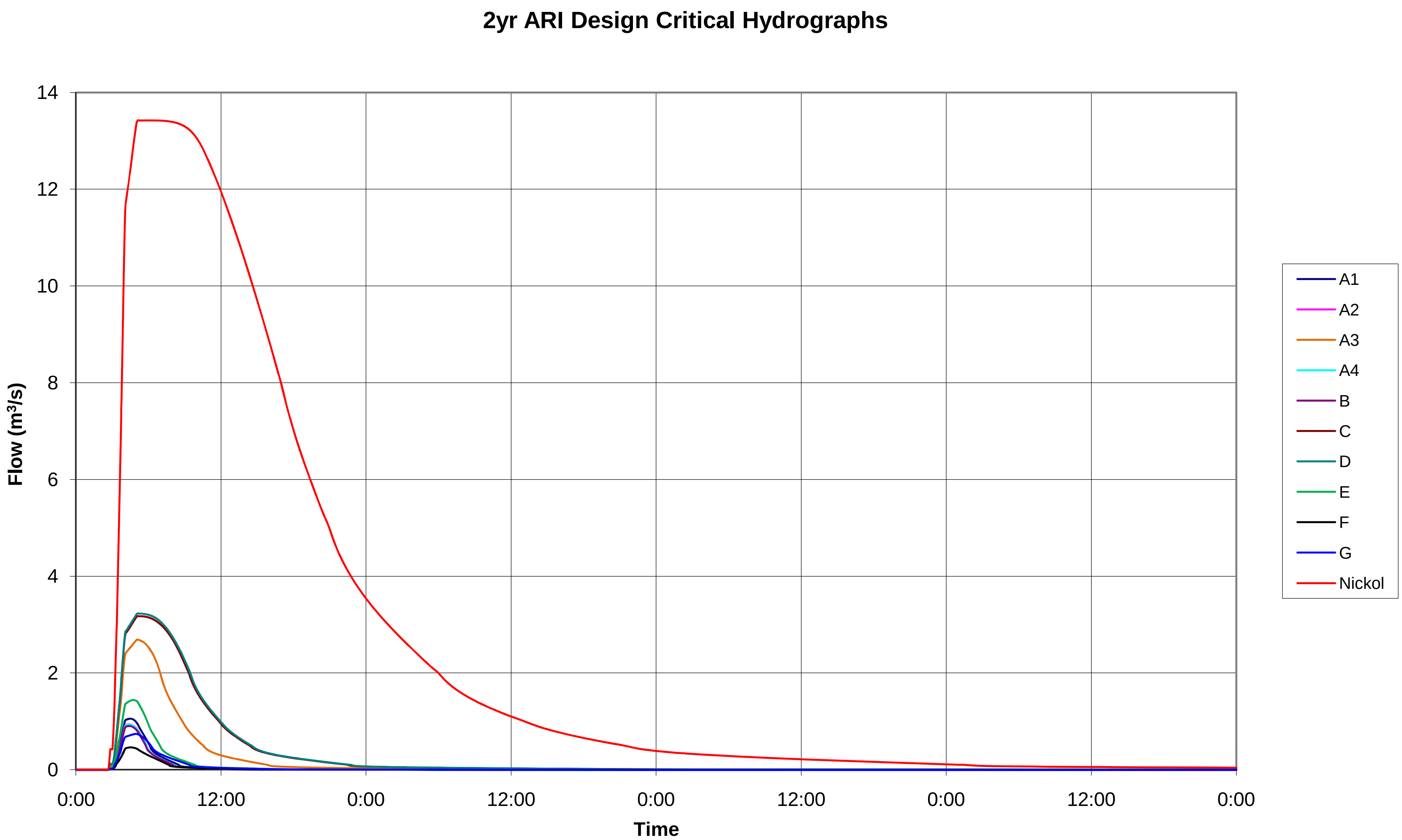
Data Source: AR&R

Job No: J4812

LandCorp

Karratha Coastal Vulnerability Study Report II: Hydrological Assessment

Figure 18: Comparison of Estimated 500yr ARI flows using XP-Storm and RORB Model



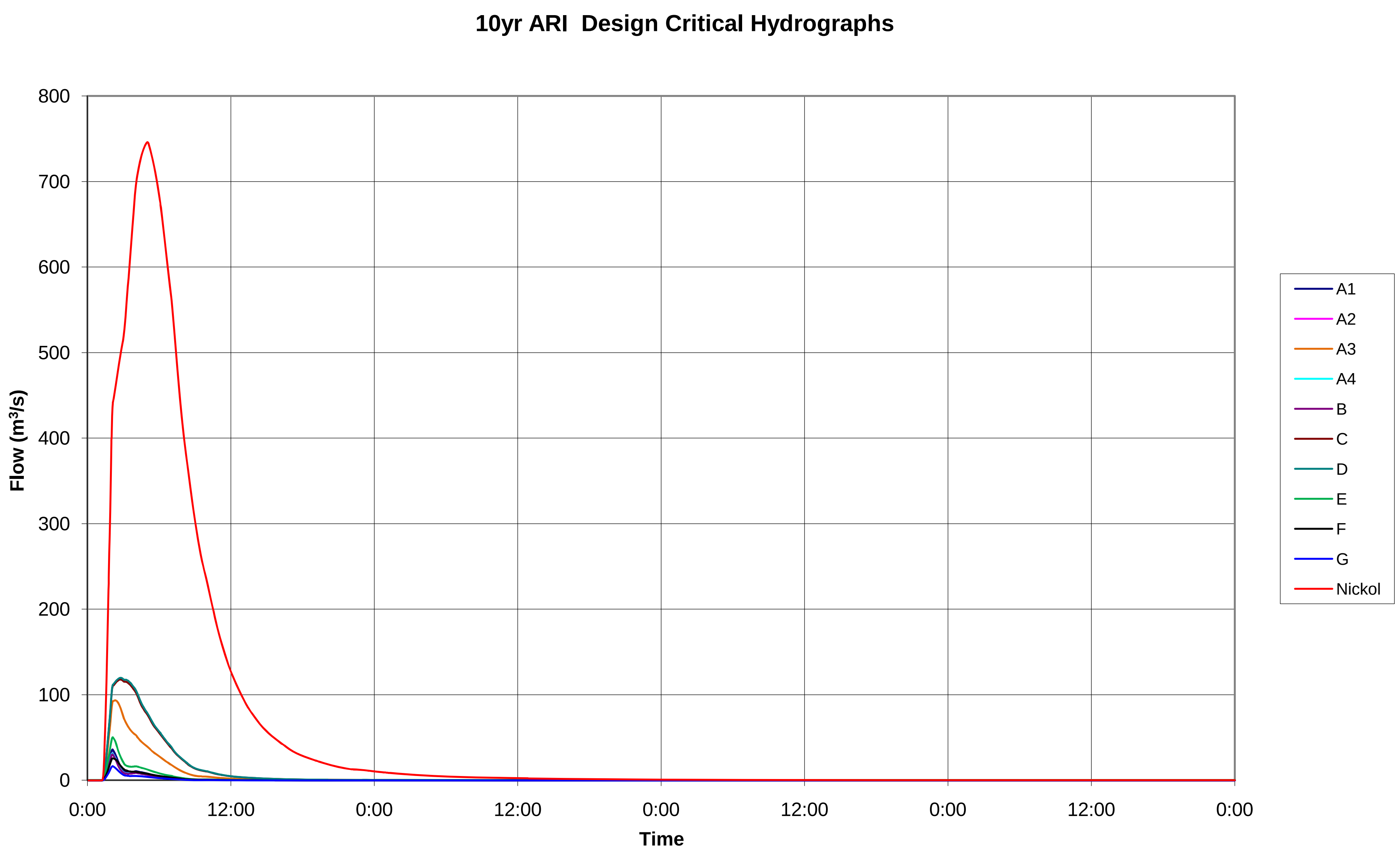
JDA

Job No: J4812

LandCorp

Karratha Coastal Vulnerability Study Report II: Hydrological Assessment

Figure 19: Design Critical 2yr ARI Flow Hydrographs for Catchment Areas External to Hydraulic Model



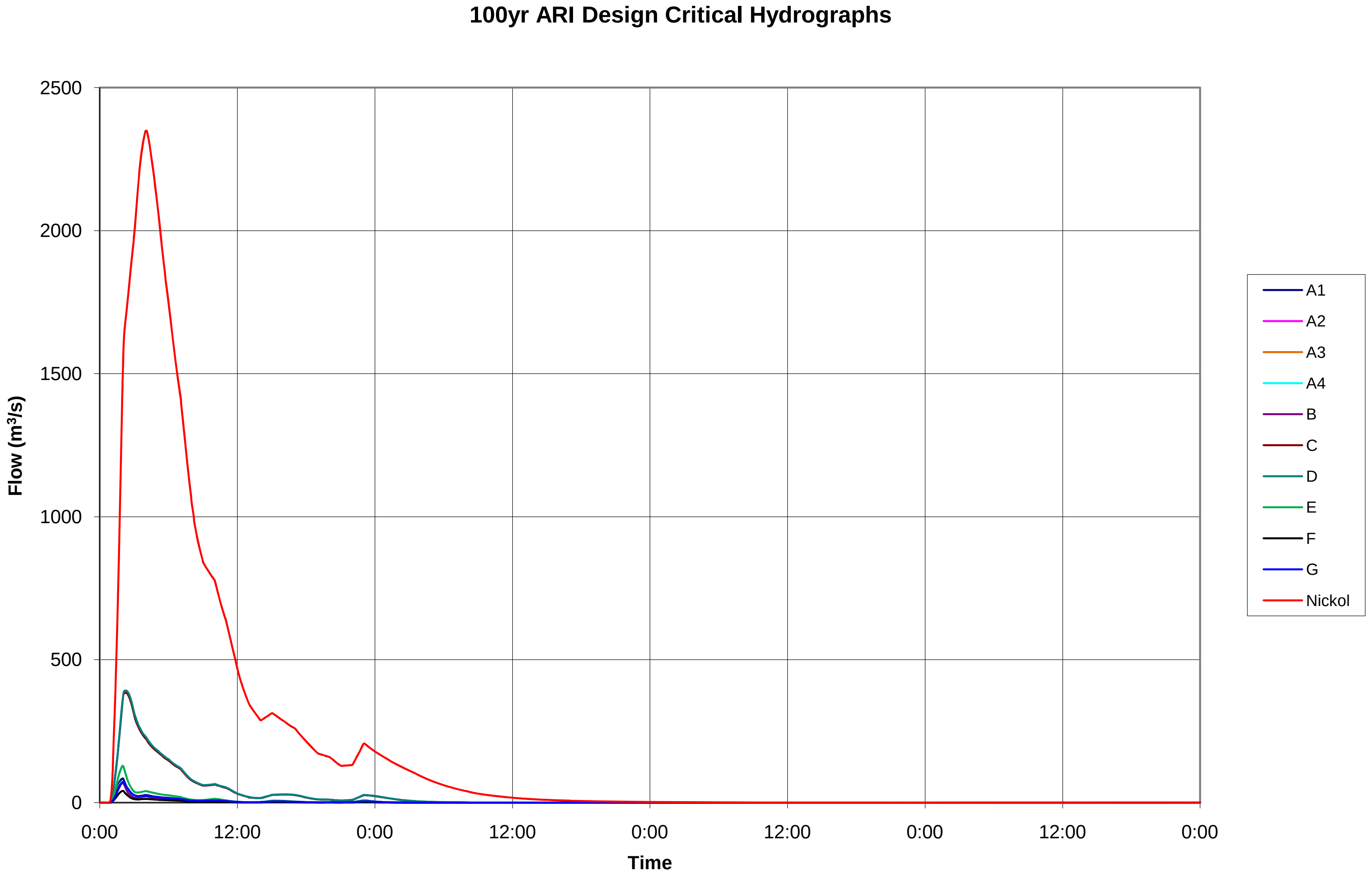
JDA

Job No: J4812

LandCorp

Karratha Coastal Vulnerability Study Report II: Hydrological Assessment

Figure 20: Design Critical 10yr ARI Flow Hydrographs for Catchment Areas External to Hydraulic Model

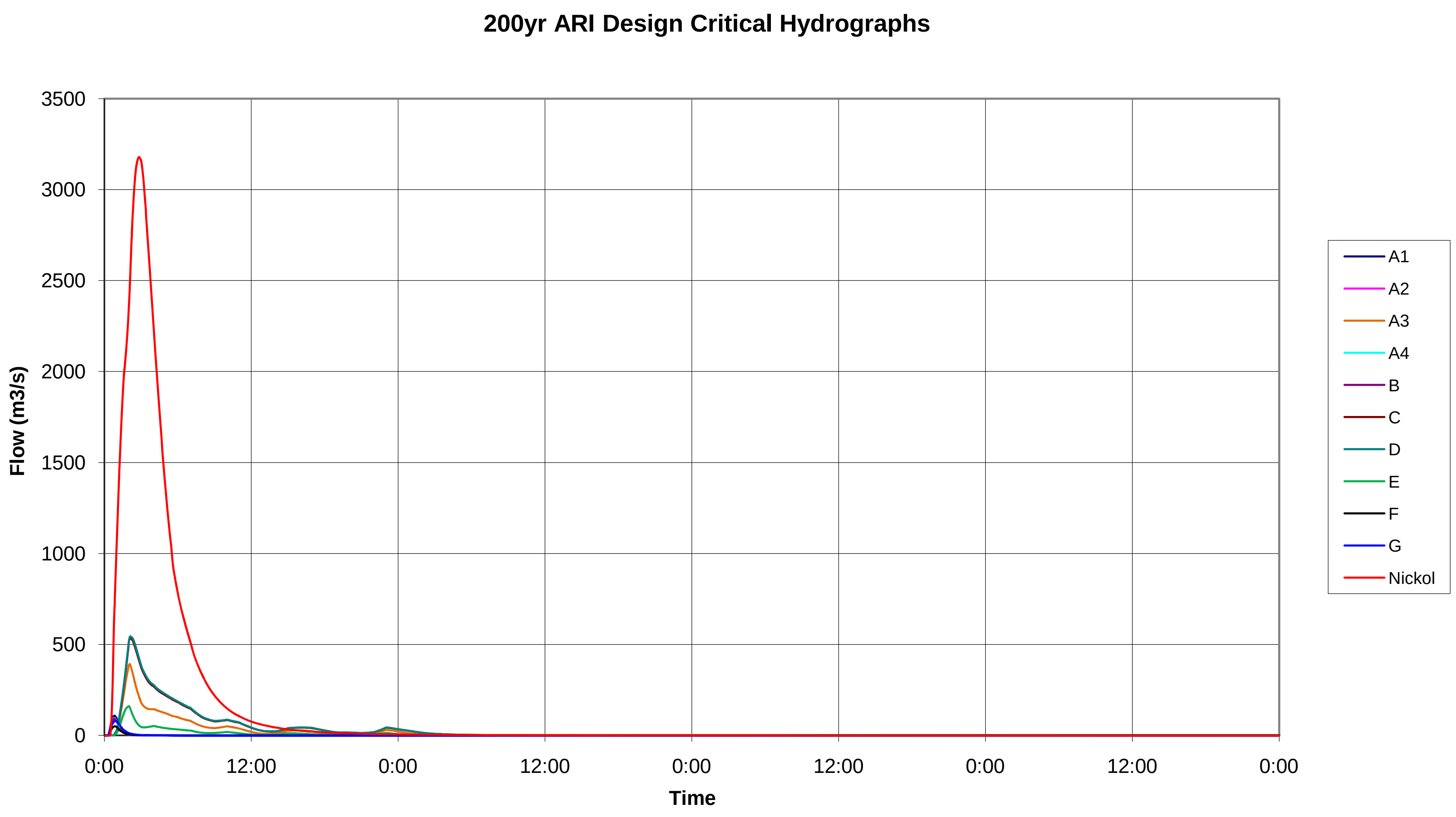


Job No: J4812

LandCorp

Karratha Coastal Vulnerability Study Report II: Hydrological Assessment

Figure 21: Design Critical 100yr ARI Flow Hydrographs for Catchment Areas External to Hydraulic Model



Job No: J4812

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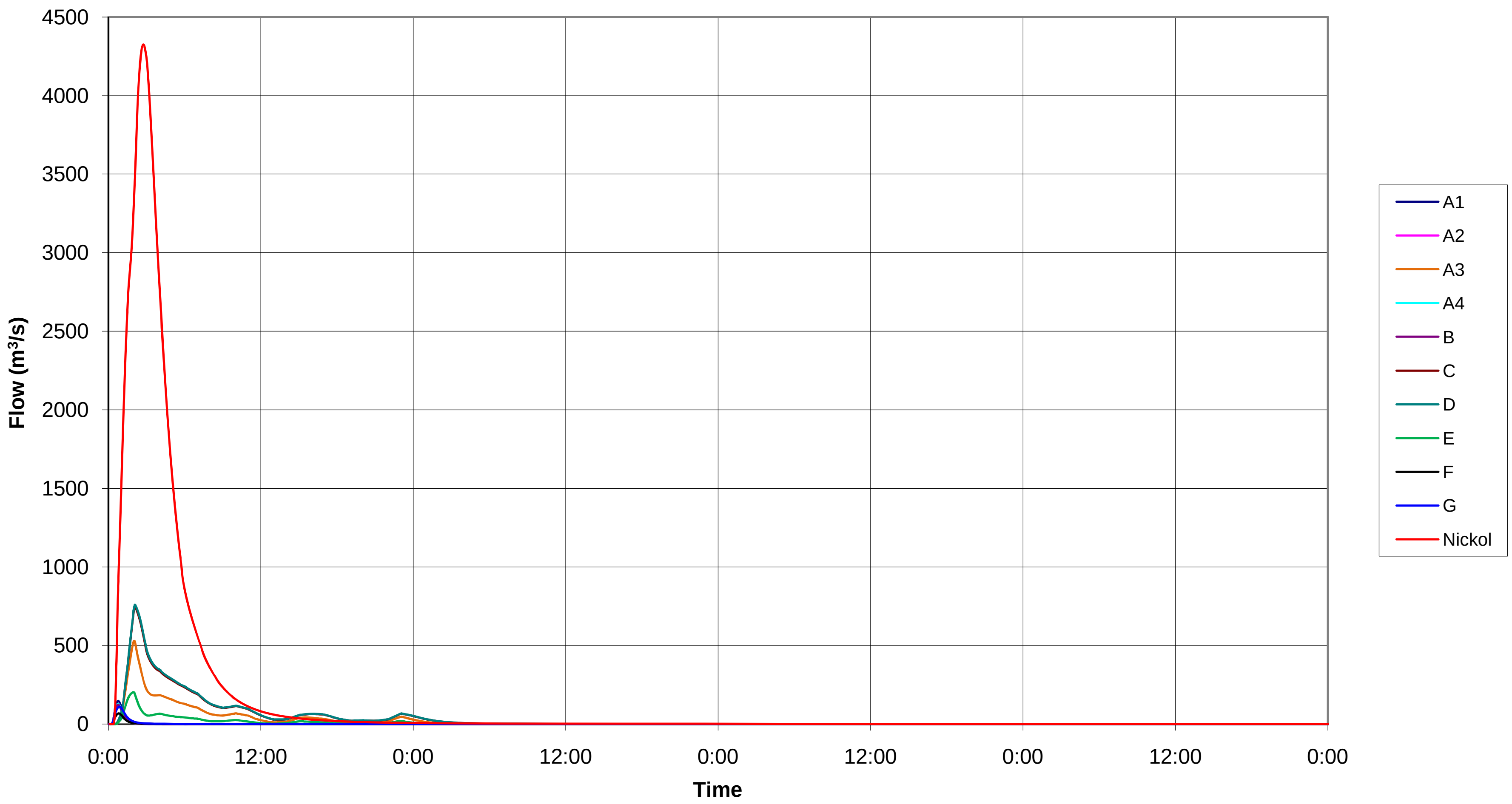
Karratha Coastal Vulnerability Study Report II: Hydrological Assessment

Figure 22: Design Critical 200yr ARI Flow Hydrographs for Catchment Areas External to Hydraulic Model

500yr ARI Design Critical Hydrographs



Job No: J4812

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Karratha Coastal Vulnerability Study Report II: Hydrological Assessment

Figure 23: Design Critical 500yr ARI Flow Hydrographs for Catchment Areas External to Hydraulic Model

KARRATHA COASTAL VULNERABILITY STUDY

ATTACHMENT IV: Storm Surge and Coastal Inundation for Karratha

August 2012

Prepared by:

Global Environmental Modelling Systems (GEMS)

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Version	Date
1 – Draft	April 2011
2 – Revised Draft	May 2011
3 – Final Draft	October 2011

Executive Summary

Global Environmental modelling Systems Pty Ltd (GEMS) has undertaken detailed storm surge modelling as part of the Karratha Coastal Vulnerability Study. This report covers work undertaken for Karratha township; similar work undertaken for the Dampier area is presented in a separate report. The modelling is based on a stochastic methodology under which more than 2000 cyclonic storm surge events have been simulated, allowing for the range of cyclonic impacts to be fully quantified.

Model simulations have been carried out for the three climate change scenarios based on the current climate and 50 years and 100 hundred years hence. These are referred to as 2010, 2060 and 2110 respectively. Changes from the existing climate for the 2060 and 2110 scenarios are based on increased sea levels (0.3m and 0.9m respectively) and a 10 per cent increase in both cyclone frequency and intensity.

For each scenario, inundation levels have been calculated on a regular grid for the region shown in Figure E1 for Average Recurrence Intervals (ARIs) ranging from 2 to 500 years. Figure E2 shows a comparison of the 100yr ARI inundation zones for the three climate scenarios. The table below presents corresponding water levels for the selected locations shown in Figure E1.

100YR ARI INUNDATION LEVELS (mAHD) AT SELECTED LOCATIONS FOR 2010, 2060 AND 2110 CLIMATE SCENARIOS.

SCENARIO	*K1*	*K2*	*K3*	*K4*	*K5*	*K6*	*K7*	*K8*	*K9*
2010	5.5	6.6	7.0	6.6	5.9	6.8	Dry	Dry	7.3
2060	5.7	5.7	6.9	6.9	6.1	7.1	Dry	Dry	7.6
2110	6.1	7.5	7.7	7.2	6.5	8.2	6.1	6.9	8.7

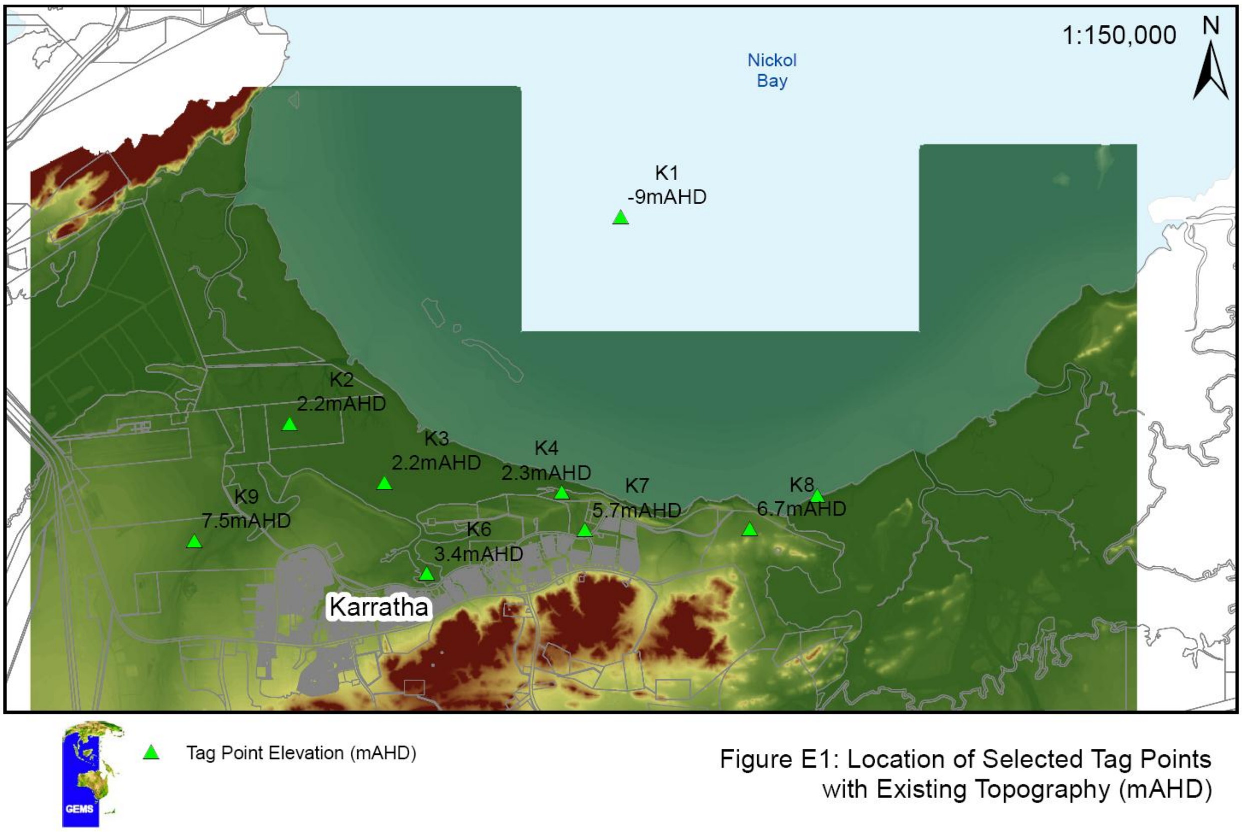

Figure E1: Location of Selected Tag Points with Existing Topography (mAHD)

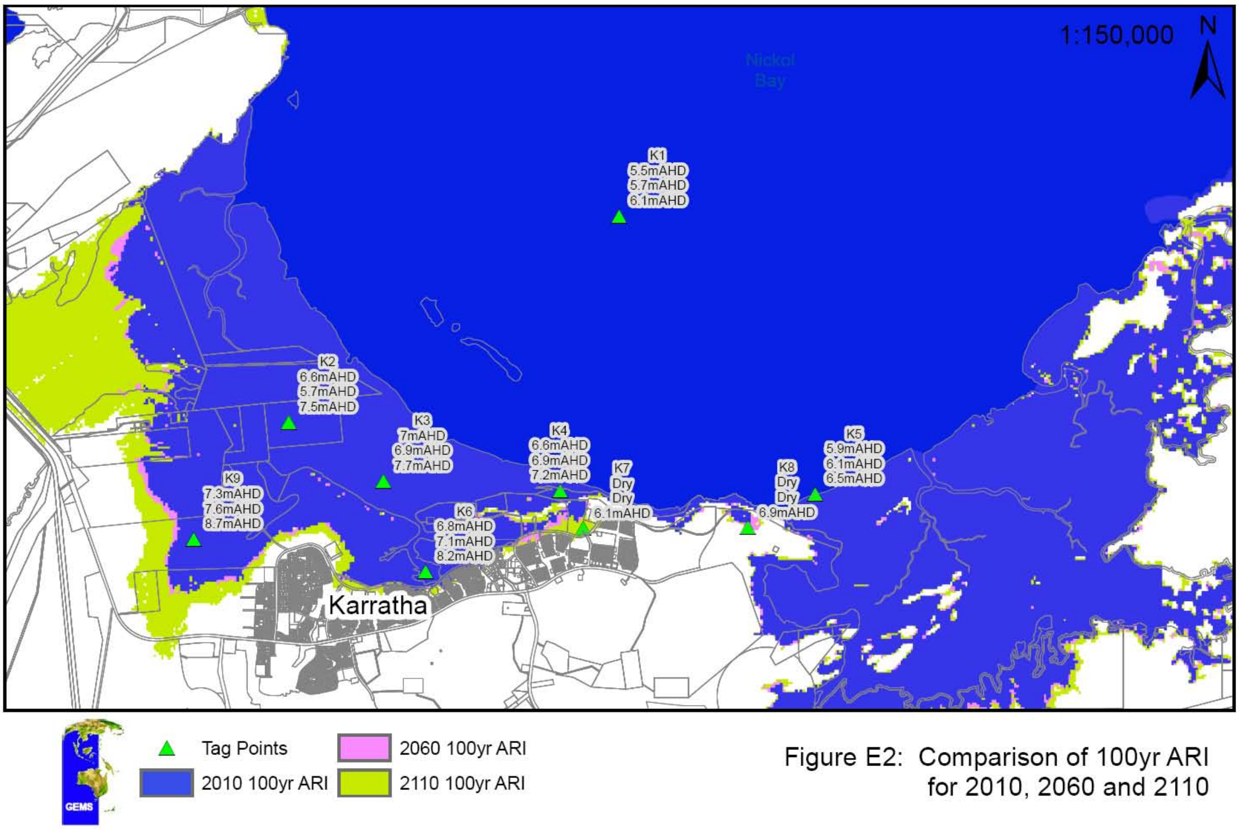

Figure E2: Comparison of 100yr ARI for 2010, 2060 and 2110

The results for the current climate (2010) are, as expected, consistent with earlier studies carried out for the Shire of Roebourne. However, the results from this study are improved by the availability ofmuch more detailed topographic data and a longer cyclone record.

Generally, storm surge levels are higher in the Seven Mile Creek region (K9) compared to the NickolRiver region. This is essentially because of the preferred angle of attack of cyclones and the orientation of Nickol Bay.

For a 100yr ARI event under current climate conditions, some lower parts of the Karratha town site would be expected to experience flooding, up to a level of the order of 6.8mAHD. Results for the 2060 and 2110 scenarios show relative increases in predicted water levels generally commensurate with predicted sea levels. That is, the modelled increases in storm frequency and intensity have only minor impact on overall results.

However, flooding for the existing Karratha town site for the 2110 scenario is much more significant with 100yr ARI levels rising from 6.6m to 7.5mAHD at K2. Points K7 and K8 remain ‘dry’ for the 2010 and 2060 climates, but are inundated for the 2010 scenario.

GLOSSARY

Australian Height Datum (AHD)	The datum to which all vertical control for mapping is to be referred to in Australia.
Average Recurrence Interval (ARI)	The averagereturnperiod or frequencyof an event.
Bathymetry	The ocean’s surface shape, relief, landforms and features.
Boundary Condition	The conditions of a parameter at the boundary of its domain, for example the water level at the downstream extent of a hydraulic model.
Digital Elevation Model (DEM)	A digital representation of ground surface topography consisting of regularly spaced elevation values.
Foreshore	The area of land that adjoins or directly influences a waterway, including the furthest extent of riparian vegetation, flood prone land and riverine landforms.
GEMSURGE	Two-d storm surge model developed by Global Environmental Modelling Systems Pty Ltd.
Holland Model	Empirical wind model for tropical cyclones for the Australian region developed by Bureau of Meteorology.
Peak Steady Water Level (PSWL)	Increase in water level incorporating the effects of storm surge, wave set-up and tide.
Radius of Maximum Winds	Distance from cyclone centre to the area of strongest winds around a tropical cyclone.
Still Water Level	As Peak Steady water level but excluding wave set-up.
Storm Surge	Increase in water level due to effects of wind stress and low atmospheric pressure.
Topography	The Earth's surface shape, relief, landforms and features.
Wave Set-up	Mean increase in sea level due to the effect of breaking waves near a shoreline.

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APPENDICES

1. INTRODUCTION

The aim of this study is to assess the storm surge impacts for the Karratha Coastal Vulnerability study. It been produced on behalf of Landcorp by Global Environmental Modelling Systems Pty Ltd (GEMS) for the Landcorp funded Karratha Coastal Vulnerability Study.

The two objectives of this study are:

- To evaluate the combined effects of storm surge, coastal inundation (flooding) and shoreline stability on the future expansion of the town site for Karratha (including Dampier town-site), and;
- To provide estimates of the storm surge components and total water levels for a range of design return periods along Karratha coastline.

Assessment of cyclonic conditions and extreme storm surge was performed to determine the corresponding peak steady water level. This included examination of the combined effects of tide, storm surge and wave set-up. Storm surge levels were determined for five return periods (2yr, 10yr, 100yr, 200yr and 500yr ARI). Model calibration and validation within the modelled area was also performed.

The storm surge levels were also determined for the 2060 and 2110 climate scenarios.

The results presented in this report cover Karratha township; similar work undertaken for the Dampier area is presented in a separate report.

1.1 GEMS

Global Environmental modelling Systems Pty Ltd (GEMS) has particular expertise in storm surge modelling and has undertaken a large number of major storm surge studies in Western Australia.

Accordingly, the role of GEMS within the broader study is to undertake all of storm surge components. This includes interfacing with JDA to provide advice on suitable downstream boundary conditions for hydraulic flood modelling. GEMS have also provided related wave model output to inform the shoreline modelling aspects of the project.

1.2 Structure of Storm Surge Model Reporting

1.2.1 Overview

Reporting of storm surge modelling for the project is presented in separate parts, one each for the Karratha area modelling (this document) and for the Dampier area modelling. In order that the reports for the two regions may be considered independently, full descriptions of the methodology and numerical models are included in each.

1.2.2 Model Validation

A separate document (Appendix B) has been included to describe the validation of the storm surge model(s). This includes references to work included in original scientific publications, validation modelling previously undertaken within the local region and specific validation modelling using the model set-up for the current project.

The quantitative validation undertaken for the current project is more heavily focussed on the Dampier area since the King Bay tide gauge provides historic measurements for water levels in that area. By comparison, there is very little quantitative information for the Karratha area.

1.3 Conventions

The following conventions apply in this report:

- unless otherwise stated, water levels are referenced to Australian Height Datum (AHD);
- wind and wave directions are the direction 'from' and are referenced to true North, and
- all geographic locations are based on the AMG 50 coordinate system.

2. REVIEW OF PREVIOUS STUDIES

Two comprehensive storm surge studies have previously been carried out for the Karratha-Dampier region. These are summarized in Table 1.

TABLE 1: SUMMARY OF PREVIOUS STUDIES

Study	Client	Year	Consultant	Overview
Karratha Storm Surge Study	Shire of Roebourne	1997	Bureau of Meteorology	Original Karratha study reporting surge levels at selected locations
West Pilbara Cyclonic Storm Surge Study	Shire of Roebourne(Study No G06/0506)	2009	GEMS	1997 study results converted to GIS layers Worst ‘track’ inundation estimates computed consistent with WA SPP 2.6

The 1997 study was carried out by the Bureau of Meteorology Special Services Unit, using the pre-cursor model to the GEMSURGE model. The study area included the greater Karratha area, Dampier Salt infrastructure and Mermaid Sound. The wave set-up component of water level (see Section 3 for description) was computed indirectly from offshore wave heights computed using the WAM wave model. Storm levels in this study were reported for spot locations, rather for the entire model grid.

The West Pilbara Cyclonic Storm Surge Study completed in 2009 was primarily focussed on the Cape Lambert area but included some work undertaken to update the 1997 study. This included computation of inundation levels for design storms to meet the requirements of WA State Planning Policy 2.6.A noted limitation of the earlier studies was the lack of a comprehensive high resolution DEM for the area.

The current study is expected to improve the accuracy of the previous work because of four main factors:

- improved definition of the topography through application of a new Digital Elevation Model based on recent LIDAR surveying for the area;
- a more extensive cyclone database;
- improved modeling techniques in relation to the treatment of wave set-up, and
- the ability to undertake a higher number of model simulations due to increased computing speed.

3. METHODOLOGY

The methodology used to determine the storm surge for different ARI events is outlined in this section of the report.

3.1 Overview of Cyclone Impacts

3.1.1 Technical Definition

The tropical cyclone season in Australia occurs typically from November to April. A tropical cyclone in the southern hemisphere is defined as a rotating low pressure system originating in the tropics in which the ten minute average winds exceed 63 km/hr (34 knots).There is characteristically a large area of convective cloud and heavy rain associated with the system; in the more intense tropical cyclones there may also be a clear region, the 'eye', situated near the cyclone centre. The strongest winds are located in a band surrounding this eye although, within the eye itself, winds are usually very light.

3.1.2 Oceanographic Response

When such a storm approaches the coast it can cause an abnormal elevation of sea level. The maximum sea elevation usually occurs close to the point of maximum winds as the cyclone crosses the coast, but the general dome of raised water can affect an area up to 50-100 km off the coast with the effect lasting for several hours. In determining the sea level elevation associated with a particular event, it is necessary to include the contributions of the:

- storm surge, resulting directly from the combined action of wind and relatively low atmospheric pressure;
- astronomical tide, and
- breaking waves at the coastlines, which include an increase in the mean sea level known as set-up as well as the intermittent effect of wave run-up.

These processes are illustrated schematically in Figure 1.The component of sea level elevation attributable to storm surge and tide is called the still water level. The peak steady water level combines the still water level and the wave set-up but excludes wave run-up. Wave set-up is the mean increase in water level near the shoreline that results from breaking waves. Wave setup (and set down) needs to be computed for each location of interest and so varies with the location's relative position within the breaker zone; this may vary in time during a particular storm event.

The magnitude of sea level elevation is dependent on, inter alia, the:

- intensity of the cyclone, as measured by its central pressure;
- size of the cyclone, usually indicated by the distance from the centre to the region of most intense winds;
- cyclone track, including the direction of movement, its forward speed and proximity to the point of interest, and
- shape and depth of the sea floor.

The probability of a cyclone of a particular intensity occurring in the region can be readily estimated. However, following from the previous discussion, it is evident that storm intensity is only one component that needs to be considered when estimating the probability of a particular sea level elevation being exceeded. For example, a significant surge might be caused by a weak cyclone with its maximum winds crossing directly over a particular location. The same sea level could also be achieved by a strong cyclone crossing further along the coast, but at lower tide.

3.1.3 Storm Database

Major cyclone events such as Cyclone Orson (1989) and Cyclone Vance (1999) are well documented, but such storms need to be put into perspective. To accurately represent storm surge and wave events in the Karratha-Dampier region, it is first necessary to specify the long-term cyclone climate of the region.

The Bureau of Meteorology (BOM) holds data relating to cyclone behaviour in the Australian region that dates back to the early part of the 20^{th} century. However, data for storms before the 1950s are considered less reliable due to the relative paucity of observation sites during this earlier period. Accordingly, only storms for the 61 seasons from 1950 to 2010 have been considered in this analysis.

Figure 2 shows the relative frequency of storm intensity based on the minimum central pressure of the storms in this regional database. The bands of storm pressure loosely correspond to the Cyclone Category scale (where Category 1 ~ 980 to 1000hPa) although it is noted that this scale is based on wind speed rather than storm central pressure per se.

Since not all storms that occur within the WA region will have a material impact on water levels within the study area, it is necessary to have a method for identifying only those storms of interest. The method for selecting and modelling storms is described in the next section.

3.2 Methodology for Determining Extreme Conditions

3.2.1 Aim

The primary requirement of the current study is to quantify recurrence intervals for water levels in Karratha-Dampier region.

3.2.2 Stochastic Approach

The simplest approach to develop the required recurrence statistics would be to model all of the storms that occurred over the 61 year period described in the previous section; the required water levels could then be computed by extrapolating from the model results. However, this method may be inaccurate since the relatively short period for which data is held does not adequately capture the range of storm-tide event combinations that may occur over a period of many centuries.

For example, the most intense storm to have crossed the coast in the general vicinity of Karratha-Dampier area is Cyclone Orson (1989) would be captured by such an approach, but it would not allow for other Orson-like storms crossing the coast at other locations.

To obtain results that address these issues, a method has been developed to create ‘synthetic’ storms based on the actual storm tracks, but which allows for variations in track, intensity and time of occurrence (the latter allowing for tidal cycle variability). This methodology has been successfully employed by GEMS in many other storm surge assessment studies.

Synthetic storms are produced by the following procedure:

i. storm central (minimum) pressures are aggregated for all storms in the region (from the 61year database) and an extreme value distribution is fitted to the data;
ii. for each storm event, a pressure is selected randomly from the pressure distribution;
iii. a storm track is randomly chosen from the subset of storms of ‘similar’ intensity to the chosen pressure, that is, within ±15hPa;
iv. all pressures for that storm are adjusted up or down based on the selected event pressure and the minimum recorded for the selected track;
v. the track is allowed to shift randomly in space, within a maximum range of of 250km;

vi. a start time is selected from anywhere in the cyclone season over the 18 year period of a full astronomical tidal cycle;

vii. the equivalent number of storm years is determined based on the number of storms generated and the measured rate of storm frequency (within the region of influence), and

viii. only storms within a defined zone of influence are included.

A zone of influence is defined to exclude cyclones that have no material effect on water levels within the study area. For this study cyclones that passed within 300km of Karratha were included.

In order to model sufficient storms to resolve event variability over the long term, the storm database was created to represent 2000 years; this is equivalent to 2351 cyclones occurring within the zone of influence, with an average recurrence rate of 1.17 storms per year.

3.2.3 Synthetic Track Example

Figure 3 shows the distribution for minimum storm central pressure for the region based on the 61 years of data. Storms are created at the average annual rate for the region of 2.36 cyclones per annum. The starting point for each storm is the minimum central pressure, which is selected from the distribution shown in Figure 3. A particular storm is then randomly selected from the sub-set of storms that have a minimum pressure within 15 hPa of the selected value – this effectively captures any relationship between track and storm intensity. The value of 15 hPa is an arbitrary value, but was chosen so as to allow variability in selecting storms of similar intensity.

The spatial shifting of the selected track occurs by shifting all locations on the track by the same amount, where the shifted distance is chosen randomly between 0 and 250km. The value of 250km was employed to allow for track variability while preserving any localised bias in track behaviour. Therefore, for example, the system will allow a track for a cyclone passing to the east than Port Hedland to the shifted westward to cross the coast near Karratha; however, the probability of this occurring is relatively small.

The process is illustrated in Figure 4. In this case the selected pressure for the event was 930 hPa which is equivalent to a 1 in 4 year event *for the region*. There are 25 cyclones in the database with similar central pressure (within 15 hPa) and Cyclone Trixie (925 hPa) was selected randomly from this group of cyclones. The pressure differential between the design storm and Trixie is +5.88% (=5 / [1010-75]) and so each pressure in the track of Trixie was adjusted by the same relative percentage.

For the spatial shifting each storm in the database are categorized as either 'coast crossing' or 'coast parallel.' Figure 4 shows the defined coastal crossing line for the Pilbara. Since Trixie crosses this line, it is defined as coast crossing and its track is moved either north-eastwards or south-westwards. For this particular case, the track shift parameter was +77.5km, and the track was moved north-eastwards by this amount, as shown in Figure 4.

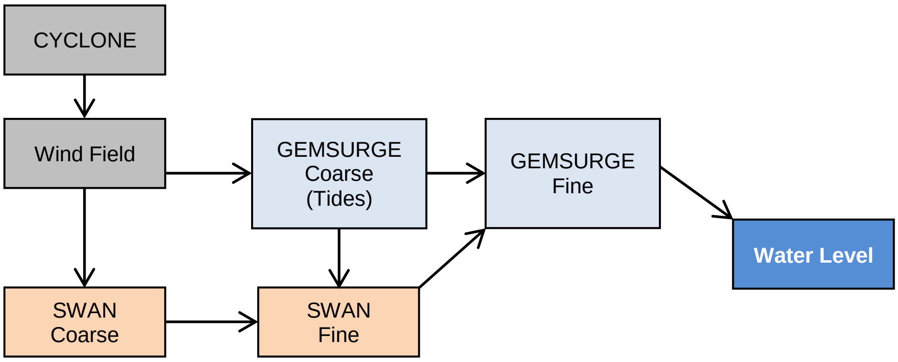
For storms that do not cross the coast, the storms are shifted in the same way, but along the normal to the coast crossing line.

Shifting the tracks allows for the natural variability in cyclone paths over time to be incorporated into the climatology. However, it is important to adjust central pressures to allow for the selection of a larger time window (in this case 2000 years). If only tracks were shifted and no account was taken of storm, intensity, the intensity distribution would represent only the distribution of events over a 61 year period and no account would be made for the potential impact of very intense cyclones.

3.3 Modelling Process

Once the storm database has been established, each storm event can be modelled according to the procedure set out schematically in the flow chart below. A suite of models, described in the next section, is applied to each event so as to represent the processes of interest – that is, the evolution of the atmospheric pressure and wind fields and the ocean response to these fields across the life of the storm.

Procedurally, wave parameters and water levels are stored as a time series at each designated location of interest for each event. After all the events have been so modelled, the time series data are processed and recurrence intervals are assigned. This is achieved by relating the modelling results to the average frequency of the storm events.



The modelling program was further streamlined by first modelling all 2351 events on the coarse grid; in order to save computational time those events which produced water levels below highest astronomical tide (HAT) were excluded from further analysis.

3.4 Description of Numerical Models

3.4.1 Overview

The suite of numerical models referred to in the last section has been employed to study the impacts of tropical cyclones impacting upon the Karratha-Dampier region. A description of the individual models is provided in this section together with the details of their set-up for the current project.

3.4.2 Cyclone Winds

The GEMS tropical cyclone model is based on the empirical model developed at the Australian Bureau of Meteorology (Holland, 1980).The model treats the wind field as an asymmetric vortex.

Wind directions and speed are a function of the storm central pressure and the environmental pressure in which the storm is embedded. The spatial distribution of winds is controlled by the Radius of Maximum Winds (RMW), which defines the distance from the storm centre to the region of strongest winds. Physically, this region of strongest winds is found around the cyclone 'eye-wall'; the eye region is the calm centre of the storm. Typically the radius of maximum winds is of the order of 20 to 50 km.

The Bureau of Meteorology cyclone records contain details of RMW for later storms (last decade) but not for earlier cyclones and so the distribution of climatology variation of RMW is not well defined.For the model simulations in the current study RMW is set to a fixed value of 30km.Another parameter (the so-called 'B'- parameter) defines the extent to which the strongest winds are concentrated around the eye-wall or otherwise extend outwards from the storm centre. Following Holland, the value of the B-parameter is related directly to storm central pressure so that the value is assigned specifically for each model time step based on the storm pressure at that time; this means that winds are more peaked for more intense storms and less so for weaker storms. Some examples of this relationship are shown in Section 3.2.3.

3.4.3 Storm Surge Model (GEMSURGE)

The 2D coastal ocean model, GEMSURGE (Hubbert and McInnes, 1999 and McInnes and Hubbert, 1995) solves the depth-averaged hydrodynamic equations over a region defined by detailed topographic and bathymetric information so as to provide currents and sea level heights resulting from specified tidal and meteorological conditions.

GEMSURGE features a grid generator to facilitate the setting up of model grids over any specified geographical region and grid resolution. It can be run over successively higher resolution regions, using the results of lower resolution outer simulations as boundary conditions. This so-called ‘nesting’ technique is an economical way of maximizing grid resolution and minimizing computational time. The user interface is capable of incorporating output from a wide range of atmospheric models to obtain surface winds and pressure. Meteorological conditions required by GEMSURGE include the 10-minute winds and surface pressure. These must be derived from a cyclone model, archived analyses or regional atmospheric model simulations. The winds are interpolated both spatially and temporally from the atmospheric model grid to the GEMSURGE coarse and fine mesh grids. In the current study the winds were obtained from the Holland model.

The model can run with or without tidal forcing. The tidal prediction model included in GEMSURGE reads the astronomical constants for each tidal constituent and calculates the tidal heights. These are applied as lateral boundary conditions in the coarse resolution GEMSURGE simulation. For this project, tidal constituents have been extracted from a regional tidal grid that was developed as part of an extensive national modelling program carried out by GEMS for the Australian Maritime Safety Authority (GEMS 2008b).

GEMSURGE has previously been established and tested extensively for applications in Australia and the Pacific. Further details for GEMSURGE are presented in Appendix A.

3.4.4 Computation of Wave Set up

Wave set-up is included in the computation of peak steady water level by calculating near-shore wave radiation stresses at each time step. These radiation stresses are then incorporated into GEMSURGE as an additional surface stress boundary condition.

3.4.5 Wave Model (SWAN)

To model wave processes occurring in the near-shore zone, it is first necessary to establish the evolution of waves over the open ocean. Typically, tropical storm winds affect a region up to a few hundred kilometres from the storm centre, and this area of influence changes with the movement of the storm.

Depending on the intensity of the cyclone, the winds in the affected area have the capacity to generate large ocean waves, which in turn propagate away from the generation region. In order to model these processes, it is necessary to establish a wave model over a regular grid, with a sufficiently large spatial extent to capture these processes.

Once these large-scale wind and wave generation processes are captured, the results can then be used to focus on the interaction of the ocean scale waves with coastlines. This latter task involves modelling the wave processes at higher spatial resolutions as the waves intersect shallower water depths.

GEMS have previously used the third generation SWAN model (Booij et al, 1999) for tropical cyclone related wave studies. SWAN, which was originally developed to model near-shore behaviour, also incorporates a smooth nesting process in which model scales can be effectively “telescoped” from spatially coarse large scale grids to small high resolution grids established over particular areas of interest.

3.5 Model Set-up for Current Project

3.5.1 Model Grids

For the current study, model grids were established over various areas and resolutions data as set out in Table 2. LIDAR data provided by the client was incorporated into these grids. Metadata for all topographic and bathymetric inputs to these grids will be included in the Final report.

TABLE 2: SUMMARY OF MODEL GRIDS (STORM SURGE AND WAVE MODELS)

MODEL	GRID NAME	MINIMUM LONGITUDE	NO.X POINTS	MINIMUM LATITUDE	NO. Y POINTS	RESOLUTION
GEMSURGE	Coarse	115.3	371	-21.4	231	1km
	Fine	117.05	463	-20.68	342	50m
SWAN	Coarse	112.0	131	-23.0	91	0.1 deg (~10km)
	Mid	116.8	181	-20.8	121	0.05 deg (~1km)
	Fine	117.065	421	-20.675	361	0.0005 deg (~50m)

3.5.2 GEMSURGE Settings

The GEMSURGE grids set out in Table 2 are shown schematically in Figure 5. The coarse grid must extend far enough from the study area so as to capture the broad scale ocean response to the cyclone wind and pressure fields. The inner grid must be large enough to capture the local topography and bathymetry and be of sufficiently high resolution to allow inundation processes to be accurately represented. Extensive testing has optimized these grids so that processes at all scales are captured while allowing for enough computation time to simulate the large number of events required.

3.5.3 SWAN Settings

The SWAN wave model was also established on two grids as specified in Table 3 and shown in Figure 6.

Table 3 provides details of the SWAN parameter settings used for the cyclone modelling component of the study. Other settings are based on the SWAN model default values (SWAN 2010).

TABLE 3: SUMMARY OF MODEL PARAMETERS

MODEL GRID	NW SHELF	CL 0.005 DEG	CL 0.0005 DEG
Grid Resolution	0.01 deg	0.005 deg	0.0005 deg
Directional Resolution	10 deg	10 deg	10 deg
Frequency Range	0.04-1 Hz	0.04-1 Hz	0.04-1 Hz
Frequency Interval	Logarithmic	Logarithmic	Logarithmic
Physics	Alves Banner	Alves Banner	Alves Banner
Computation	Non-stationary	Non-stationary	Stationary

Friction Scheme	JONSWAP C_{JON}=0.067	JONSWAP C_{JON}=0.067	JONSWAP C_{JON}=0.067

Frequency space for the model was established over a range of 0.04 to 1.0 Hz. Frequency intervals were based on the logarithmic relationship:

$$\Delta f = [-1 + \left[\frac{fhigh}{flow}\right] 1/(n-1)] f$$

Where: f is the frequency

n is the number of intervals (set to 36 for the current study)

flow=0.04

fhigh=1.0

SWAN has the ability to input time varying depth files. Accordingly, time series of water depths were taken from across the GEMSURGE grid and applied as boundary conditions in SWAN.

3.5.4 Model Output

GEMSURGE computes total water level equivalent to peak steady water level at each model grid point at each model time step. The model can output these water level heights (and currents) as time series for nominated output locations. The model also stores the maximum water level obtained throughout the course of the model run at each grid point and outputs these maxima on a ‘zpeak’ grid.

3.6 Statistical Analysis

A key aim of the study is to produce water levels for the range of average recurrence intervals specified by the client, as set out in Section 1 of this report. To achieve this, maximum water levels were extracted for each model grid point for each cyclone event simulation. These data were then subjected to extreme value analysis, grid point by grid point.

Following from previous studies, GEMS has applied algorithms to fit the Generalized Pareto Distribution (GPD) to these water level maxima. The GPD is well-suited to type of analysis as the fitting method relies on analysing data over a suitably selected threshold and thereby eliminates the less intense events (Holmes and Moriarty, 1997 and Lin, 2003).

The estimated water level Z_{ARI} for a return period R is then given by

$$Z_{ARI} = z_0 + [1- (\lambda R)^{-k}]/k \qquad (1)$$

where z_0 is the selected threshold, λ is the exceedance rate of z_0 (per year) and σ and k are fitting parameters for the distribution. These fitting parameters are determined by plotting the mean excess of all observations over incremental values of z; provided the data lie along a straight line, the slope and intercept of the line equate to –k/(1+k) and σ / (1+k), respectively. These relationships are solved for k and Equation (1) can be computed accordingly.

This process is repeated for each model grid point as follows:

- The maximum water level, z, is extracted for each modelled event;
- A suitable value for z_0 is selected;
- Mean exceedances over z_0 are computed;
- A line is fitted to the exceedance data and the slope and intercept of the line are computed;
- The rate λ is calculated from the number of events that exceed the threshold for the modeling period (2000 years), and
- The ARIs are computed from Equation 1.

For return periods above 10 years a threshold of order 2.5(m) was applied, with events below this level eliminated from the analysis. In order to compute lower ARI estimates (two to ten years) it was necessary to analyse results over a lower threshold, so that smaller scale events could be considered. This was achieved by fully modelling all events within a fifty year period and applying the same method with z_0 set to zero.

Following from this point by point analysis, the required ARI heights are mapped onto the underlying grid and can then be readily presented as GIS layers. Data from each (ARI) grid layer can be extracted for any location of interest.

It is important to note that this approach produces estimates for water level aggregating the relative probabilities of different storm-tide combinations. As such, there is no one cyclone event which corresponds to a particular ARI level – many storm and tidal combinations (based on cyclone track and intensity and tidal phase) may contribute to inundation to a particular level.

3.7 Climate Change Scenarios

3.7.1 Cyclones

In order to accommodate the proposed changes to cyclone intensity and frequency for the 2060 and 2110 scenarios, it was necessary to modify the cyclone database and post processing analysis. The intensity change was accommodated as follows:

- the randomly chosen cyclone pressure was converted to a deficit to the background pressure (1010);
- this difference was increased by ten per cent; and
- the deficit was converted back to its absolute value

For example the deficit for a 950hPa pressure cyclone is 60hPa, which is increases to 66hPa and the new cyclone pressure is 944hPa. The storm frequency change was made by increasing the storm rate of occurrence by ten per cent.

3.7.2 Shoreline Change

Shoreline change considerations were based on work undertaken as part of a separate coastal movement study for Karratha, the results of which are described in Attachment III. These coastal impacts were incorporated into the storm surge modelling in two ways:

- All mangrove regions were changed to mud flats in the model terrain file, so that bottom friction settings were commensurately reduced, and
- The topography identified dune areas was effectively flattened by reducing dune heights to a maximum level of 2.0 m AHD.

3.8 Model Validation

Details relating to the validation of the model suite employed for the current project are presented in Appendix B. Details included in the validation report include:

- references to publications relating to specific models;
- the performance of the model suite for other projects and locations, and
- quantitative comparison of model output and observations for the particular model configurations applied in the current study.

4. LIMITATIONS OF ANALYSIS

The results of the storm surge modelling described in this report are based on best practice. However, some limitations of the methodology and the analysis should be considered when applying the results.

4.1 Representation of Cyclone Climatology

Although best practice techniques and processes have been applied in this study, it should be noted that a level of uncertainty exists in relation to the representation of the cyclone climate. This is because there is an underlying assumption that the cyclone data used are wholly representative of a stationary climate. Since there is an implicit recognition of the potential for climate impact on the cyclone climatology in the study brief, the specification of a '2010 cyclone climate' is based on an artificial assumption. However, this 'current climate' state provides a suitable and appropriate baseline for developing planning standards.

4.2 Statistical Analysis

Following from the previous section, a further limitation of the analysis results from the length of the cyclone records used. Even if it is assumed that the climate is stationary, there is statistical uncertainty as a result of the duration of the record. For a one in hundred analysis, it would be preferable to have at least 100 years of accurate records so as to limit any bias arising from the sampling error, particularly in relation to the frequency and intensity of cyclones. Any error associated with such bias will increase for longer return periods.

However, as the results show in the following sections, some change to overall frequency and intensity does not have a significant effect on water levels associated with longer return periods. This is because these longer return period events are associated with relatively rare, worst track cyclone impact.

4.3 Model Limitations

Provided the storm surge and wave models used in the study are initialized with representative winds and topographic data they have been shown to accurately represent the ocean response in the coastal environment. The winds for the cyclone events modelled in the study are based on an idealized and somewhat simplistic representation of cyclonic wind fields. Thus the fine scale detail of winds generated in individual events may not necessarily be accurately represented. However, since the aim of the study is to aggregate impacts over longer time scales, these storm specific characteristics should be effectively averaged out in the analysis process.

4.4 Localized Storm Surge Impacts

The methodology presented in this report has been applied for a range of studies and applications. It is considered highly appropriate for developing a planning response to storm surge risk. However, as it is being applied a cross a region, rather for a specific location it cannot by its nature account for highly localized effects such as the extent of wave run-up. This aspect of storm surge risk is largely accounted for in consideration of set-back beyond nominal inundation areas and is considered separate to this storm surge report.

5. RESULTS

The modelling results for this Study are provided below.

5.1 ARI Analysis

The results presented in this section are for the 2010, 2060 and 2110 scenarios. Table 4 includes corresponding results figure references.

TABLE 4: SCENARIO SUMMARY

SCENARIO	2010	2060	2110
Topography	Current	Unchanged	Flattened in current mangrove areas
Cyclones	Current	10% increase	10
Water Level	Current	+ 0.3m	+0.9m
Mangroves	Current	Current	Eliminated
ARI (Years)	Results shown in:		
2	Figure 8	Figure 13	Figure 18
10	Figure 9	Figure 14	Figure 19
100	Figure 10	Figure 15	Figure 20
200	Figure 11	Figure 16	Figure 21
500	Figure 12	Figure 17	Figure 22

The results for each scenario are based on the stochastic modelling procedure described in Section 3. Estimates for peak inundation associated with each scenario were computed at each model grid point and the results of this analysis are presented as spatial plots, each of which is referenced in Table 4. These spatial plots are also provided as ESRI grids for ingestion into GIS systems that allow grid point values to be extracted for each scenario.

In addition, ARI values were extracted at several representative locations within the study area. The locations of these 'tag point' locations are set out in Table 5 and shown in Figure 7. The extracted peak inundation levels for these locations for the three climate scenarios are presented in Tables 6 to 8 respectively.

Figure 23 shows an overlay of the 100yr ARI inundation zones for each climate scenario.

TABLE 5: SUMMARY OF TAG POINT DETAILS

NAME	K1	K2	K3	K4	K5	K6	K7	K8	K9
Easting	486106	479393	481320	484910	490095	482176	485379	488728	477462
Northing	7714453	7710266	7709069	7708870	7708803	7707225	7708104	7708125	7707887
Grid Height (mAHD)	-9.0	2.2	2.2	2.3	0.2	3.4	5.7	6.7	7.5

TABLE 6: 2010 CLIMATE SCENARIO INUNDATION ESTIMATES FOR TAG POINTS (mAHD)

ARI (Years)	K1	K2	K3	K4	K5	K6	K7	K8	K9
2	2.6	Dry	2.4	Dry	2.6	Dry	Dry	Dry	Dry
10	3.4	2.8	3.4	3.4	3.5	Dry	Dry	Dry	Dry
100	5.5	6.6	7.0	6.6	5.9	6.8	Dry	Dry	7.3
200	5.9	7.0	7.5	7.0	6.3	7.7	6.0	6.7	8.3
500	6.3	7.4	7.8	7.4	6.7	8.4	6.6	6.9	8.6

TABLE 7: 2060 CLIMATE SCENARIO INUNDATION ESTIMATES FOR TAG POINTS (mAHD)

ARI (Years)	K1	K2	K3	K4	K5	K6	K7	K8	K9
2	3.0	3.0	2.3	2.8	3.0	Dry	Dry	Dry	Dry
10	3.9	3.9	35	4.2	4.1	Dry	Dry	Dry	Dry
100	5.7	5.7	6.9	6.9	6.1	7.1	Dry	Dry	7.6
200	6.1	6.1	7.4	7.3	6.5	8.0	4.6	7.0	8.6
500	6.6	6.6	7.7	7.6	6.9	8.6	7.0	7.4	9.2

TABLE 8: 2110 CLIMATE SCENARIO INUNDATION ESTIMATES FOR TAG POINTS (mAHD)

ARI (Years)	K1	K2	K3	K4	K5	K6	K7	K8	K9
2	3,6	2.4	2.9	3.5	3.6	Dry	Dry	Dry	Dry
10	4.4	4.6	4.6	4.9	4.6	Dry	Dry	Dry	Dry
100	6.1	7.5	7.7	7.2	6.5	8.2	6.1	6.9	8.7
200	6.6	7.8	8.0	7.6	7.0	8.5	6.3	7.4	8.9
500	7.1	8.1	8.2	8.0	7.4	9.0	7.4	7.7	9.3

5.2 Event Duration

As well has the maximum water, the duration of the storm surge event may be an important consideration. The shape of the inundation curve associated with any storm surge event will depend on the storm intensity, storm path and speed of movement and the state of the tidal cycle.

Figure 25 and 26 show example time series for selected events; these events are for peak water levels approximately corresponding to 10 and 100 year ARIs at K4.

Table 9 presents the mean duration for water levels exceeding various percentages of the peak for 10 year and 100 year events at the same two locations. The analysis was based on all modelled events for which the peak water level was within 0.5m of the computed ARI at each location.

TABLE 9: DURATION (IN HOURS) OF WATER LEVEL ABOVE DESIGNATED THRESHOLDS

ARI (Years)	Statistic	K4			K5		
		Fraction of peak water level					
		90%	75%	50%	90%	75%	50%
10	Median	2.0	5.0	11.7	2.1	4.5	10.4
	Maximum	4.4	10.8	18.8	4.6	8.4	18.2
100	Median	1.6	3.5	7.0	1.8	3.5	7.1
	Maximum	3.2	5.2	8.0	3.0	5.0	9.0

5.3 Boundary Conditions for Hydraulic Modelling

In addition to determining inundation areas, a second requirement of the storm surge modelling was to provide downstream boundary conditions for the hydraulic modelling. Five boundary condition locations were specified by JDA and these are shown in Figure 24. The required ARI levels were selected for each of these five locations and then a corresponding representative event was selected for each from the model database. This database included time series of peak steady water level for each of the five points for each storm-tide simulation modelled.

6. DISCUSSION

The results presented in the previous section are broadly consistent with the results of earlier Karratha storm surge carried out on behalf of the Shire of Roebourne (BOM 1997). However, there are some important differences that occur, primarily as result of:

- the high resolution topography available for the current study
- better definition of significant terrain features, including in particular mangrove areas.
- improved methods for modelling the contribution of wave set-up

The spatial plots shown in Figures 8 to 23 illustrate the relative extent of inundation across the range of return periods included in the study. In all cases the relative highest water levels occur in the seaward approaches to the western half of Karratha town-site. This is primarily because this area is most directly exposed to strongest on-shore (north-east) winds and wave stress which push sea water against the shoreline.

Water levels further eastward, toward the Mulataga area and the entrance to the Nickol River diminish relative to the highest water levels in each of the cases shown. In certain circumstances north to north-west winds may occur as a cyclone passes Karratha but although winds from this direction directly attack the Nickol River area, they will be relatively less intense and occur less frequently. This is because to cause winds from the north-west, a cyclone has to be centred over land and is therefore generally weakening. In addition, winds from this direction produce wave action which is fetch limited and so the wave set-up contribution to overall water level is less. For the larger events, the contribution of wave set-up from waves propagating into Nickol Bay from the north-east (and therefore directly impacting on western side of the bay) is typically of the order of 0.5 to 1.0 metres.

The results also show that surge levels are attenuated as the surge propagates into the entrance to the Nickol River. The degree of attenuation of the surge in this area is greater than for the previous study; this relative reduction in surge levels is most likely associated with the topographic detail provided by the LIDAR data and frictional effects associated with delineation of mangroves. However, a note of caution should be associated with these results as it may be that the LIDAR topography heights are slightly overestimated due to the presence of mangrove vegetation. For the climate change scenario simulations to be the mangroves are omitted and the topography in this area is effectively flattened.

For the current climate the 100yr ARI, inundation at Tag Point 6 is 6.8m at which level the town site can be expected to suffer some direct impact. The level of impact increases in this area for the 200yr (7.7m) and 500yr (8.4m) ARIs. Further to the east, at Tag Point 7 inundation levels are restricted by higher ground seaward of the town-site and there appears to be encroachment into the existing town only at 200yr and 500yr ARIs. At Tag Point 9 which adjoins Seven Mile Creek the 100yr ARI current climate water level is 7.3m, reaching 8.6m for the 500yr ARI.

Due to higher topography around Tag Point 8 there is no inundation evident for the 100yr ARI event with water levels seaward of this location of the order 6.9m during the 500yr ARI event.

For the 2060 and 2010 runs the water levels increase commensurately with the change in the corresponding change in mean sea level (0.3 and 0.6m respectively). The ten percent increase in storm intensity and frequency have comparatively small impacts on the overall results. The water levels at Tag Point 6 for 2010 100yr ARI increases from 6.9m to 8.2m for the 2110 scenario. This increase would cause significant inundation in the lower parts of the town site.

Spatially, the increase in the area of inundation is generally not large; this is because of the gradient at the inundation front. The exception is in the area around Seven Mile where the area of inundation increases markedly from the 2060 to the 2110 scenarios.

The duration of events is variable; the statistics presented in Table 9 provide estimates for the median period of raised water level based on fractions of the peak for order 10 year and 100 year events. The ten year event durations are much more likely to be controlled by the tide compared to the 100 year events and have longer relative duration (see Figures 25 and 26).

For the more extreme events, the duration above 50 per cent of the peak is typically of order seven to eight hours and order one to two hours above 90 per cent.

7. CONCLUSIONS

Inundation levels have been calculated on a regular grid for the Karratha region for Average Recurrence Intervals (ARIs) ranging from 2 to 500 years for three climate scenarios.

The results for the current climate (2010) are, as expected, consistent with earlier studies carried out for the Shire of Roebourne. However, the results from this study are improved by the availability of much more detailed topographic data and a longer cyclone record.

Generally, storm surge levels are higher in the Seven Mile Creek region compared to the Nickol River region. This is essentially because of the preferred angle of attack of cyclones and the topographic orientation of Nickol Bay.

For a 100yr ARI event under current climate conditions, some lower parts of the Karratha town-site would be expected to experience flooding, up to a level of the order of 6.8mAHD. Results for the 2060 and 2110 scenarios show relative increases in predicted water levels generally commensurate with predicted sea levels. That is, the modelled increases in storm frequency and intensity have only minor impact on overall results relative to the effect of sea level change.

Nevertheless, flooding for the existing Karrathatown-site becomes more significant under predicted 2110 climate conditions, with 100yr ARI levels in the town site area rising to levels of the order of to 7.5mAHD.

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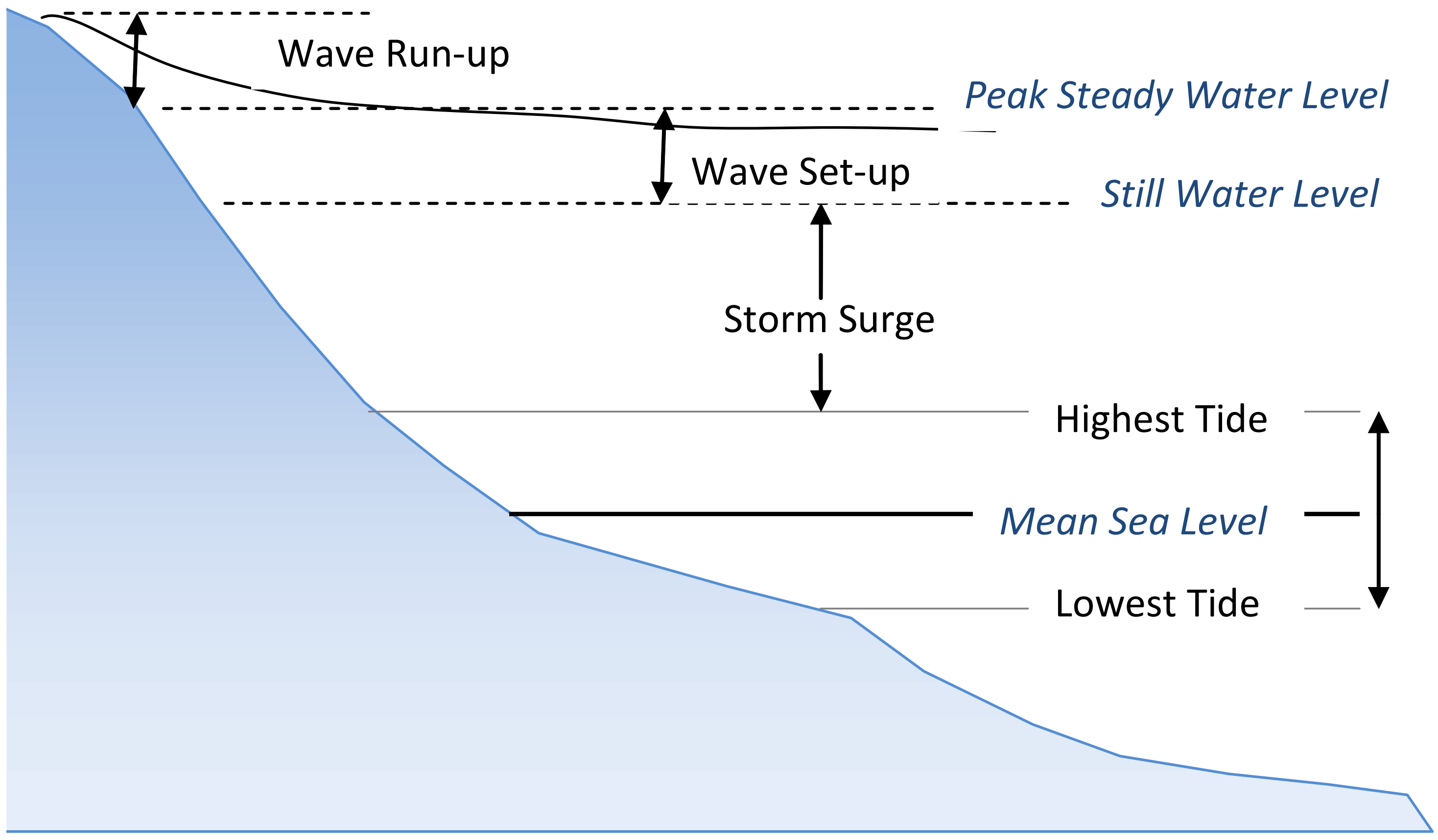
FIGURES



Data Source: GEMSURGE Modelling 2011

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Figure 1: Contributing Components of Sea Level Elevation during Cyclonic Impact (see Glossary)

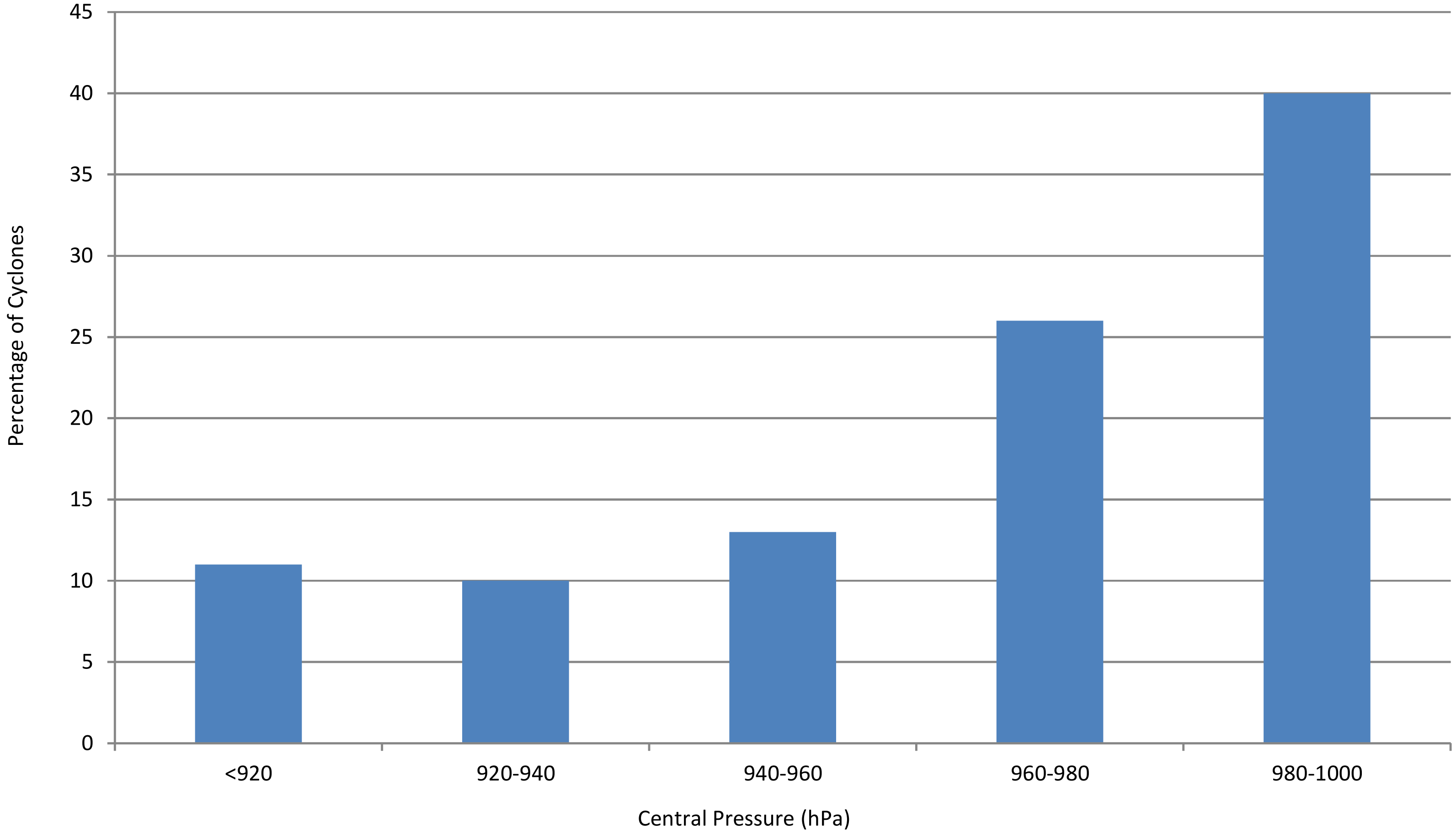

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Figure 2: Distribution of Minimum Central Pressures for Storms included in the Regional Database

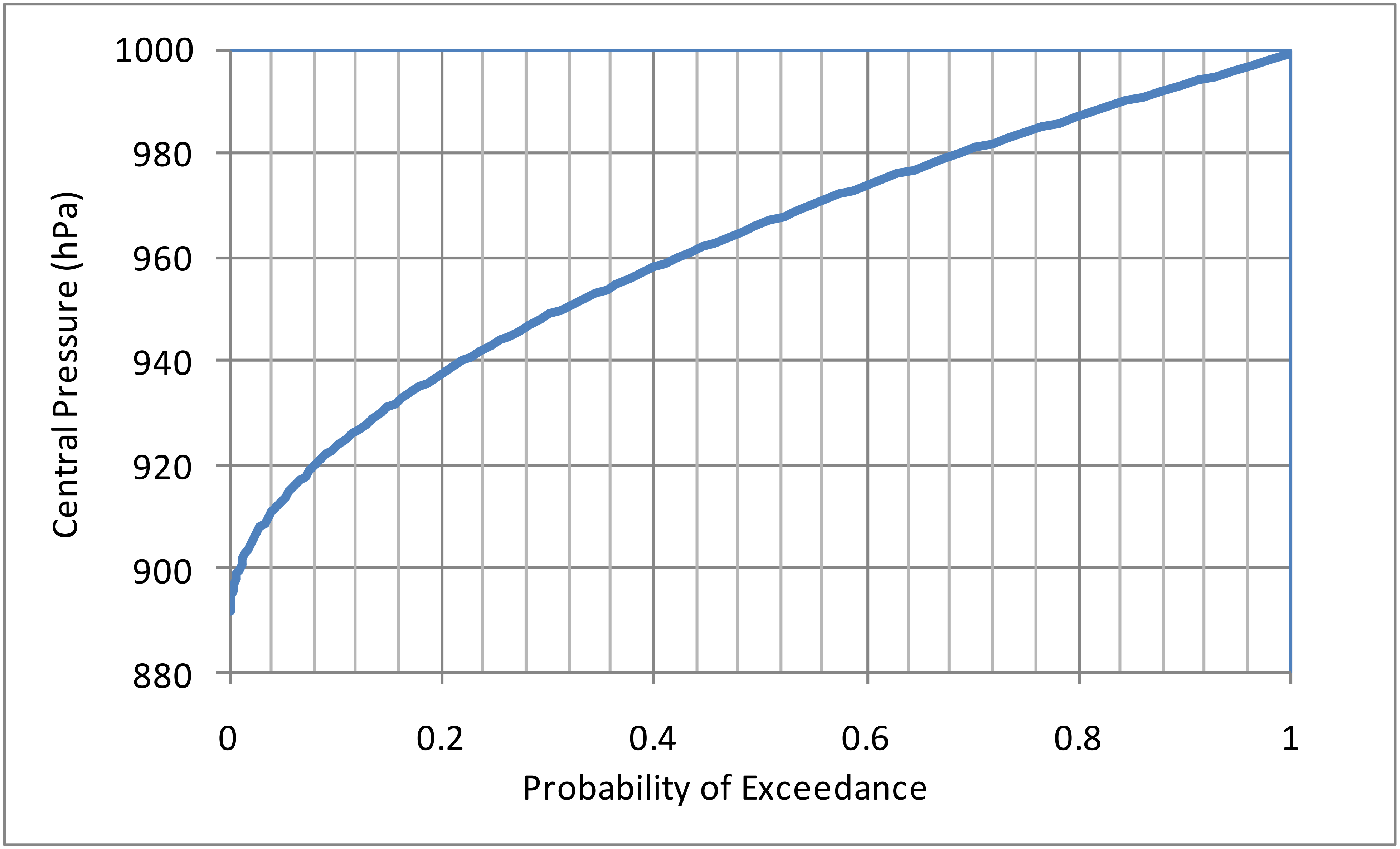

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Figure 3: Probability Distribution of Cyclonic Minimum Pressure for North West Shelf Region

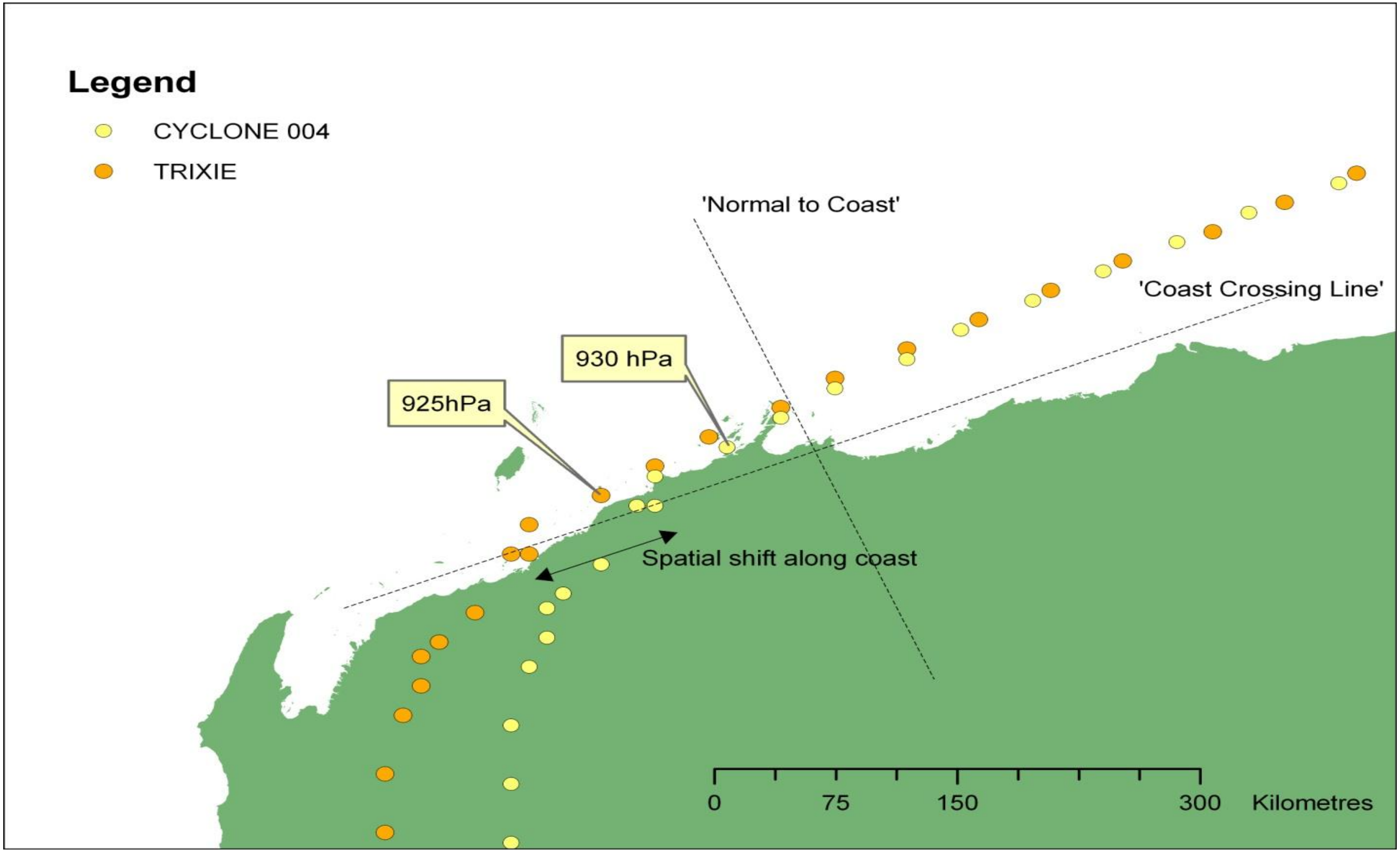

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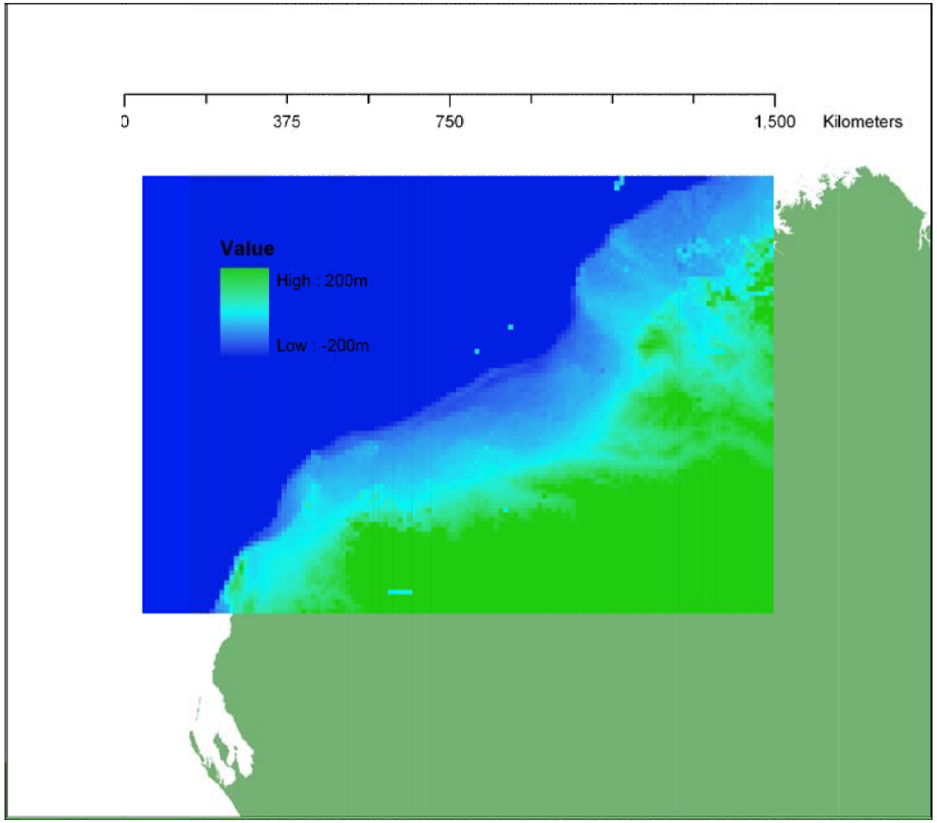
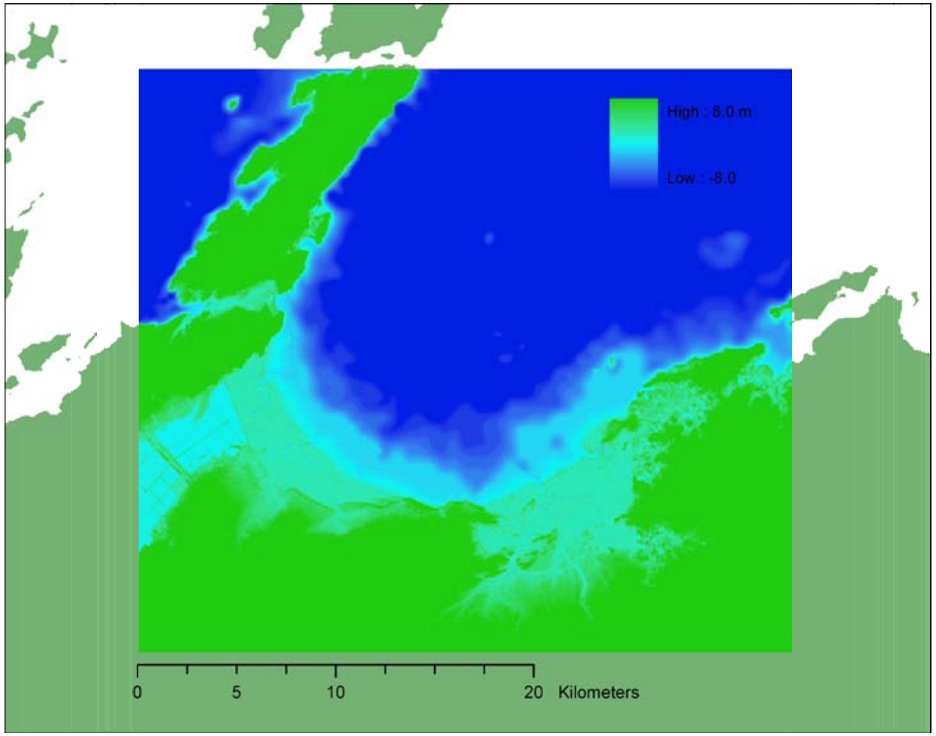
Figure 4: Example of Synthetic Track Generation Based on Track of Cyclone Trixie





Data Source: GEMSURGE Modelling 2011

Job No. J4812

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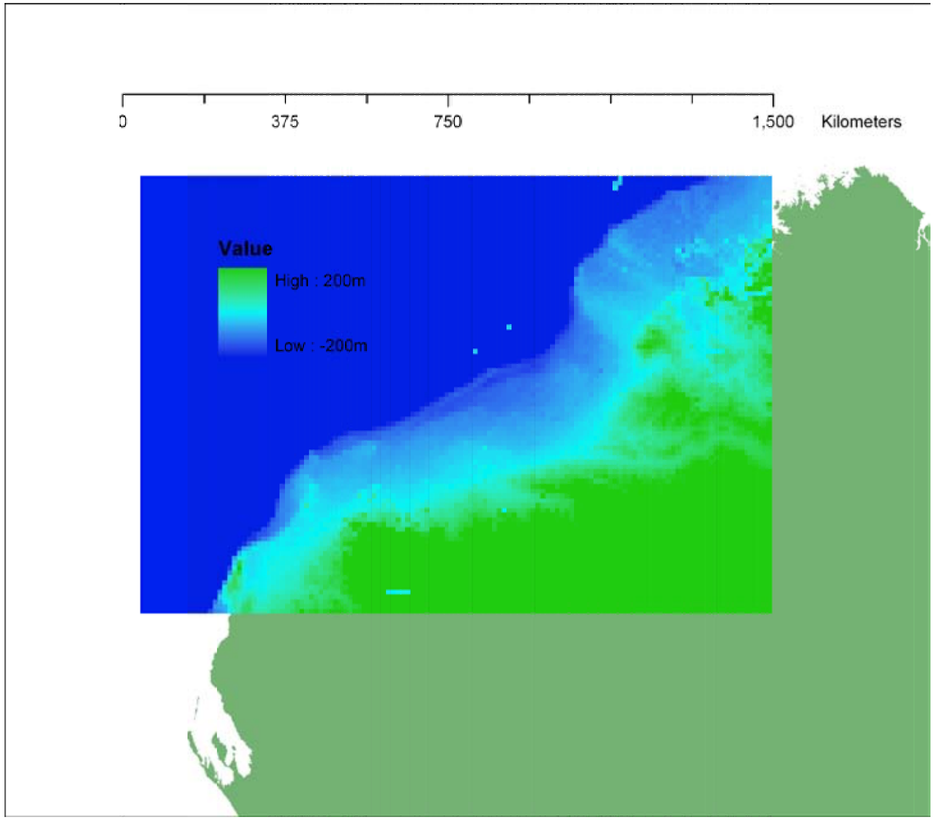
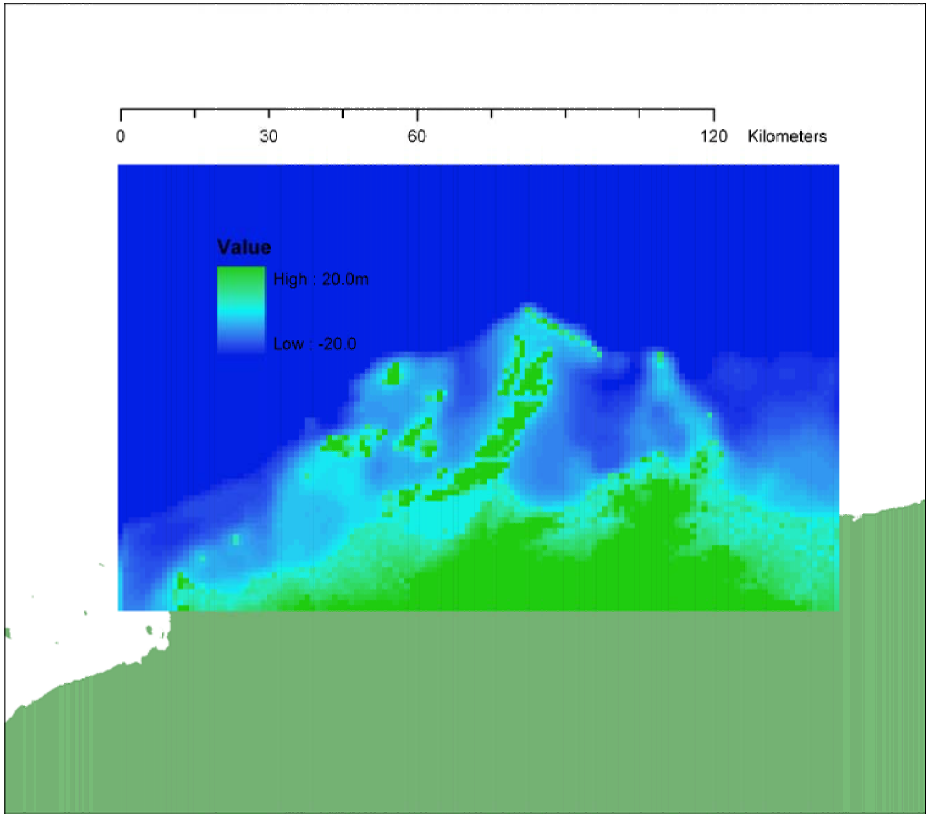
Figure 5: Bathymetry and Topography of Model Storm Surge Grids





Data Source: GEMSURGE Modelling 2011

Job No. J4812

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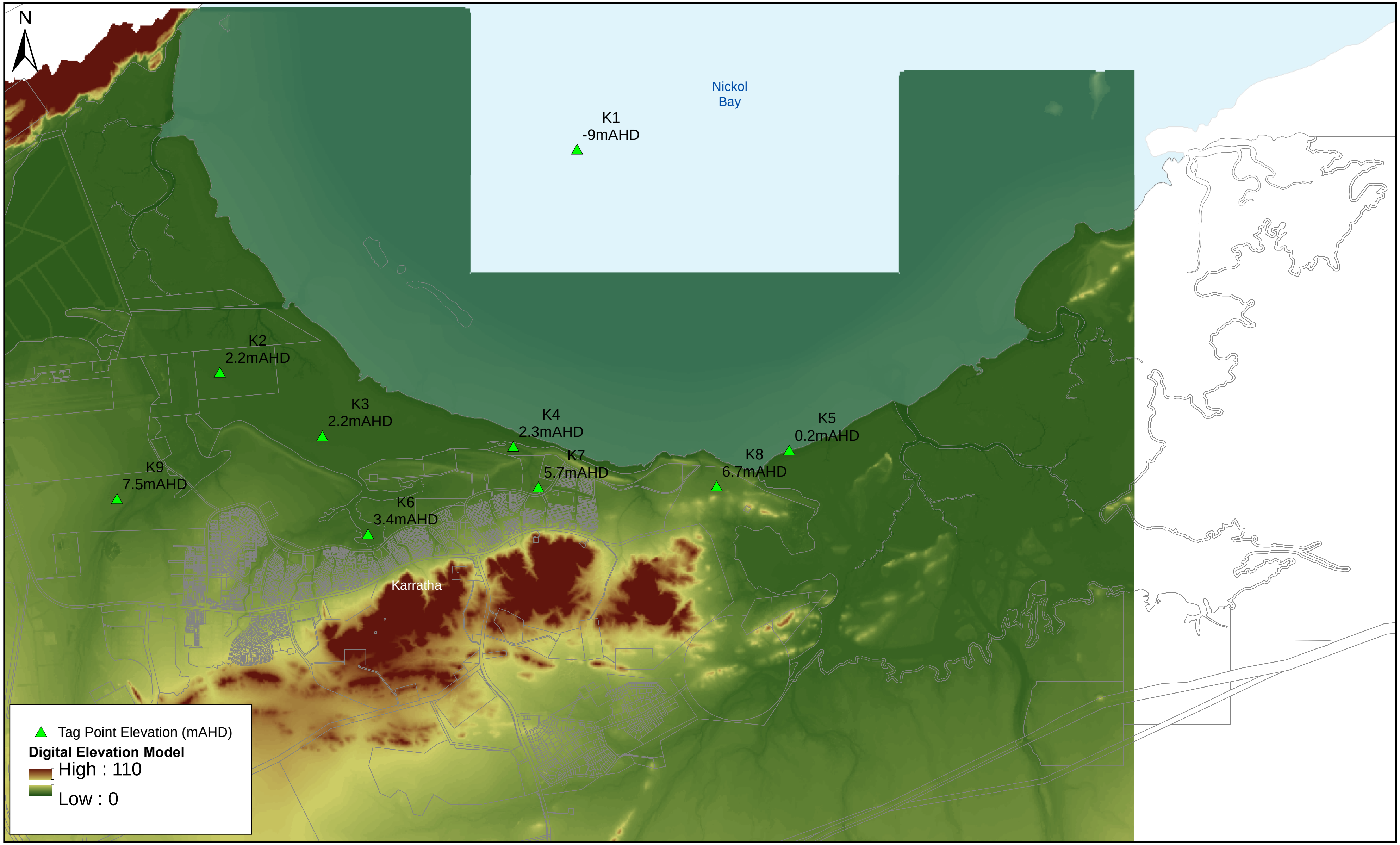
Figure 6: Bathymetry and Topography of Model Wave Grids



Data Source: GEMSURGE Modelling 2011

Job No. J4812

Scale:1:100,000

0 1 2 3 4 Kilometers

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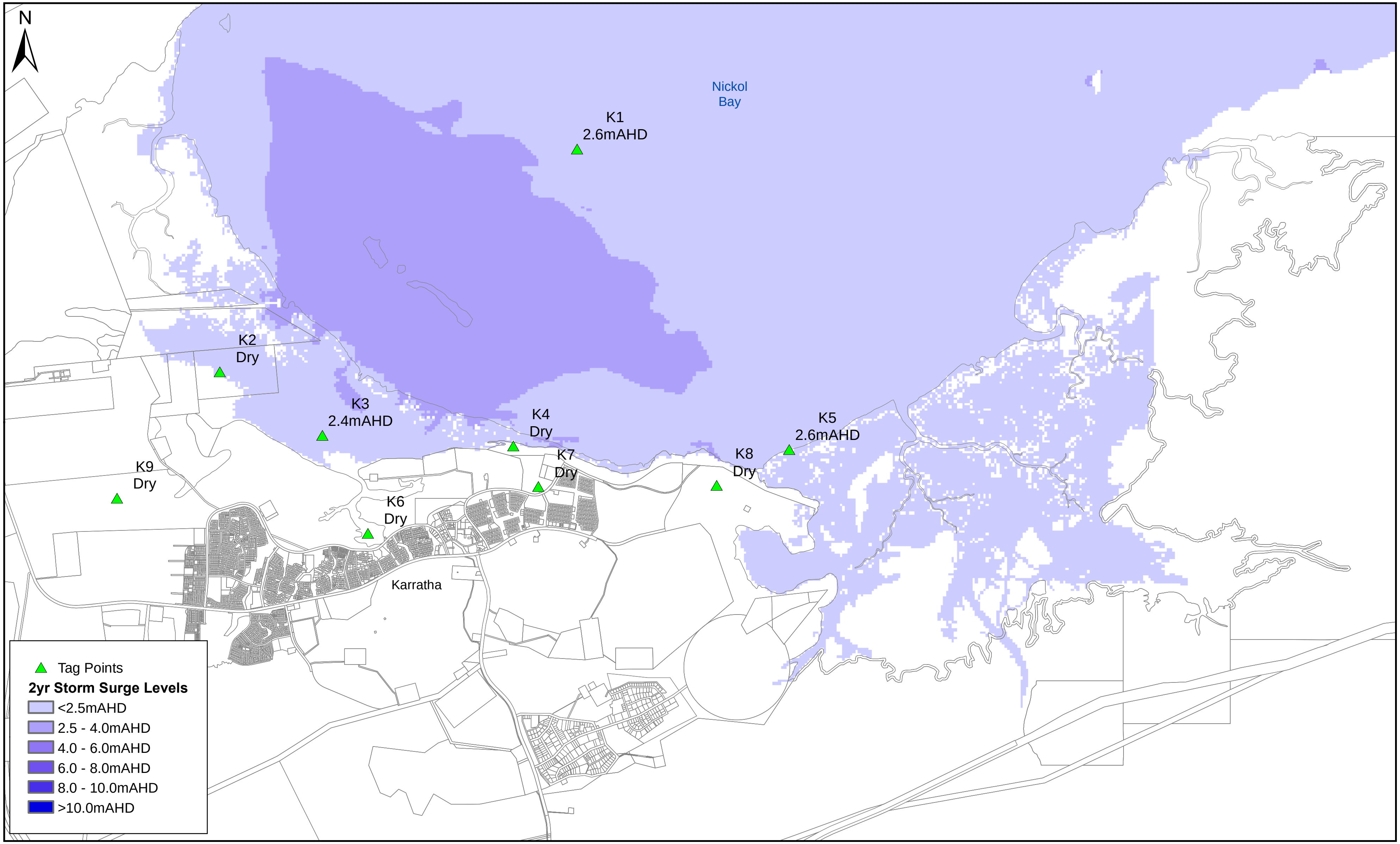
Figure 7: Location of Selected Tag Points with Existing Topography



Data Source: GEMSURGE Modelling 2011

Job No. J4812

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LandCorp

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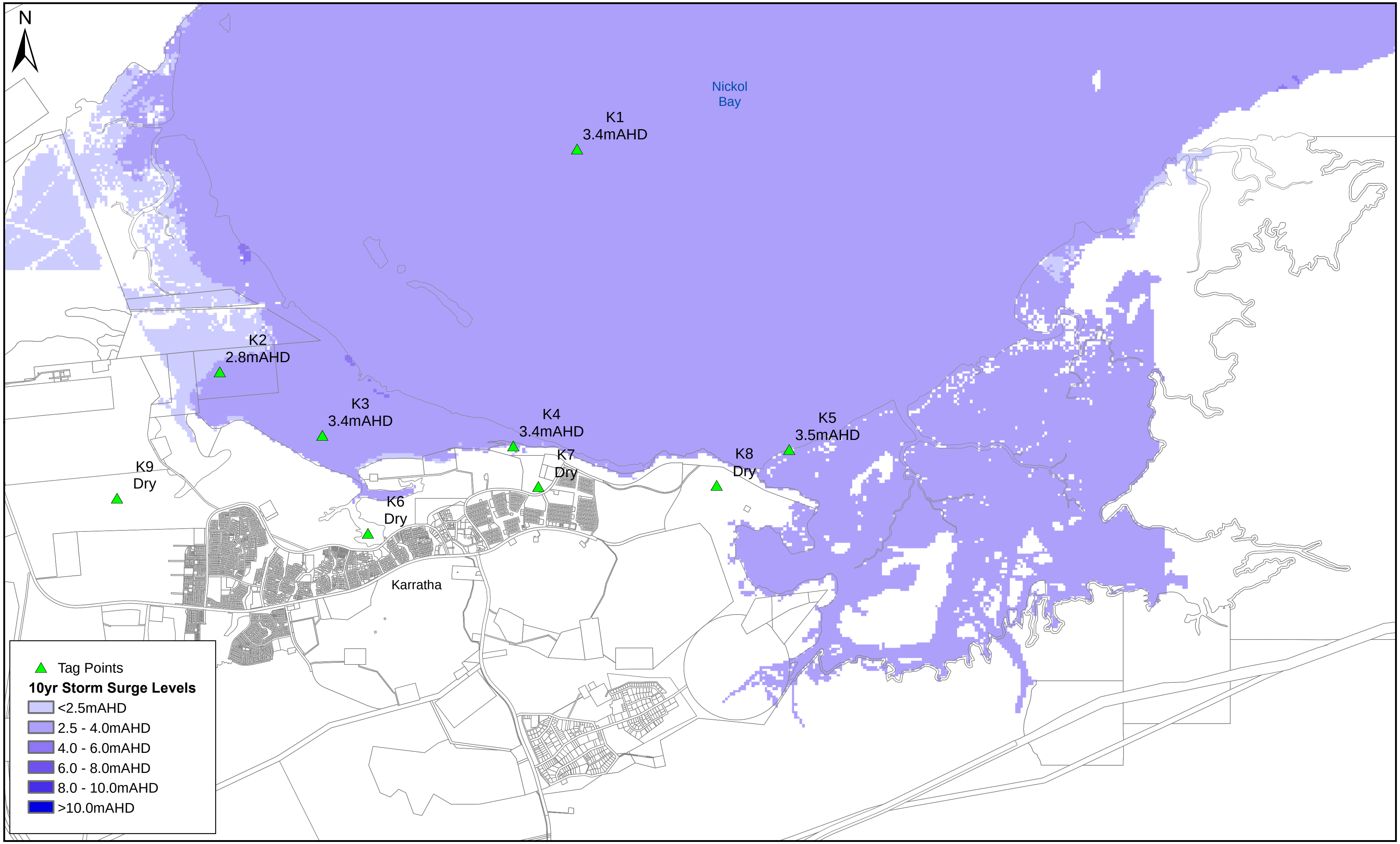
Figure 8: 2yr ARI Coastal Inundation - 2010 Climate Scenario



Data Source: GEMSURGE Modelling 2011

Job No. J4812
Scale: 1:100,000
0 1 2 3 4 Kilometers

LandCorp
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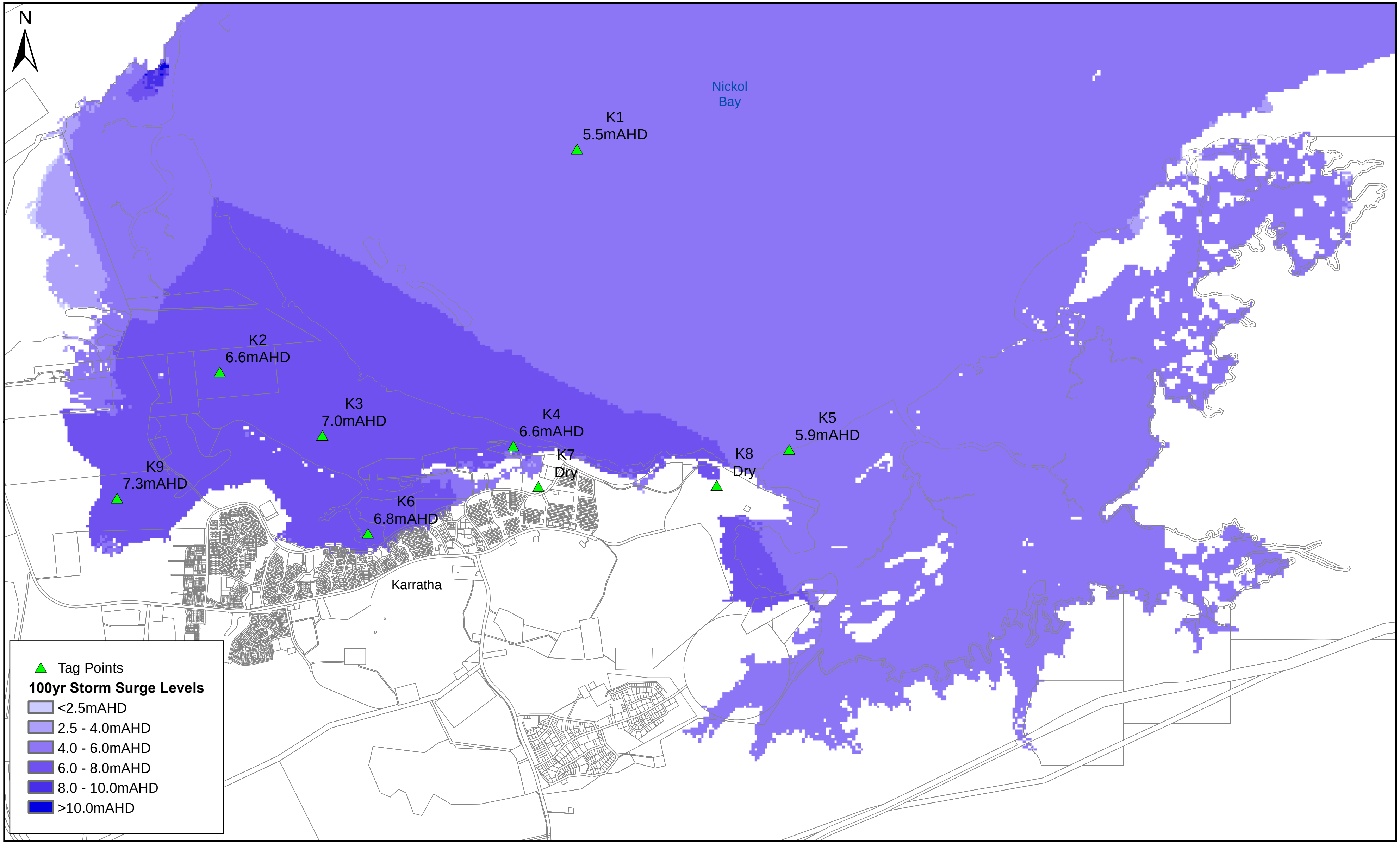
Figure 9: 10yr ARI Coastal Inundation - 2010 Climate Scenario



Data Source: GEMSURGE Modelling 2011

Job No. J4812

Scale: 1:100,000

0 1 2 3 4 Kilometers

LandCorp

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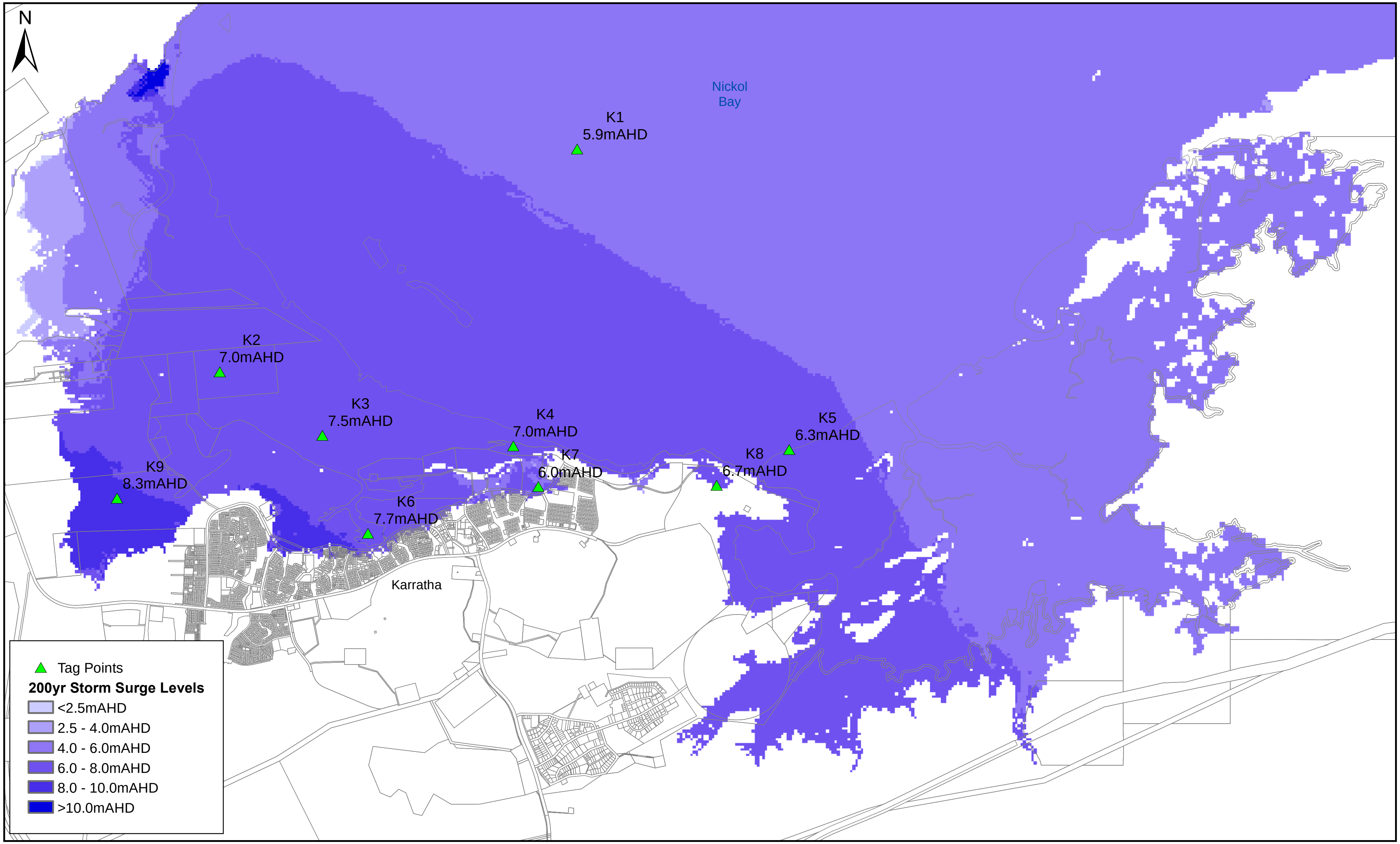
Figure 10: 100yr ARI Coastal Inundation - 2010 Climate Scenario



Data Source: GEMSURGE Modelling 2011

Job No. J4812

Scale: 1:100,000

0 1 2 3 4 Kilometers

LandCorp

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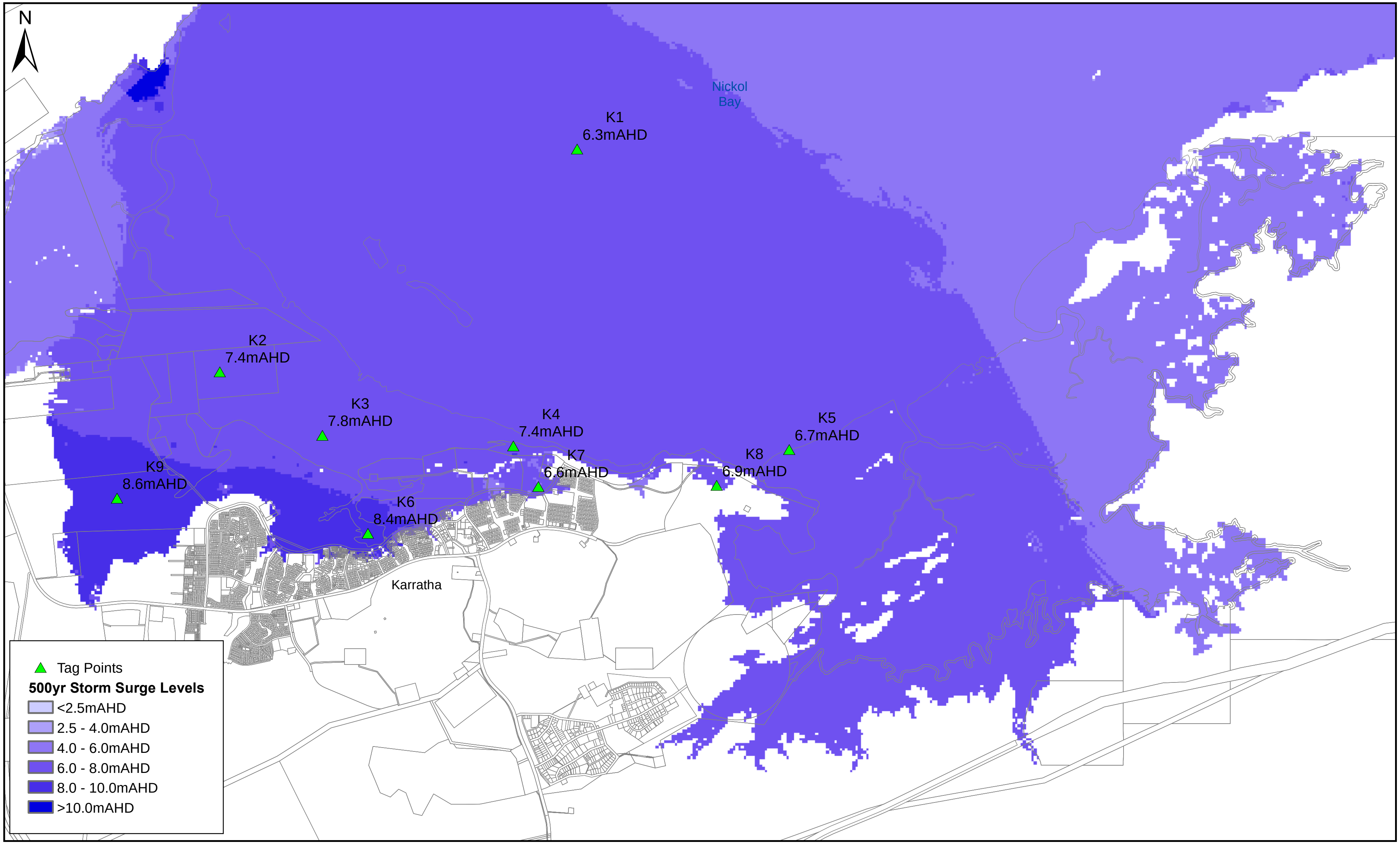
Figure 11: 200yr ARI Coastal Inundation - 2010 Climate Scenario



Data Source: GEMSURGE Modelling 2011

Job No. J4812

Scale: 1:100,000

0 1 2 3 4 Kilometers

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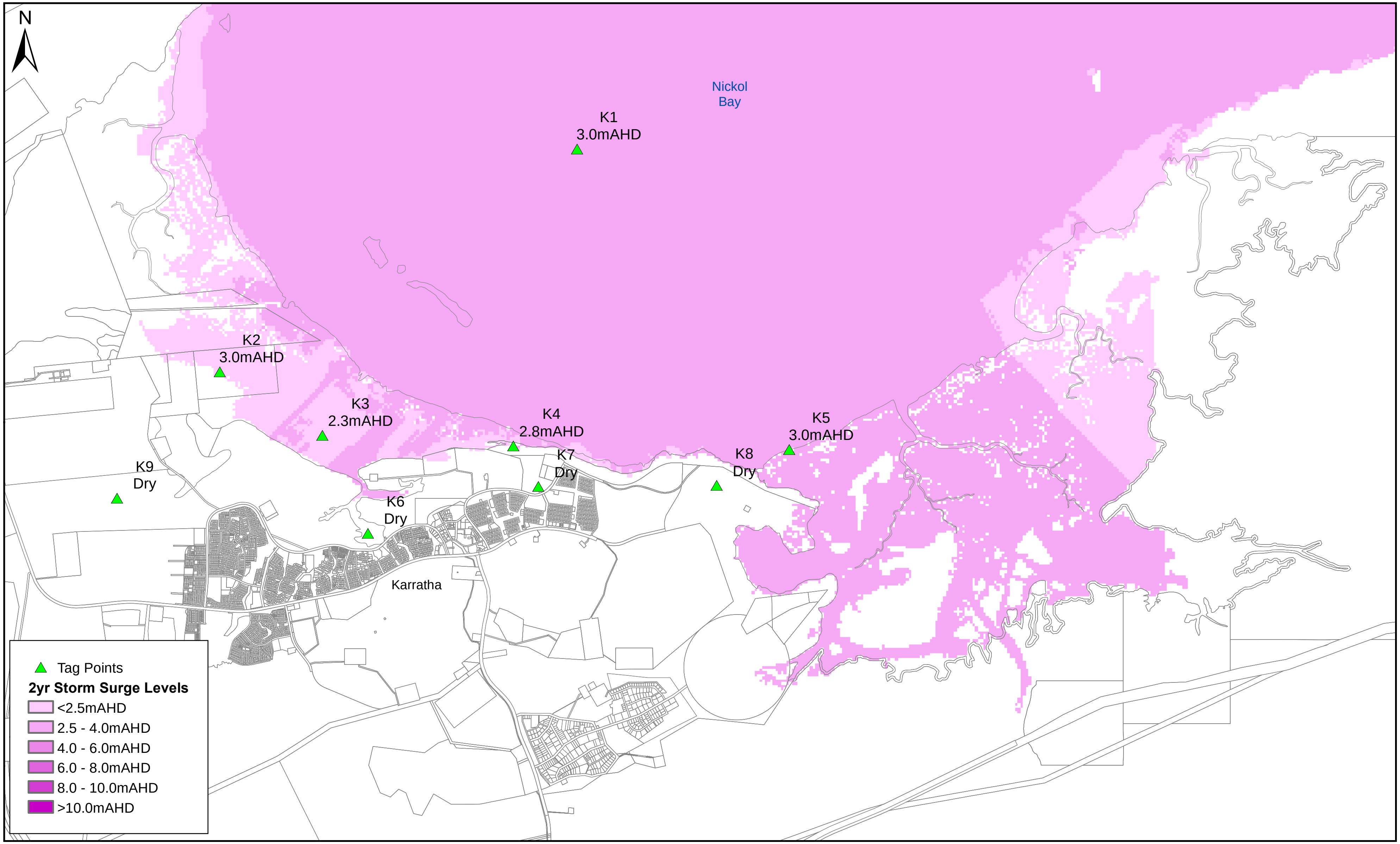
Figure 12: 500yr ARI Coastal Inundation - 2010 Climate Scenario



Data Source: GEMSURGE Modelling 2011

Job No. J4812

Scale: 1:100,000

0 1 2 3 4 Kilometers

LandCorp

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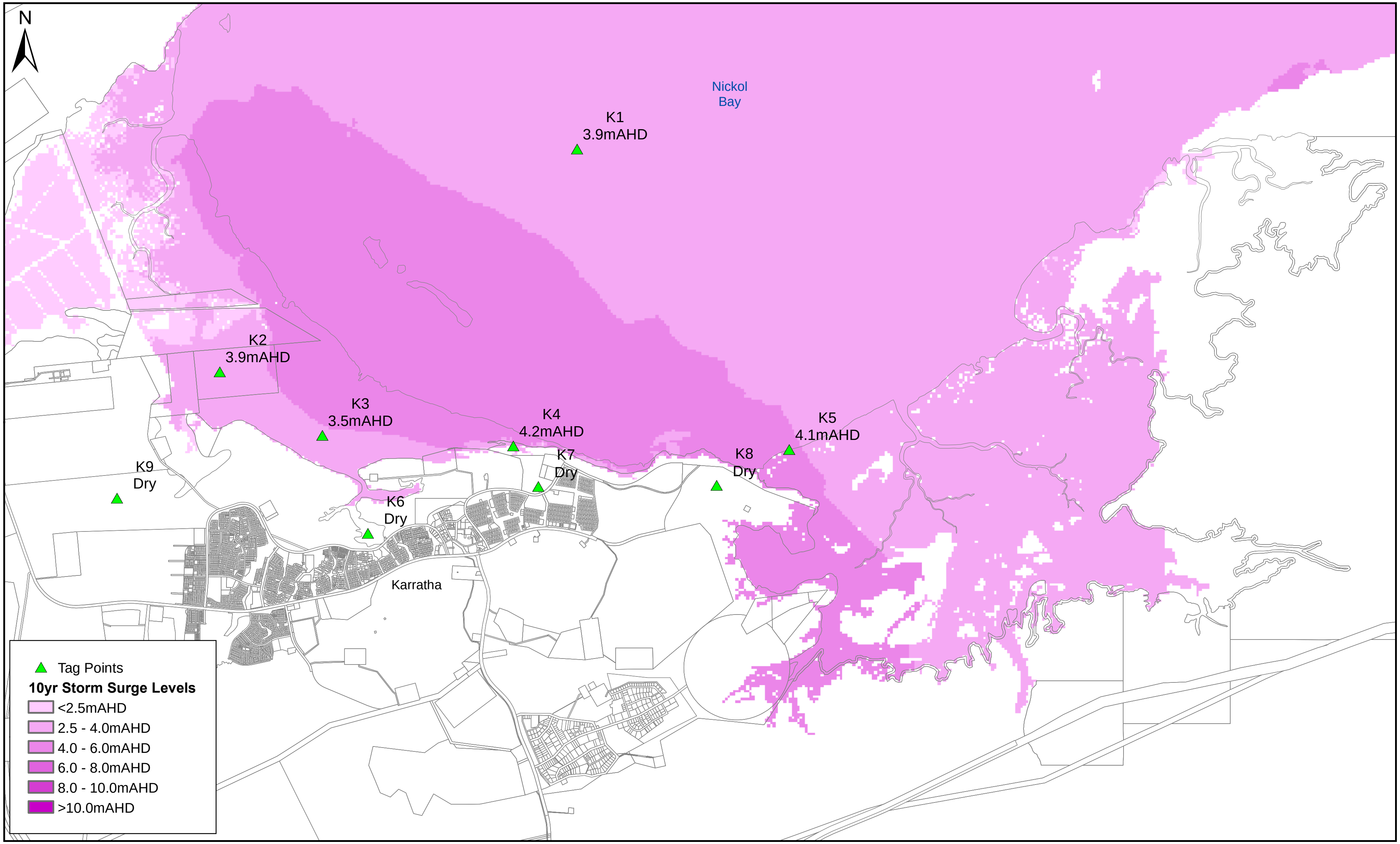
Figure 13: 2yr ARI Coastal Inundation - 2060 Climate Scenario



Data Source: GEMSURGE Modelling 2011

Job No. J4812
Scale: 1:100,000
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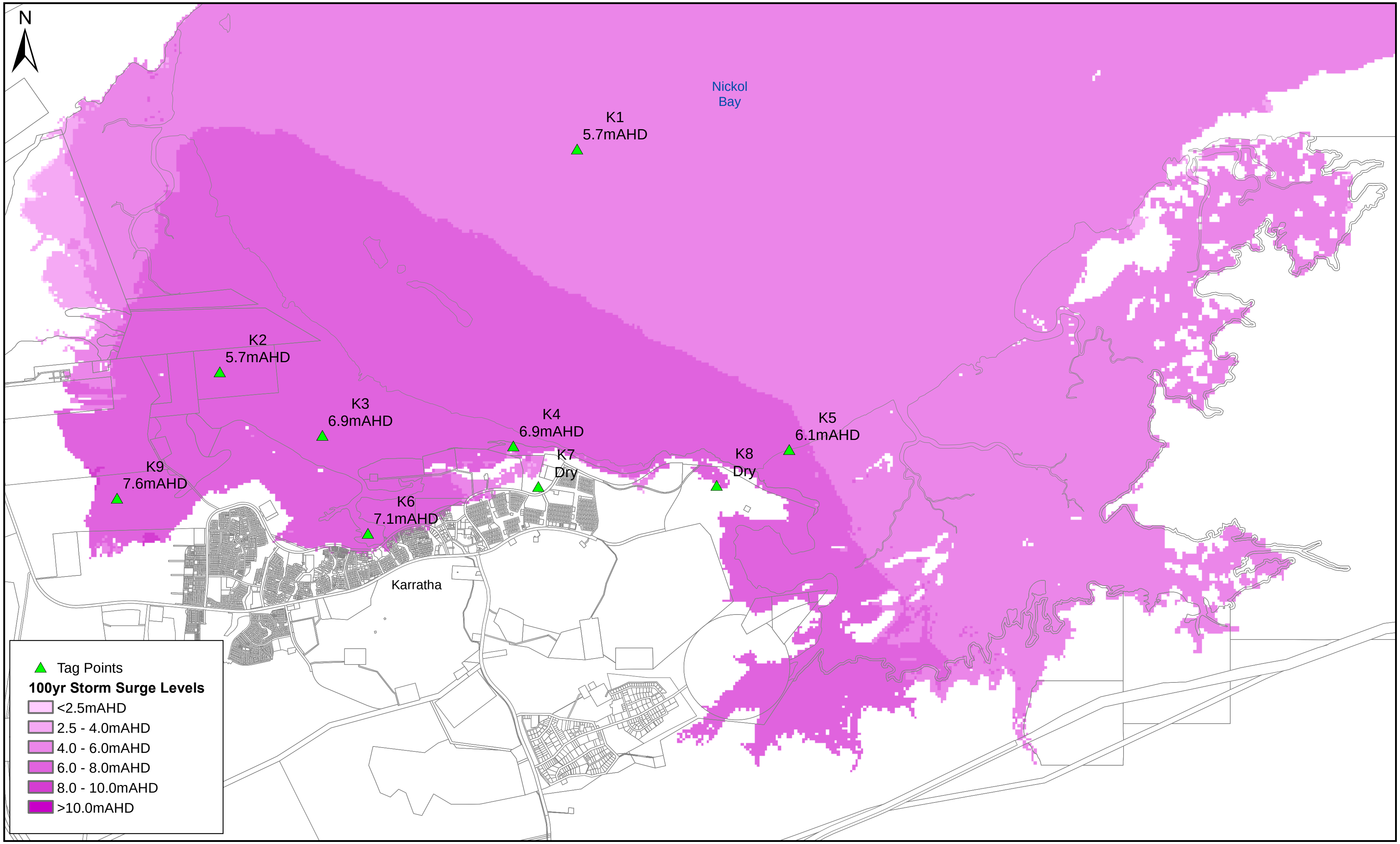
Figure 14: 10yr ARI Coastal Inundation - 2060 Climate Scenario



Data Source: GEMSURGE Modelling 2011

Job No. J4812

Scale: 1:100,000

0 1 2 3 4 Kilometers

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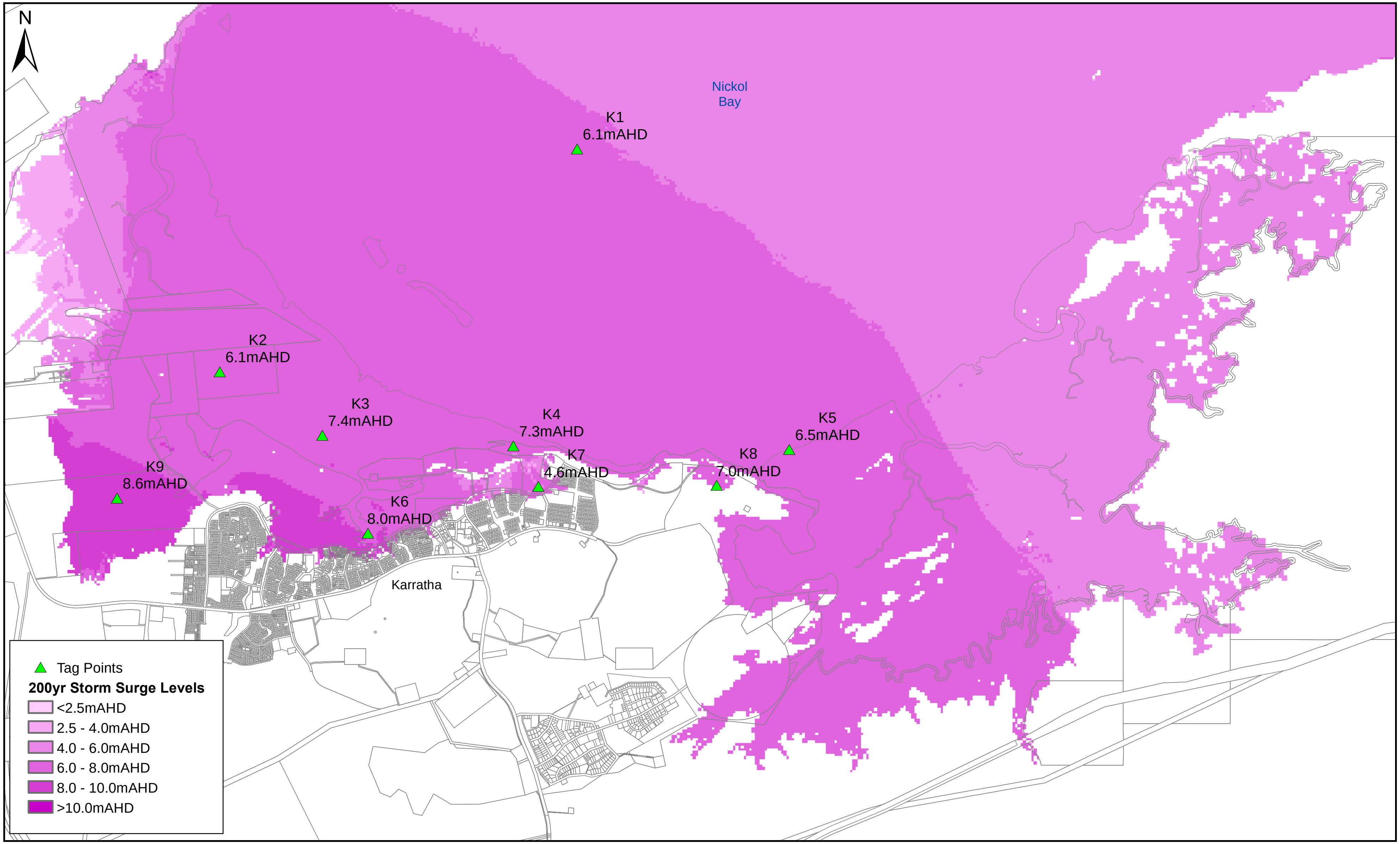
Figure 15: 100yr ARI Coastal Inundation - 2060 Climate Scenario



Data Source: GEMSURGE Modelling 2011

Job No. J4812
Scale: 1:100,000
0 1 2 3 4 Kilometers

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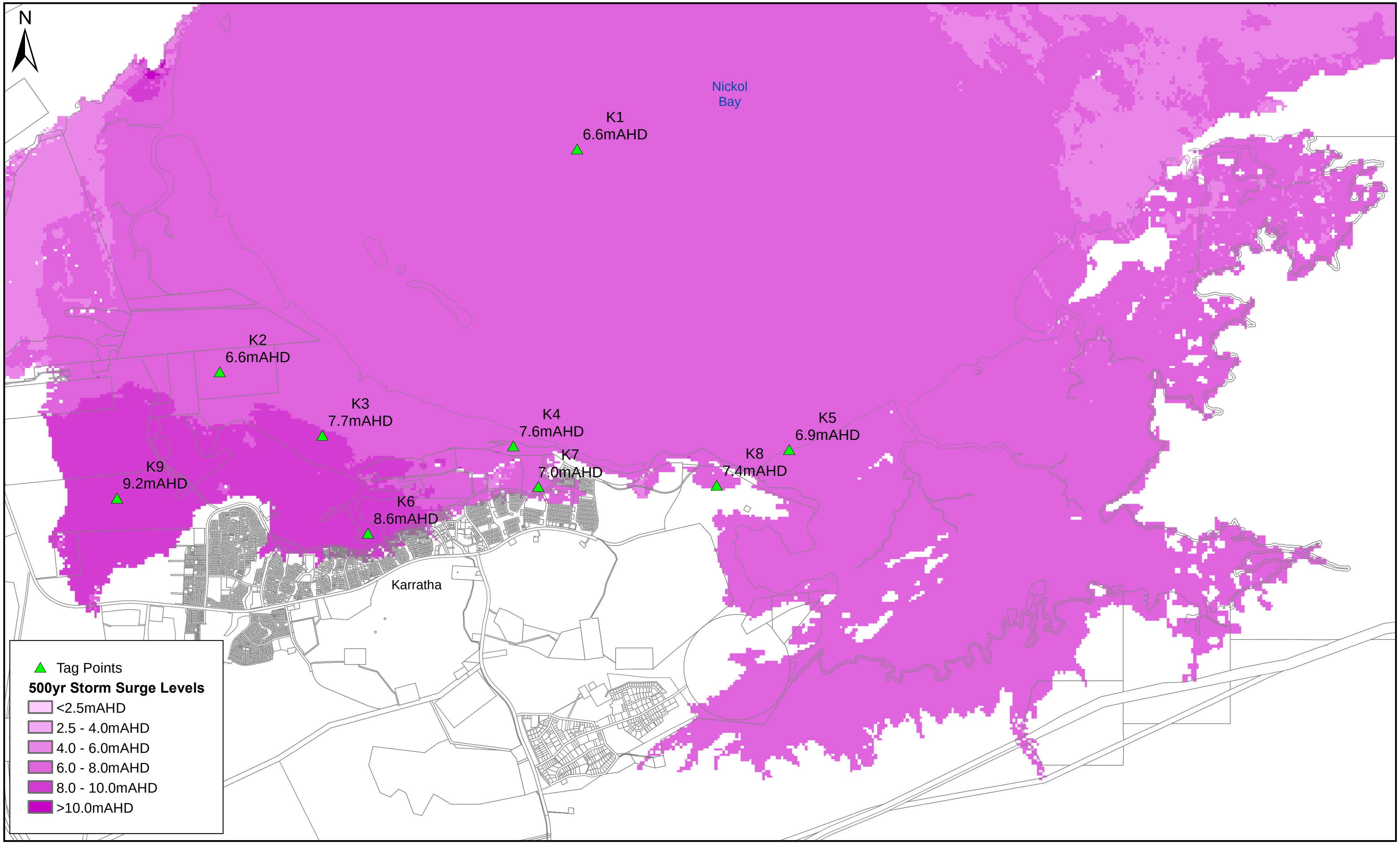
Figure 16: 200yr ARI Coastal Inundation - 2060 Climate Scenario



Data Source: GEMSURGE Modelling 2011

Job No. J4812

Scale: 1:100,000

0 1 2 3 4 Kilometers

LandCorp

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Figure 17: 500yr ARI Coastal Inundation - 2060 Climate Scenario

Data Source: GEMSURGE Modelling 2011

Job No. J4812

Scale: 1:100,000

0 1 2 3 4 Kilometers

LandCorp

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Figure 18: 2yr ARI Coastal Inundation - 2110 Climate Scenario

Data Source: GEMSURGE Modelling 2011

Job No. J4812
Scale: 1:100,000
0 1 2 3 4 Kilometers

LandCorp
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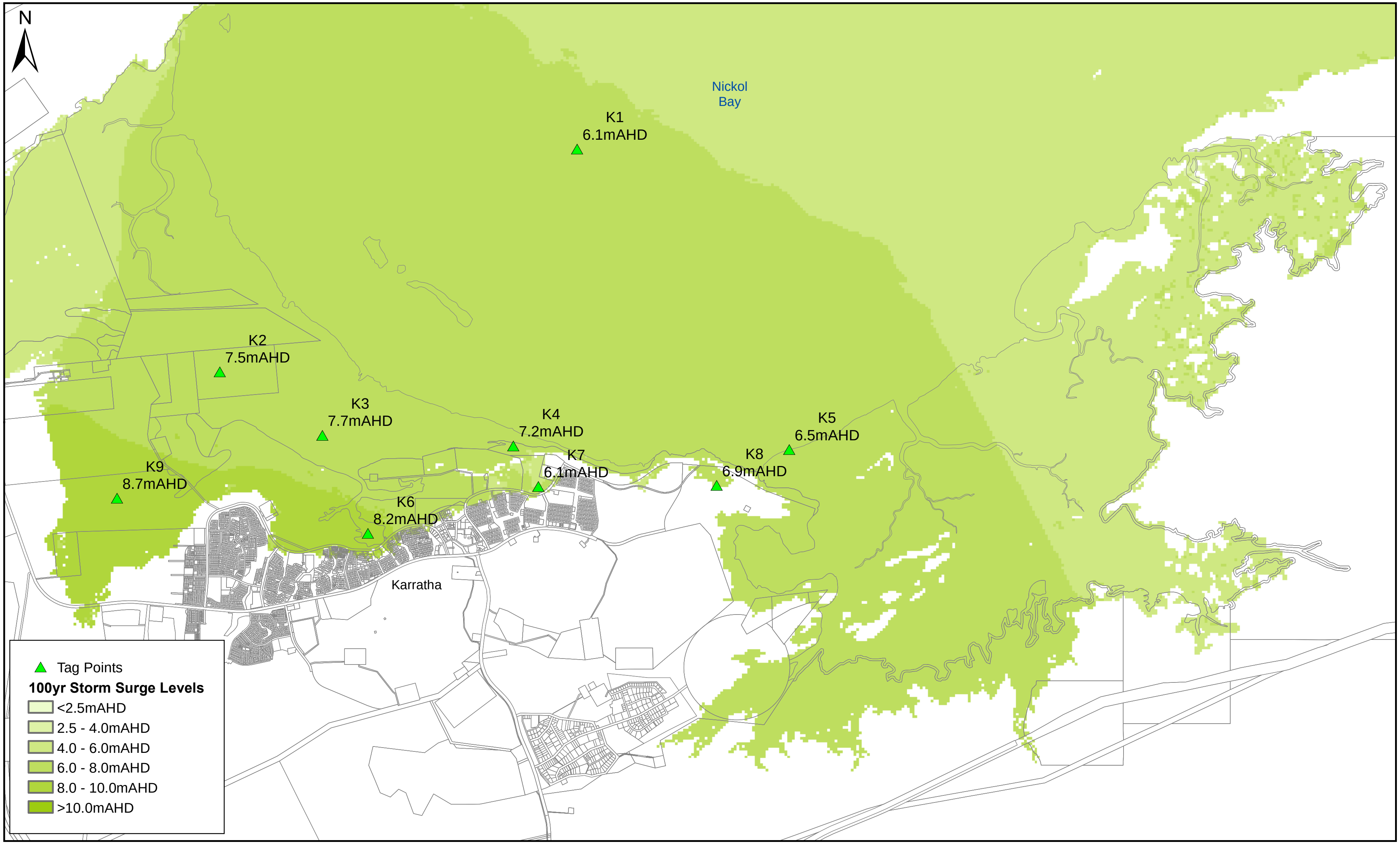
Figure 19: 10yr ARI Coastal Inundation - 2110 Climate Scenario



Data Source: GEMSURGE Modelling 2011

Job No. J4812

Scale: 1:100,000

0 1 2 3 4 Kilometers

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Figure 20: 100yr ARI Coastal Inundation - 2110 Climate Scenario

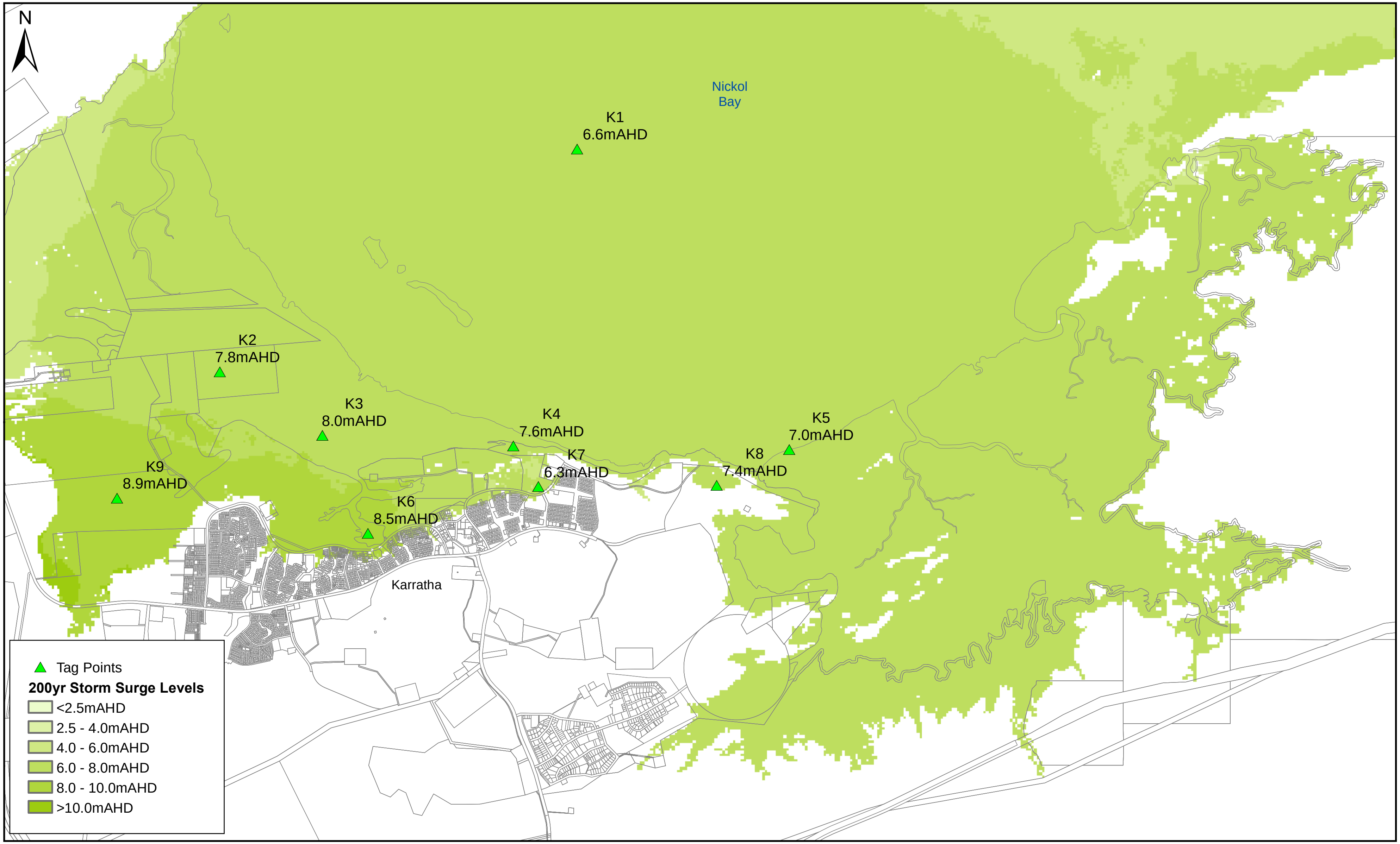

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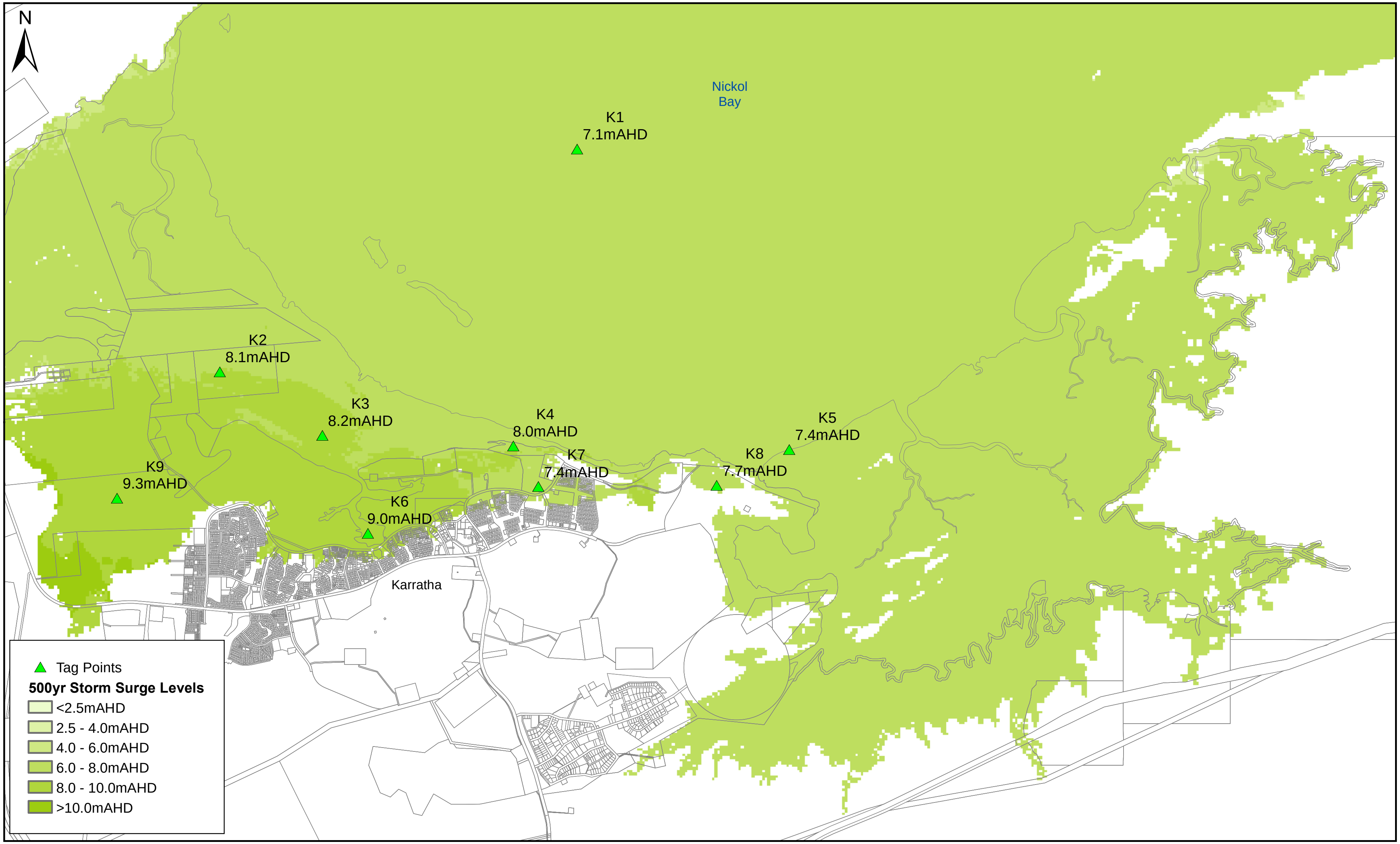
Figure 21: 200yr ARI Coastal Inundation - 2110 Climate Scenario



Data Source: GEMSURGE Modelling 2011

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LandCorp

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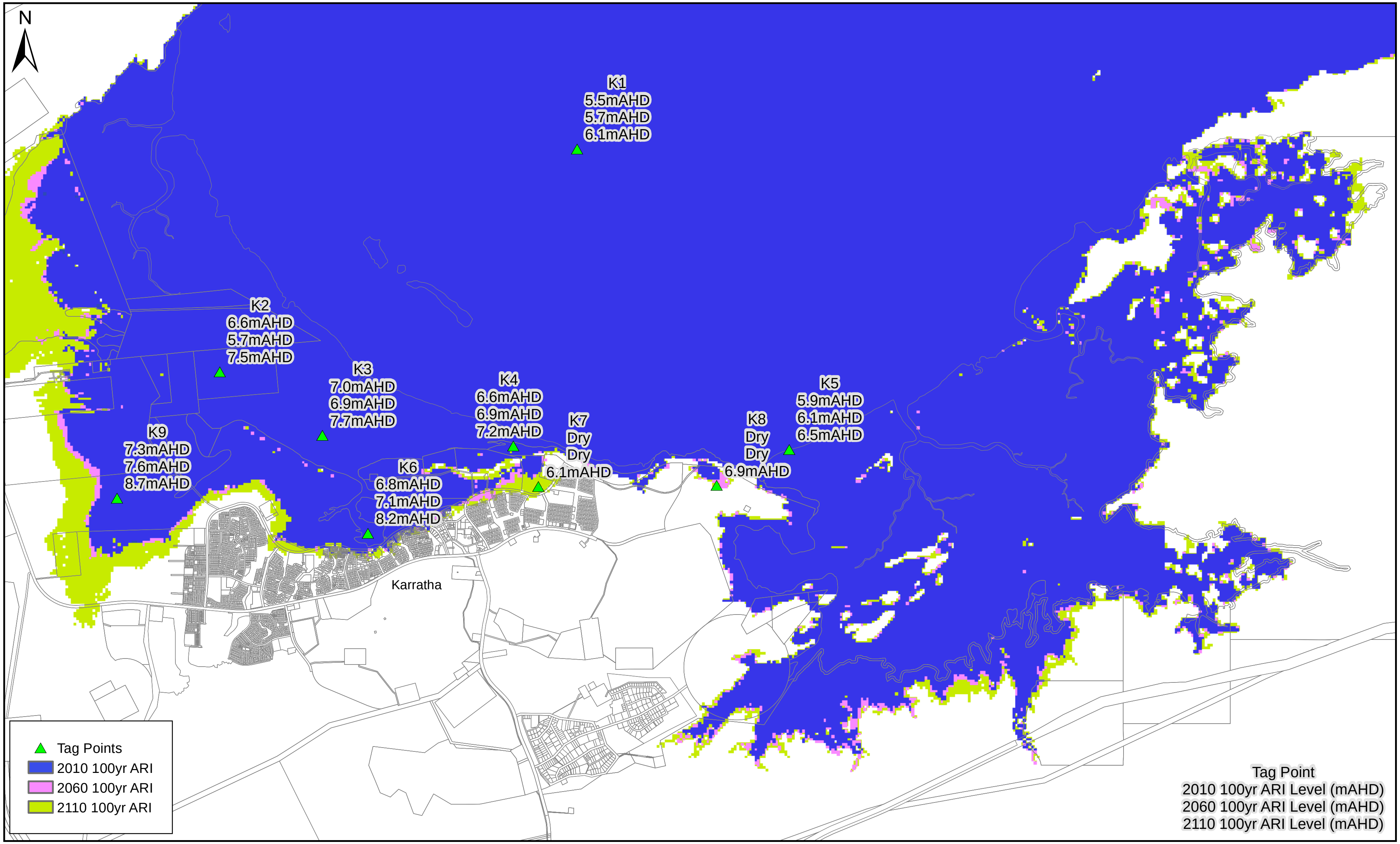
Figure 22: 500yr ARI Coastal Inundation - 2110 Climate Scenario



Data Source: GEMSURGE Modelling 2011

Job No. J4812

Scale: 1:100,000

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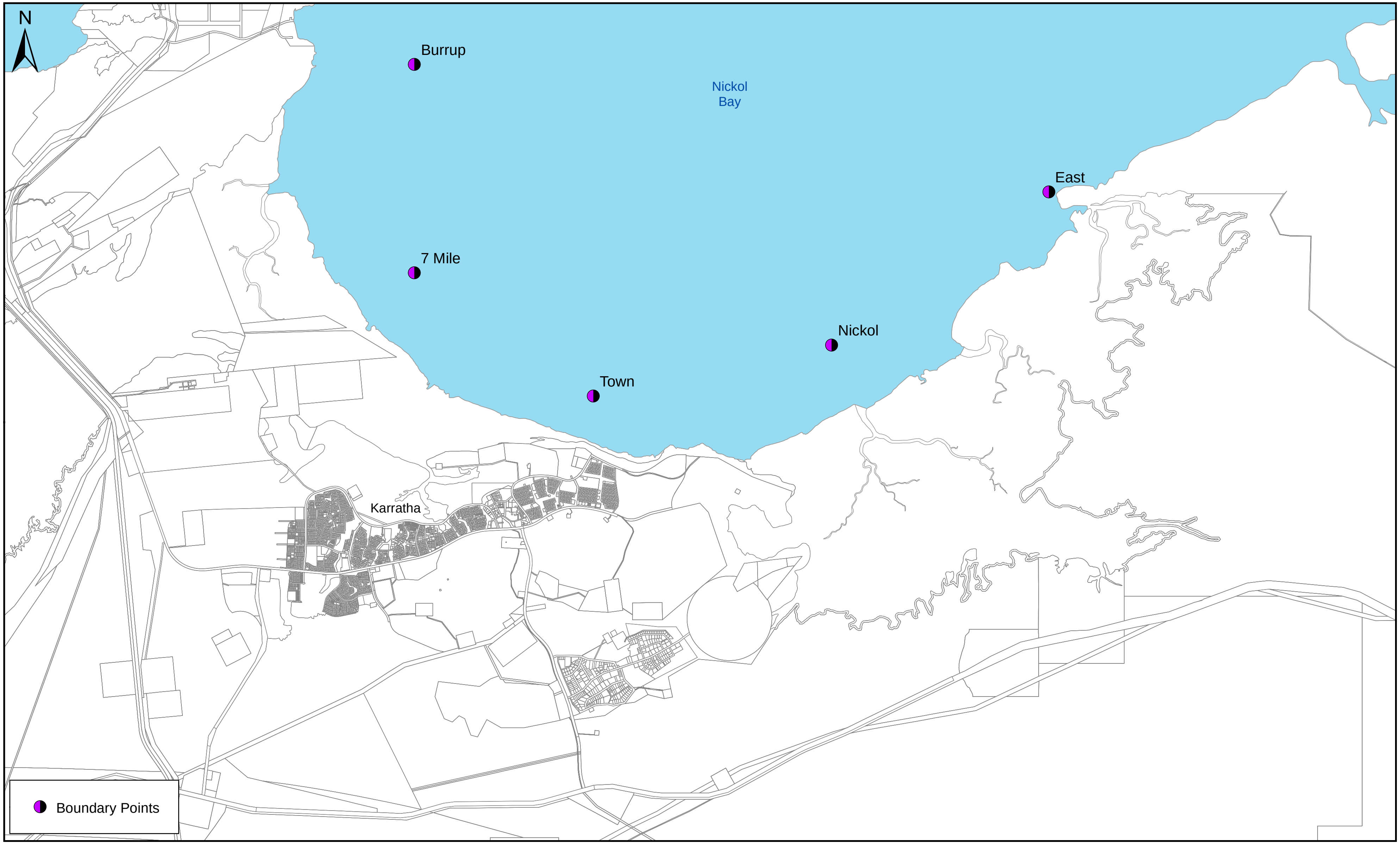
Figure 23: Comparison of 100yr ARI for 2010, 2060 and 2110



Data Source: GEMSURGE Modelling 2011

Job No. J4812

Scale: 1:125,000

0 1 2 3 4 Kilometers

LandCorp

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Figure 24: Locations for Hydraulic Model Boundary Conditions

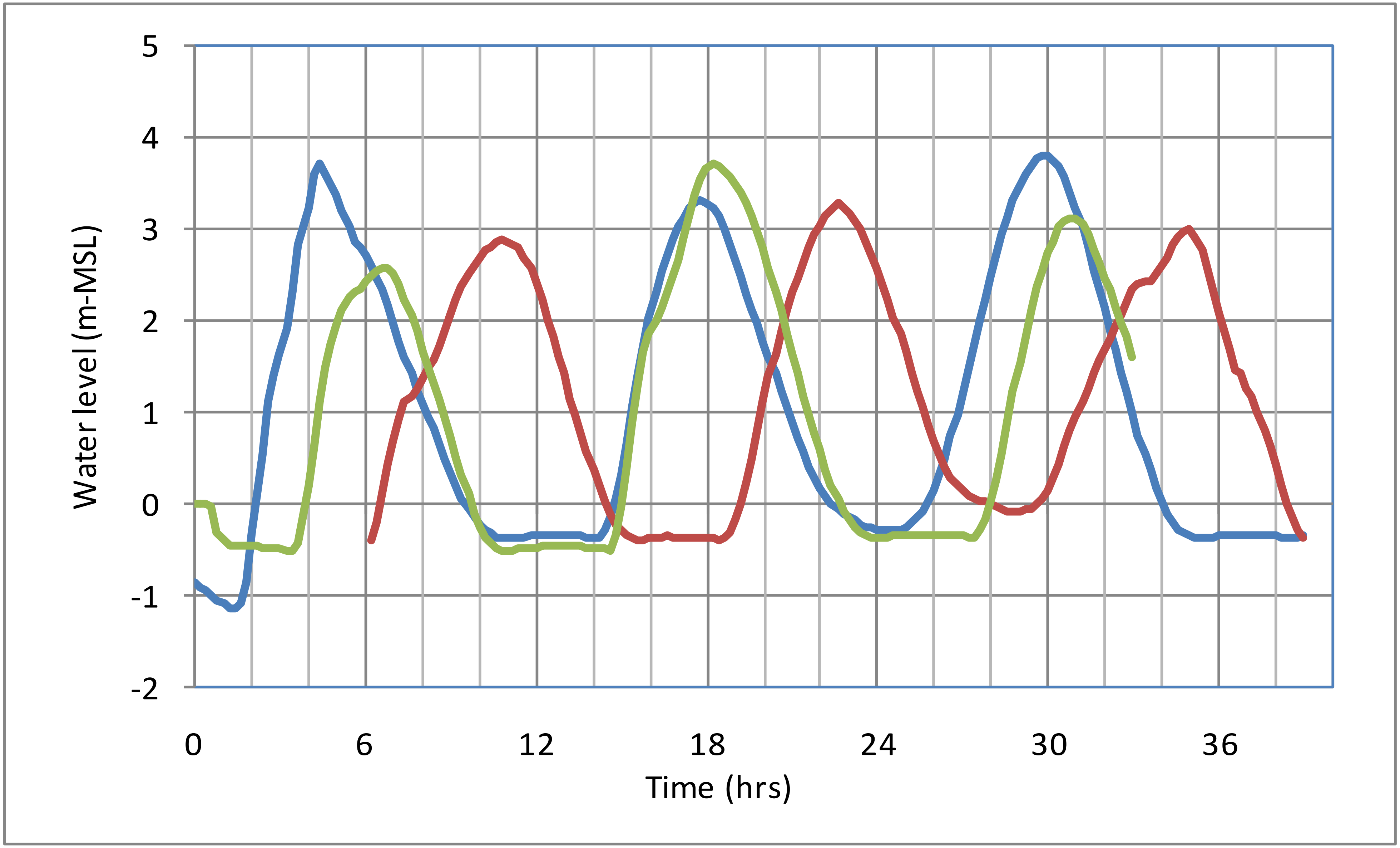

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Figure 25: Sample Time Series for 10yr ARI Level Events, K4 Location

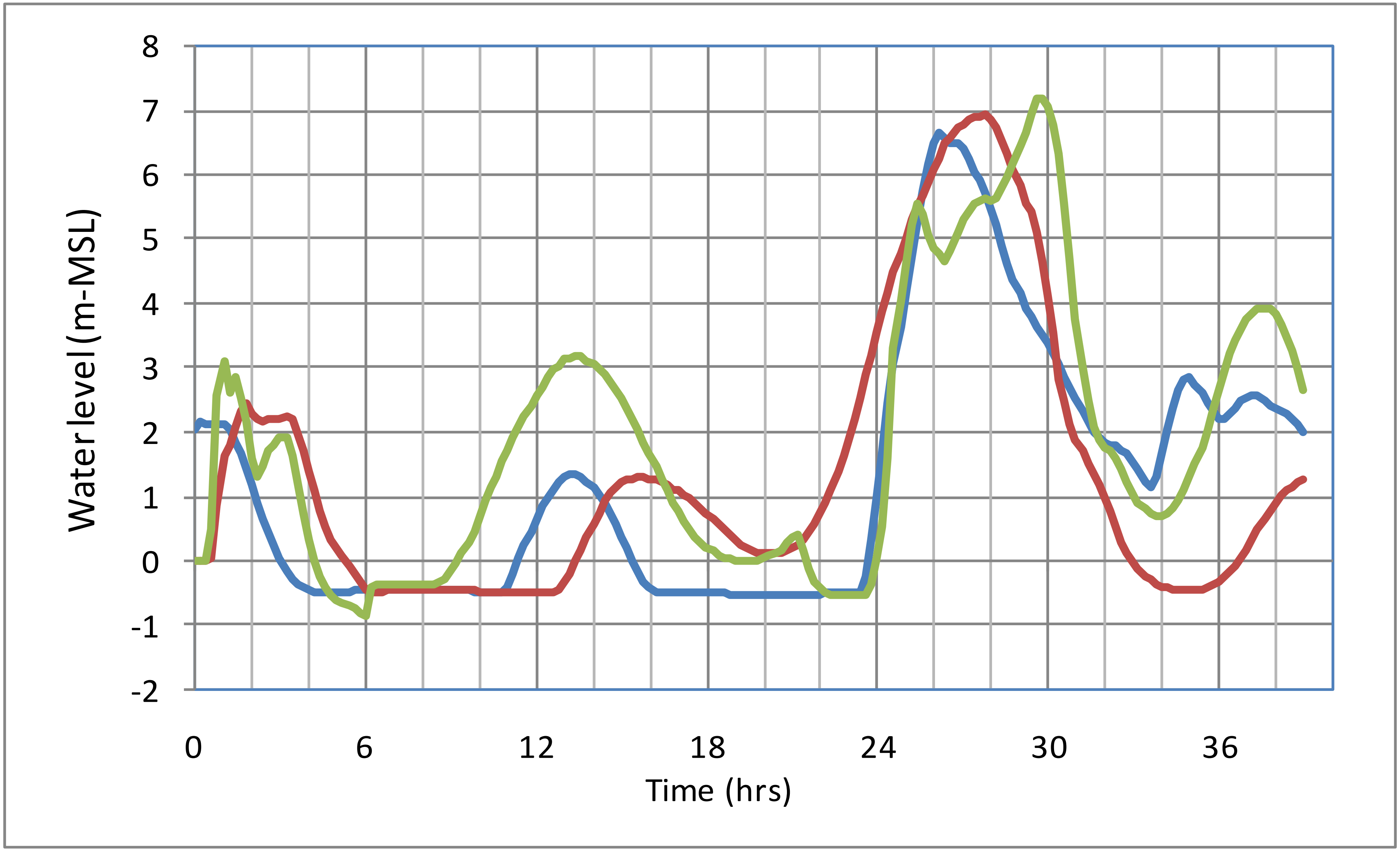

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Figure 26: Sample Time Series for 100yr ARI Level Events, K4 Location

Karratha Coastal Vulnerability Study

Report IV: Storm Surge and Coastal Inundation

APPENDIX A

GEMSURGE

A1.1 Technical Description

For studies of hydrodynamic circulation and sea level variation under ambient and extreme weather conditions, GEMS has developed the GEMS 3-D Coastal Ocean Model (GCOM3D). GCOM3D is an advanced, fully three-dimensional, ocean-circulation model that determines horizontal and vertical hydrodynamic circulation due to wind stress, atmospheric pressure gradients, astronomical tides, quadratic bottom friction and ocean thermal structure. The system will run on Windows/NT or UNIX platforms. GCOM3D is fully functional anywhere in the world using tidal constituent and bathymetric data derived from global, regional and local databases. Although GCOM3D has never been fully published, details appear in publications (Hubbert 1991, 1993, 1999). Further information is given below.

GEMSURGE is the 2D depth-integrated (single layer) version of GCOM3D.

A1.1.1 History and Physics

The history of development of GCOM3D began in 1982, initially stimulated by the 3D model development by Lendertsee (1973) who applied a “z” co-ordinate 3D barotropic model to a number of coastal engineering tasks in the 1970’s.

The publication of what was the predecessor to the Princeton Ocean Model in 1987 by Blumberg and Mellor (1987) raised the standard of 3D ocean modelling by incorporating the vertical mixing schemes then used in atmospheric modelling into an ocean model for the first time.

GCOM3D was the first “z” coordinate ocean model to incorporate the Mellor-Yamada (1974, 1982) vertical mixing scheme and was first used for consulting purposes in 1984 for the Geelong ocean outfall study near Barwon Heads in Victoria.

GCOM3D is a fully baroclinic ocean model but is most often run in barotropic (hydrodynamic) mode due to either the lack of data on ocean thermal structure or the dominance of winds and tides as the major forcing factors.

A1.1.2 General Description

GCOM3D is a fully three-dimensional, ocean-circulation model that determines horizontal and vertical circulation due to wind stress, atmospheric pressure gradients, astronomical tides, quadratic bottom friction and ocean thermal structure.

GCOM3D is formulated as a re-locatable model which can be applied anywhere in the world using tidal constituent and bathymetric data derived from global and local databases.

The three-dimensional structure of the model domain, tidal conditions at the open boundaries, thermodynamics and wind forcing are defined for each model application by extraction of data stored in gridded databases covering a wider geographical area of interest.

The model scale is freely adjustable, and nesting to any number of levels is supported in order to suit the oceanographic complexity of a study area.

As the model is fully three-dimensional, output can include current data at any or all levels in the water column.

A1.1.3 Horizontal and Vertical Structure

The model operates on a regular grid (in the x and y directions) and uses a z-coordinate vertical-layering scheme. That is, the depth structure is modelled using a varying number of layers, depending on the depth of water, and each layer has a constant thickness over the horizontal plane.

The horizontal resolution and the vertical layer depths and thickness can be varied according to the situation to be modelled and the ocean physics which needs to be represented.

The vertical scheme decouples surface wind stress and seabed friction and avoids the bias of current predictions for a particular layer caused by averaging of currents over varying depths, as used in sigma co-ordinate and "depth-averaged" model schemes.

In the upper water column levels are typically a few metres apart, increasing to several hundred metres in deep waters.

A1.4 Numerical Procedures

The basic equations are solved using a split-explicit finite-difference scheme on an Arakawa-C grid (Mesinger and Arakawa, 1976) as described in Hubbert et al. (1990). The continuity equation and the gravity wave and Coriolis terms in the momentum equations are solved on the shortest time step, (the adjustment step) using the forward-backward method.

The non-linear advective terms are solved on an intermediate advective time step using the two-time-level method of Miller and Pearce (1974). Finally, on the longest time step, the so-called physics step, the surface wind stress, bottom friction stress and atmospheric pressure terms are solved using a backward-implicit method. This approach is extremely efficient in oceanographic models with free surfaces because of the large disparity between advective speeds and gravity-wave phase speeds in deep water.

The numerical scheme used for the advective step is the two-time-level method of Miller and Pearce (1974). This scheme alternates the Euler and Euler-backward (Matsuno) schemes at odd and even advective time-steps and has the major advantage of an amplification factor of almost exactly unity for the Courant numbers that are found in ocean models (Hubbert et al. 1991).

The adjustment and advective integration cycle is carried out N times to produce an interim solution which is completed with the inclusion of the physics terms using a numerical technique similar to that described for the adjustment step.

A1.1.5 Boundary Conditions

Boundary conditions can be applied in a range of ways depending on the type of process being modelled.

Meteorological forcing is applied via the wind stress and surface pressure gradient at all submerged model grid-points in the computational domain. The surface drag co-efficient used when calculating the wind stress is based on Smith and Banke (1975).

Tidal and meteorological forcing at lateral boundaries is achieved by specifying the incremental displacement of the water surface due to changes in tidal height and atmospheric pressure. These boundary conditions are applied using a 'one-way nesting' technique to the appropriate model variable with a logarithmic decreasing intensity from the boundary to some specified number of model grid-points (typically 10-15) into the domain.

At coastal boundaries and along river banks, the wetting and drying of grid cells is accomplished via the inundation algorithm published in Hubbert and McInnes (1999a and b).

On outflow, a radiation boundary condition, as described in Miller and Thorpe (1981) is applied to the velocity field to prevent the buildup of numerical energy, while on inflow boundaries, a zero-gradient condition is applied.

A1.1.6 Tidal Data Assimilation

In order to improve the simulation of tidal forced dynamics the model includes the facility to “nudge” the solution with tidal height predictions at locations within the model domain.

The nudging method is based on deriving a new solution at grid points near each tidal station from a weighted combination of the model solution and the station sea level prediction.

A1.1.7 Model Applications

GCOM3D has undergone exhaustive evaluation and verification in the 15 years it has served the coastal engineering industry in Australia and has a proven record of accurately predicting the wind and tidal driven ocean currents around the Australian continental shelf (and in many other parts of the world).

The Australian National Search and Rescue system is based on ocean currents from GCOM3D, which has been running in real-time at the Australian Maritime Safety Authority in Canberra for the past 4 years. It is the first real-time ocean prediction model in Australia.

The U.S. Navy also purchased GCOM3D for its coastal ocean forecasting system. GCOM3D has also been used in a wide range of ocean environmental studies including prediction of the fate of oil spills, sediments, hydrotest chemicals, drill cuttings, produced formation water and cooling waters as well as in other coastal ocean modelling studies such as storm surges and search and rescue.

A1.1.8 GCOM3D/GEMSURGE References

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Smith, S. D. and Banke, E.G., 1975: Variation of the sea surface drag coefficient with wind speed. Q. J. R. Meteorol. Soc., 101: 665-673.

A1.2 Validation

GEMSURGE has been employed in a range of major storm surge studies both in outside Australia. Two examples of model validation are included here:

a) The GEMS inundation model was subjected to detailed testing in a variety of channel configurations by the CSIRO Coastal Impacts Group during flood modelling of the Nerang River and the Broadwater for the Gold Coast City Council in 1999 and 2000. Figure A1 shows the complex Nerang River grid and Figure A2 shows the verification of the tidal levels at Carrara, a location several kilometres up the river at which no previous model had achieved verification. Details of the model inundation method and verification have been published in the international journals (Hubbert and McInnes, 1999a) and in a book on coastal processes (Hubbert and McInnes, 1999b).

b) During Tropical Cyclone Vance the Onslow Salt levees were breached in several places and the measured storm surge at the mouth of Beadon Creek was 3.3 m. GEMSURGE reproduced the storm surge maximum height exactly (without any tuning) and predicted the locations where overtopping of the levees occurred with excellent agreement. Figures A3 and A4 show the flooding during Tropical Cyclone Vance in the vicinity of the township and the predicted overtopping of the Onslow Salt external levees near Beadon Creek where the fishing vessel “Zora Dawn” was found perched on the remains of the levee. Figure A5 shows the remodelling of Tropical Cyclone Vance to determine the new design height for the external levees for the rebuilding program.

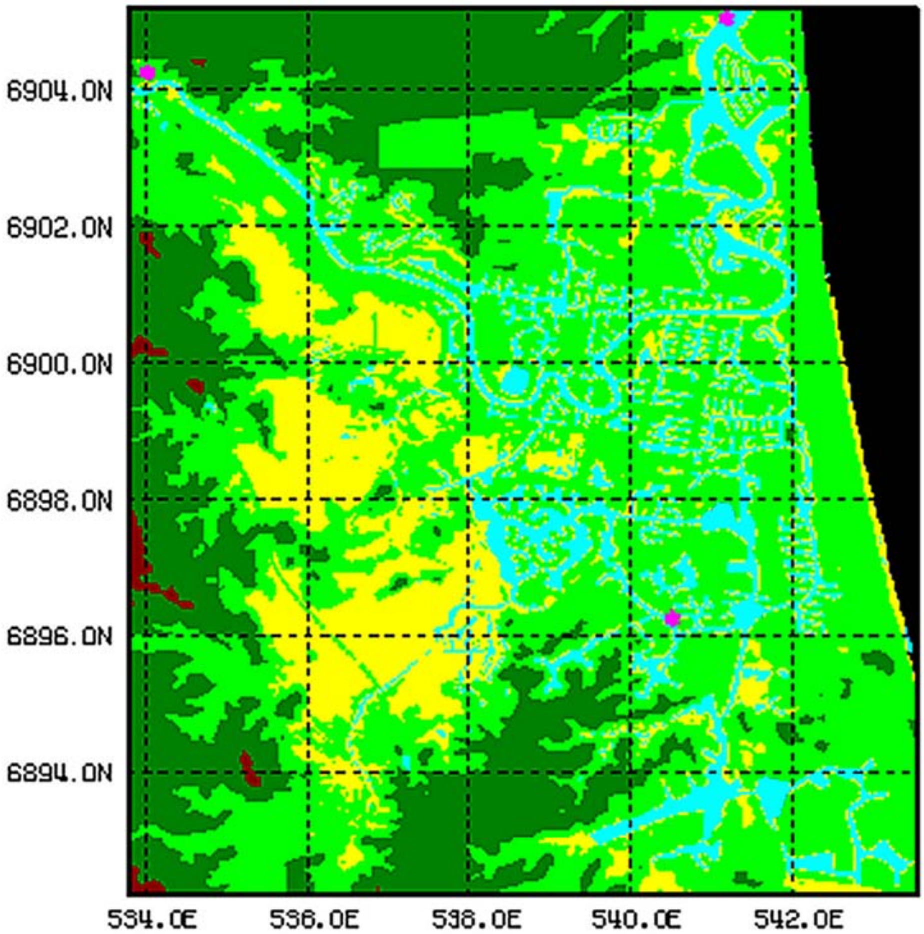

Figure A1. The complex Nerang River, Gold Coast, flood study grid.

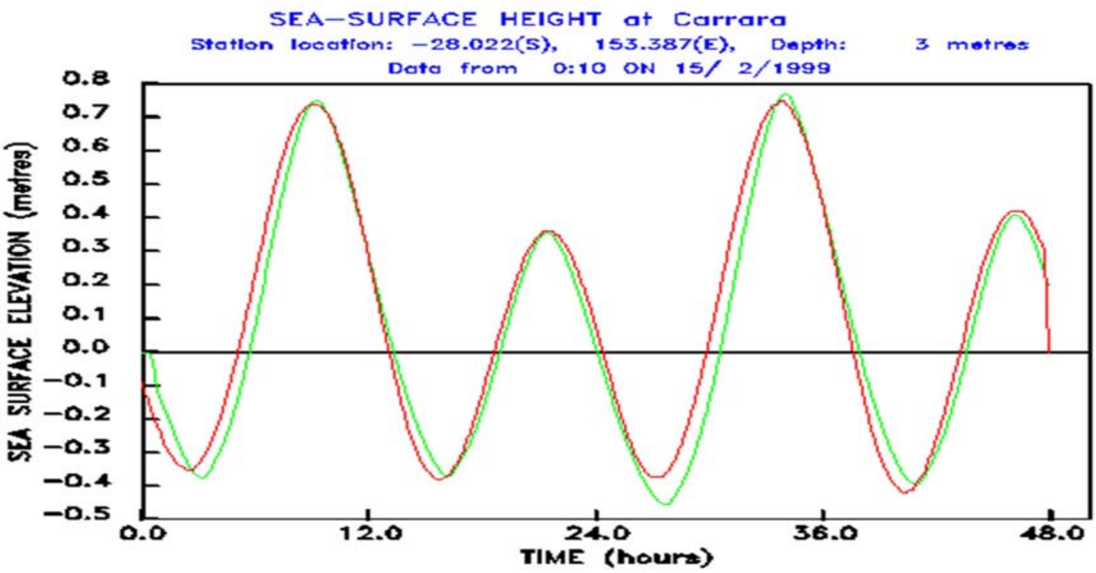

Figure A2. Verification of the Nerang River model against the Carrara tide gauge.

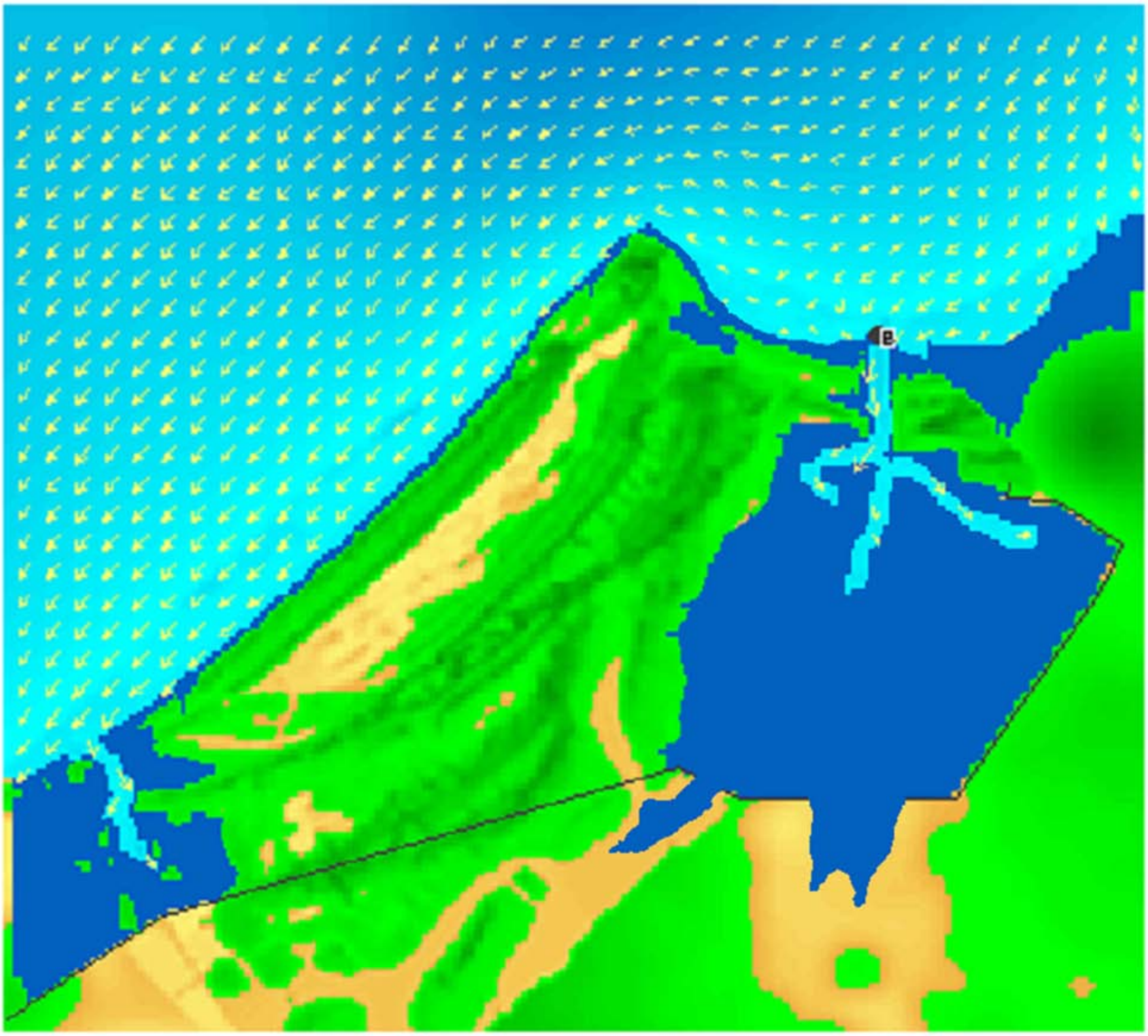

Figure A3. Flooding in the vicinity of Onslow township and Beadon Creek 1 hour before the peak of the flood during Tropical Cyclone Vance.

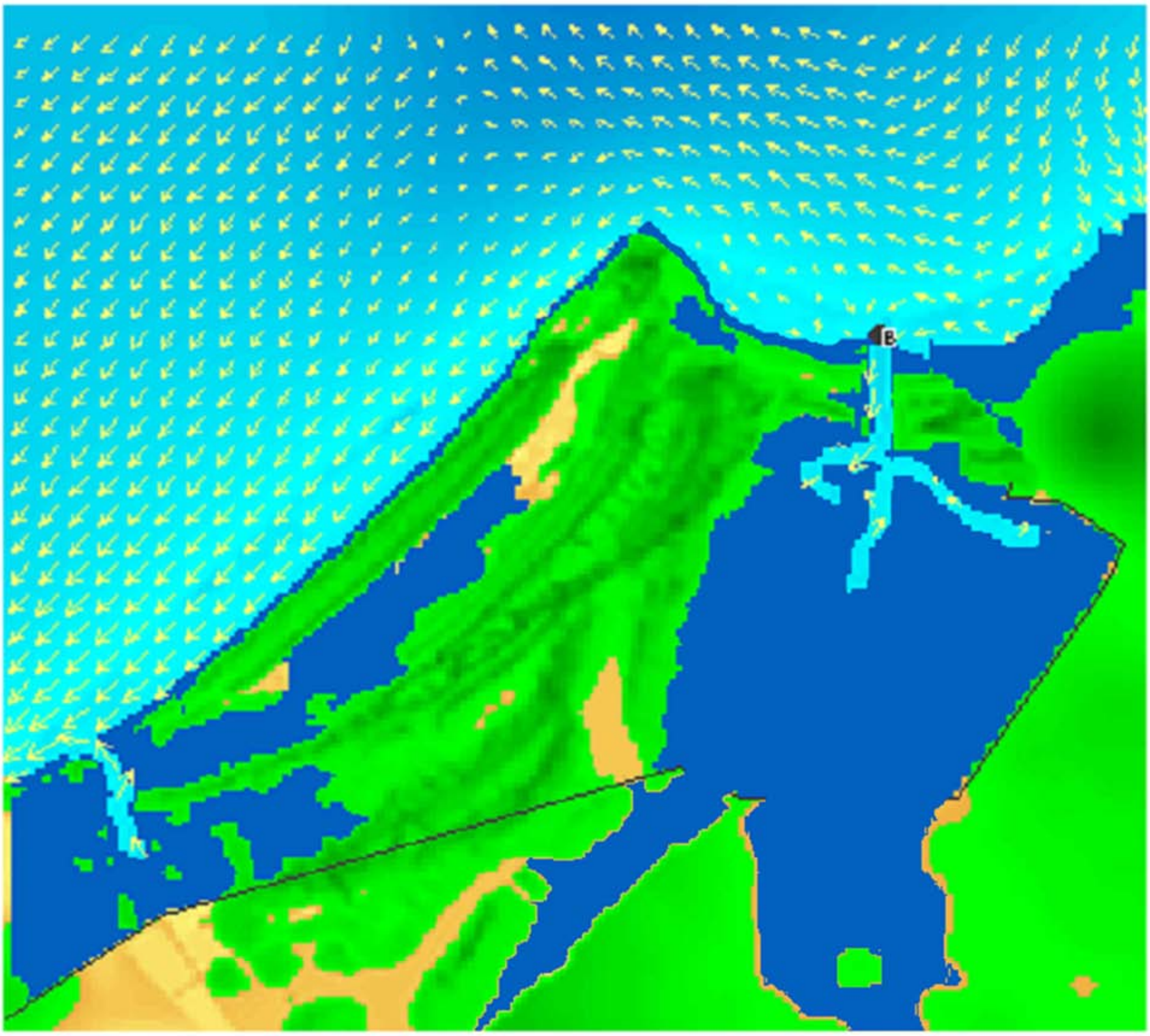

Figure A4. Flooding in the vicinity of Onslow township and Beadon Creek at the peak of the flood during Tropical Cyclone Vance.

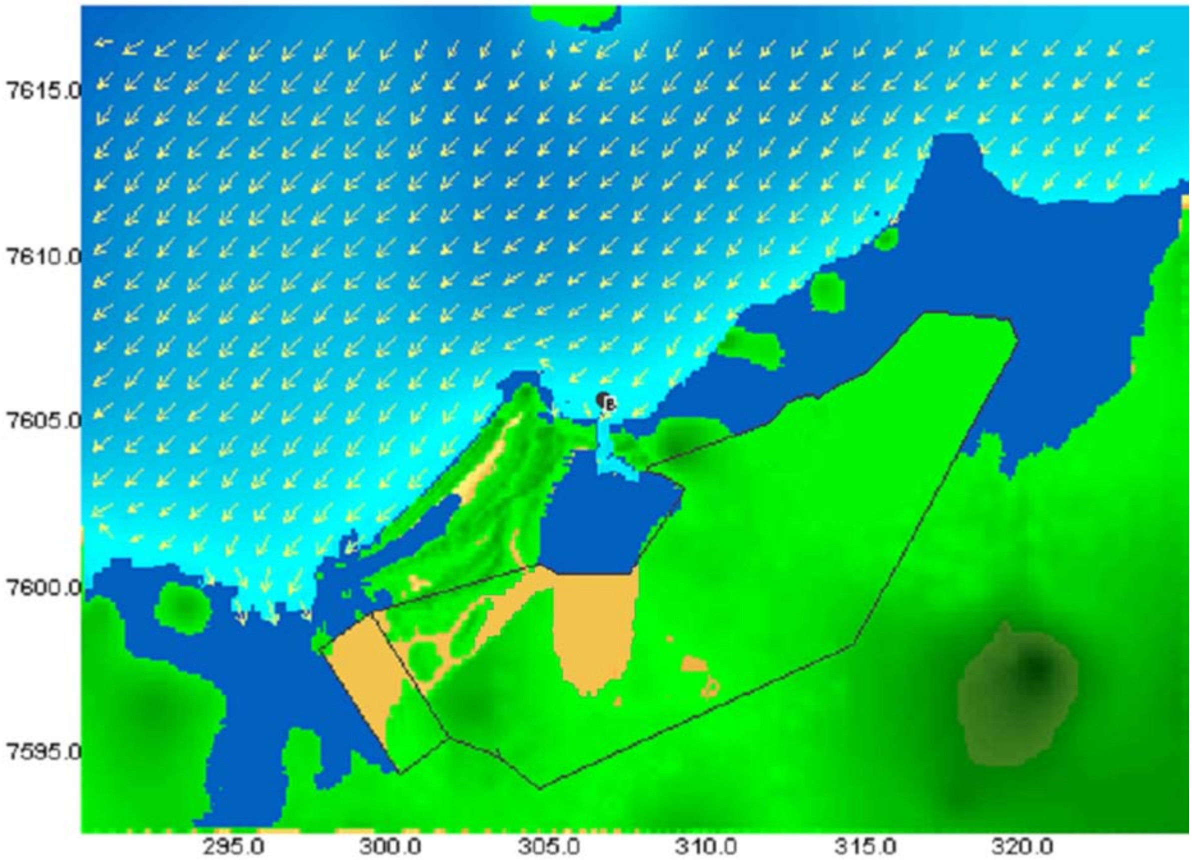

Figure A5. Flooding around the Onslow Salt external levees during the redesign program after Cyclone Vance.

Karratha Coastal Vulnerability Study

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APPENDIX B

Model Validation and Accuracy

Karratha Coastal Inundation Study

Storm Surge & Coastal Inundation

Model Validation & Accuracy

October 2011

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1. INTRODUCTION

The aim of this document is to provide a guide to the general accuracy of the models employed in the study, and how the models have been verified, both in a general sense and for the specific configuration employed in the study.

As a general point, it is noted that precise verification of a model suite for particular event cannot be made without making assumptions when quantifying the various physical processes contributing to a storm surge event. This is because of data limitations where observations are limited to a relatively few wind and tide gauge locations.

2. STORM SURGE MODEL VALIDATION

2.1 Overview

Details relating to the validation of the model suite employed for the current project are presented in section. These details include:

- references to publications relating to specific models;
- the performance of the model suite for other projects and corresponding locations, and
- quantitative comparison of model output and observations for the particular model configurations applied in the current study.

2.2 Scientific Literature

A formal description of the storm surge model is given in Hubbert et al (1991). Details of the model inundation method and verification have been published in the international journals (Hubbert and McInnes, 1999a) and in a book on coastal processes (Hubbert and McInnes, 1999b).

2.3 Regional Validation

Earlier model versions have been validated over multiple locations during the course of undertaking consultancy projects. Samples of this validation work are presented in this section for three locations – Gold Coast, Onslow and the Cape Lambert area. Reference is also made to validation study for the 1939 Port Hedland storm surge event.

2.3.1 Gold Coast

The GEMS inundation algorithms were subjected to detailed testing in a variety of channel configurations by the CSIRO Coastal Impacts Group during flood modeling of the Nerang River and the Broadwater for the Gold Coast City Council in 1999 and 2000. Figure 1 shows the complex Nerang River grid and Figure 2 shows the verification of the tidal levels at Carrara, a location several kilometres from the river mouth. No other model had achieved comparable accuracy for the text scenario at the time this work was carried out. This example is presented in order to show the capacity of the model to accurately represent flows in a complex environment.

2.3.2 Onslow (Tropical Cyclone Vance)

During Tropical Cyclone Vance the Onslow Salt levees were breached in several places and the measured storm surge at the mouth of Beadon Creek was 3.3 m. GEMSURGE accurately reproduced the storm surge impact and predicted the locations where overtopping of the levees occurred with a high level of agreement.

Figure 3 shows the flooding during Tropical Cyclone Vance in the vicinity of the township and the predicted overtopping of the Onslow Salt external levees near Beadon Creek where the fishing vessel “Zora Dawn” was found perched on the remains of the levee.

2.3.3 Cape Lambert and Cossack Area

In 2009 GEMS undertook an extensive storm surge study (GEMS 2009) for parts of the West Pilbara including Karratha, Cape Lambert, Dixon Island and Cossack; this work was commioned by the Shire or Roebourne. A part of the study included validation simulations for two significant cyclones Clare and Glenda that occurred during the active 2005-06 cyclone season. The tracks of the two storms are shown in Figure 5.

Cyclone Clare

Clare was a relatively moderate cyclone (minimum pressure, 960hPa), but it crossed the coast just to west of Dampier, so that its strongest winds passed close to Cape Lambert. Figure 6 shows predicted and measured water levels at the Cape Lambert tide gauge during Cyclone Clare. The time series data plotted in Figure 6 shows that the storm surge residual was of the order of 1.6m and that the peak of the storm surge occurred close to high tide on 9 January 2006.

Figure 7 shows the best fit model wind speed versus observed wind speeds recorded at Roebourne, the closest AWS site to Cape Lambert and Figure 8 shows the model versus observed water levels at Cape Lambert jetty. The storm surge predictions for this event accurately represent measured water levels.

Cyclone Glenda

The track of Glenda was similar to that of Clare, but it was a more intense storm (minimum pressure, 910 hPa) and crossed the coast further to the west. No tide gauge data at Cape Lambert was available for the storm due to instrument malfunction, but there is significant evidence of inundation accompanying the event. This evidence indicates water levels of at least 3.7m at Port Sampson and up to 5.0 m at Cossack (Bond Store) and 4.8m at Johns Creek Boat Harbour. Figure 9 shows photographs demonstrating the extent of inundation at the boat harbor during the event.

Figure 10 shows modelled water levels versus tidal prediction for Cape Lambert and Figure 11 shows water levels for three locations in the general Cape Lambert area. These model simulations were again based on the best fit to the Roebourne wind data. Although no measured were available for the study area, the overall peak water level model prediction at Cossack Bond Store 8.3m Chart Datum or 5.1m AHD is close the level inferred from visual observations (for which there is recorded video evidence). Similarly, the predicted value for the boat harbor was close to anecdotal estimates of peak levels at Pt Sampson.

2.3.4 Port Hedland

Several detailed storm surge modelling projects have been undertaken for the Port Hedland area using earlier versions of GEMSURGE. The model was used to verify the large inundation event that occurred at Port Hedland in 1939. Water levels were obtained from news records describing the event.

The results of this validation exercise are described in detail in Hubbert and Smith (1994).

2.4 Project Validation

Validation results for the model configuration for the current project are presented in this section.

2.4.1 Karratha

Although GEMSURGE has been validated for a number of significant cyclone events in the North West Shelf region of WA, no quantitative data has previously been available to allow direct validation of the model for the Karratha area. However, the occurrence of Tropical Cyclone 'Carlos' in February 2011 has provided an opportunity to undertake site specific validation of the model. Although a relatively weak storm, with mean wind speeds reaching 60-70 mph at Karratha Airport, 'Carlos' still produced an abnormal increase in water levels in Nickol Bay. Jim Davies and Asscociates (JDA) subsequently undertook a debris survey in the study area and the results of this survey are compared with inundation modelling for the event.

Cyclone 'Carlos' was a Category 1 (bordering 2) cyclone which moved in a general south-west direction along the coast over several days, passing close to Karratha on 23 February with a central pressure of 980 hPa. The storm surge model suite as set up for the current project was used to simulate storm levels for 'Carlos' based on operational track data provided by the Bureau of Meteorology, as shown in Figure 12.

Figure 13 shows a plot of maximum inundation levels from the model together with the locations form the debris survey. The apparently correspond quite well, with the storm surge debris typically in the 3.5 to 4 metre (AHD) range. This corresponds with model peak levels around 3.8m. It is noted here that the model does not allow for any wave run-up above the predicted mean water level.

2.4.2 Dampier

Records from the King Bay tide gauge (Figure 14) provide quantitative data for validating the model, as established for the current project.

Since this instrument is located well within the complex topographic area that includes Mermaid Sound and the Burrup Peninsula, accurate representation of water levels at the tide gauge by would imply the model is properly capturing the propagation of the broad scale surge into the area.

Model simulations were undertaken for four significant cyclone events:

A. Orson, 1989

B. Bobby, 1995

C. Olivia, 1996

D. Vance, 1999

The tracks of these storms are shown in Figure 15.

Model simulations are based on Bureau of Meteorology (BOM) best track data and wind model parameters (radius of maximum wind and shape parameters) selected to match regional wind observations.

Time series plots comparing model and observed water levels are shown in Figures 16 to 19 respectively. Error statistics for the simulations are presented in Table 1.

TABLE 1: SUMMARY OF PEAK WATER LEVELS – OBSERVED VERSUS MODELED – FOR SELECTED CYCLONE EVENTS.

CYCLONE	DATE	PEAK WATER LEVEL (m)		
		OBSERVED	MODEL	ERROR
Orson	23/4/89	2.0	2.3	0.3
Bobby	24/2/95	0.6	0.7	0.1
Olivia	10/4/96	0.9	1.3	0.4
Vance	22/3/99	0.5	0.7	0.2

3. ESTIMATES OF ACCURACY

3.1 Overview

The overall accuracy of the storm surge water levels presented in this report is contingent on multiple factors, including:

- the accuracy of the cyclone database, including locations for each storm, its intensity as measured by the central pressure and other parameters relating to the structure of the wind field;
- the extent to which the sample period is representative of the longer term cyclone climate for the region and uncertainty associated with fitting a probability distribution to storm central pressure;
- the extent to which the cyclone climate is stationary over the period data has been collected;
- the accuracy of the wind fields and corresponding surface stress fields developed from the wind model employed;
- the accuracy of bathymetry and the corresponding sensitivity of the storm surge and wave models;
- the accuracy of the digital terrain model;
- the degree to which spatially varying terrain types are accurately represented;
- the accuracy of the physics and numeric of the storm surge and wave models,
- representation of climate change in modelling process.

It should be clear that not all of uncertainties can be accurately quantified, but the sensitivity of the results to each is considered in the following discussion.

3.2 Discussion of Contributing Factors

3.2.1 Cyclone Database and Sampling Period

The results of this study are fundamentally based on the cyclone database provided by the Australian Bureau of Meteorology. This database, which dates back to the early part of the 20th century, is considered the 'official' record and therefore the appropriate basis for developing storm surge levels.

However, it is well known that the accuracy of the database, both in terms of storm numbers and storm intensity is variable over time. This relates directly to the evolution in technology and techniques as discussed first by Holland (1981) and more recently by Harper et al (2006). It has been the practice of GEMS to consider cyclones only from the 1960's onwards, corresponding to the introduction of satellite imagery into cyclone analysis.

It is likely though, that other changes, particularly relating to techniques for estimating cyclone central pressure and corresponding maximum wind speeds, will have produced variability in the database. Harper et al have examined these potential influences in detail in the context of assessing climate change impacts on cyclone frequency and intensity.

As part of their analysis, they undertook a re-analysis of 200 north-west Australia region cyclones (187 from the 1968/69 season to 2000/01 and 17 earlier Timor Sea cyclones) and concluded 44.3 % of these events should have their intensity increased by at least 5%. This included eight events for which the minimum central pressure was decreased by at least 20hPa. They concluded an overall trend in which, in pressure terms, there is an order of 10 to 5 hPa reduction over the period from 1970 to the late 1990s. That represents, in terms of pressure deficit a requirement to adjust downwards by about 20% in 1970 to about 55 per cent by 2000.

It must be emphasized that there is no formal acceptance of this suggested re-evaluation of storm intensities by BOM. However, the analysis provides a useful pointer to assess the sensitivity of storm surge estimates to database uncertainty.

Figure 20 compares probability distributions for cyclones employed in the current study and for the same data set with the Harper et al adjustments. This shows a relatively small overall increase in the cyclone intensities – typically 2 to 3 hPa for 50 to 100 year events.

To test the general sensitivity of storm surge levels to this result an event that produces close to the estimated 100 year water level for King Bay (2010 climate) was re-modelled with a 3hPa decrease in storm central pressure. This produced an increase in maximum water level at King Bay of less than 0.1m.

3.2.2 Wind Model

Harper (2002) provides a comprehensive discussion of a range of empirical models, including the seminal model of Holland (1980). Notwithstanding potential improvements that may be made to the Holland model, GEMS has used it as its primary source for generating tropical cyclone wind fields. One of the shortcomings of the model is its tendency to under-forecast wind strength in regions distant from the storm centre. However, since the focus of a study of this type is more focused on more significant surges, this is not considered likely to have material impact on the overall accuracy of the estimates.

As shown in the Section 2 above, the model can generally be forced to accurately simulate observed time series through tuning of parameters representing storm size (radius of maximum wind or RMW) and the shape of the wind field (the B-parameter). However, for multiple simulations used to represent the cyclone climate the assignment of values for these parameters is more problematic.

For this study, and others following from Holland, the shape parameter is based on the relationship between the parameter and storm intensity (central pressure). A mean value for RMW is then employed for each simulation. Demara (2010) developed a storm climatology which related the mean storm scale to latitude; this suggests a regional value for eye radius for Karratha of about 18km, but eye radius and RMW are not identical.

Sensitivity modelling was undertaken based on a limited number of more significant storms impacting the Karratha–Onslow region (Figure 15) following the introduction of one hourly (AWS) wind reporting. Figure 21 shows correlation plots of modelled versus observed winds speed for Karratha comparing results for RMW 25 and 20km. These comparisons are for observations within 3 hours of the observed wind maximum for each event. The plots presented show only a small difference but the mean errors presented in Table 2 show better overall accuracy for the 20km case. Accordingly, the modelling has been undertaken with RMW set to 20km in the current study.

For a more intense storm, a change of radius of maximum wind from 30 to 20 km for a particular can typically change the peak surge by 0.5 to 1.0m. However, from a spatial perspective the primary effect is to shift the area of the peak, so that the result is close to that which results from shifting the whole storm by the same amount. This means that for multiple simulations the effect is largely averaged out by the variability of the location of storm track.

TABLE 2: ERROR STATISTICS FOR MODEL VERSUS OBSERVED WINDS AS A FUNCTION OF RMW.

RMW (km)	Mean Error (m/s)	Standard Deviation (m/s)	Bias (m/s)
25	4.6	3.6	4.6
20	2.9	3.2	2.5

3.2.3 Storm Surge Model

Overall accuracy

The general accuracy of the storm surge model suite, including the wind model, is demonstrated in Section 2 above. Provided the wind forcing through the cyclone climate and the wind forcing is accurate, the surge model will generally predict peak water levels to within 0.2 to 0.3m. This estimate is based on a range of validation simulations, which essentially tunes the wind field to surface observations, but this approach includes assumptions and so this should be treated as an indicative statistic.

Comparison of simulations for 100 year order events for Karratha showed that peak water levels changed by less than 0.1m for simulations with and without the grid changes made to incorporate dune reductions in the Karratha region.

Contribution of Radiation Stress (Wave set-up)

An important contribution to peak steady water level is made through the process of wave set-up. Typically the contribution of set-up to the peak storm surge residual is of the order of 10 per cent. Set-up is incorporated into the storm model through radiation stresses computed from the wave model. This formulation has some numerical problems as highlighted by Rodgers (2011) in addition to any errors associated with modeling the wave field.

Determining the wave error can be achieved by comparing model and observed wave parameters, but the wave set-up component of the storm surge residual in cyclonic conditions is extremely difficult to verify. In the error calculations presented in the following section, it is subsumed into the overall storm surge model error.

3.3 Error Estimates

There are multiple, non-independent inputs that impact on the accuracy of the overall estimates presented in storm surge modeling for Karratha and Dampier. In the preceding discussion, potential uncertainties associated with the cyclone database, selection of wind field and the accuracy of the model itself have been identified.

In order to quantify the potential impact of these errors, numerical computations were used to randomly generate errors for a random selection of modeled events using error estimates for the factors outlined above. These calculations were made on the residual component rather than overall water level.

These results were then used to generate overall error values for the 90 per cent confidence level. The results of the analysis are shown in Table 3. It is emphasized that these results should be taken as indicative as a fully detailed error analysis is outside the scope of the current project.

It is also noted that this analysis does not include consideration of error for the climate change scenarios included in the study.

TABLE 3: 90% CONFIDENCE ERRORS FOR STORM SURGE LEVELS

ARI (years)	2	10	50	100	200	500
Confidence Estimate (m)	0.2	0.3	0.4	0.5	0.5	0.6

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FIGURES

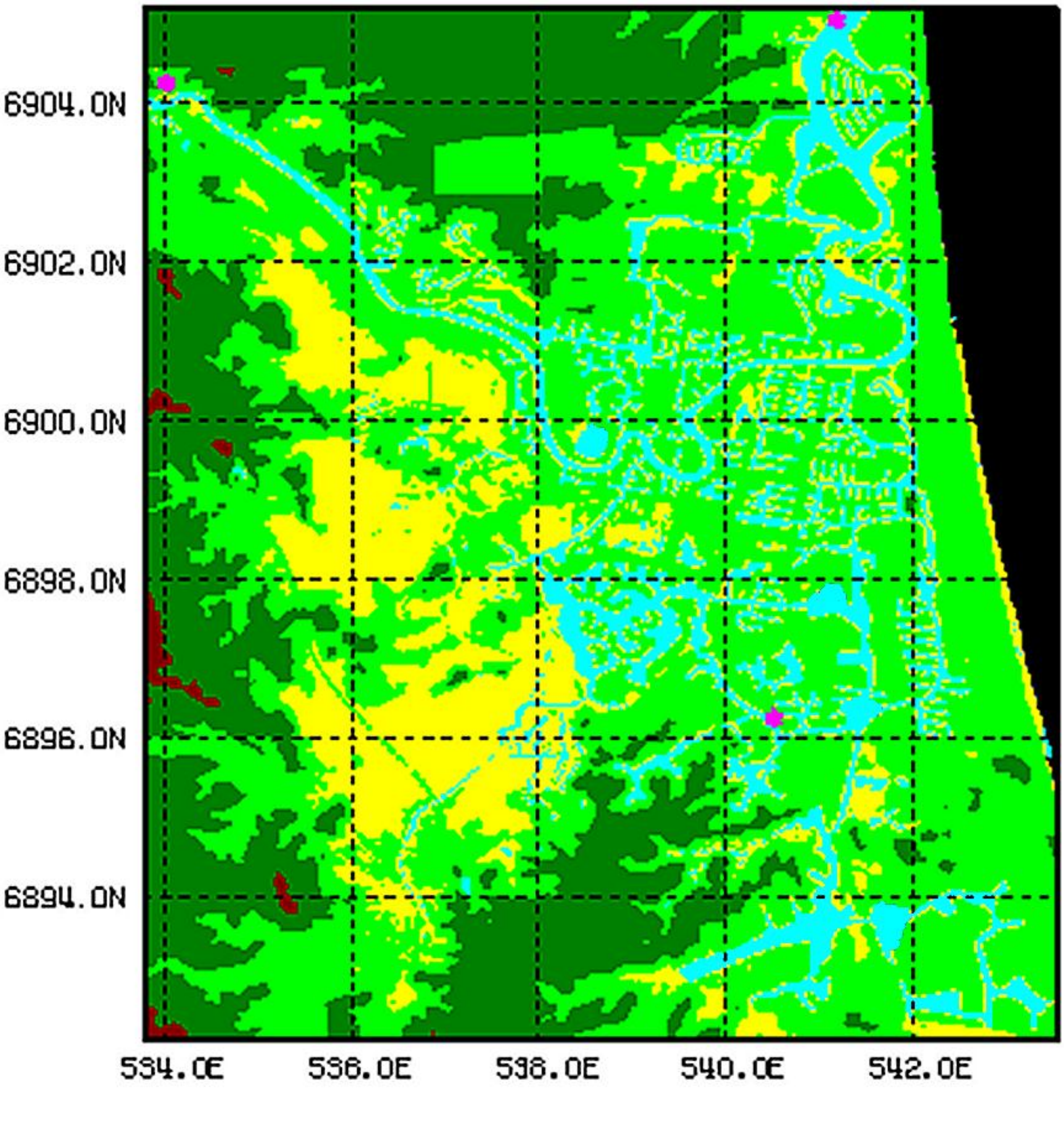

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Figure B1: The Complex Nerang River, Gold Coast, Flood Study Grid

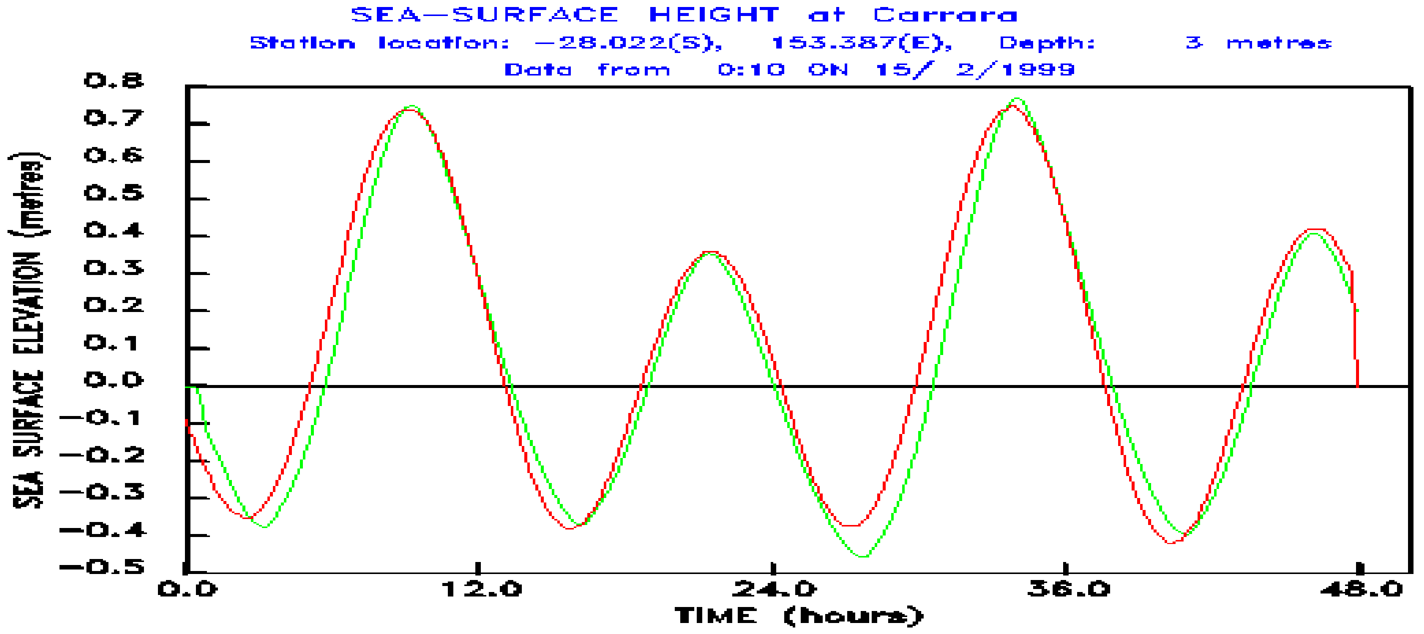

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Figure B2: Verification of the Nerang River Model Against the Carrara Tide Gauge

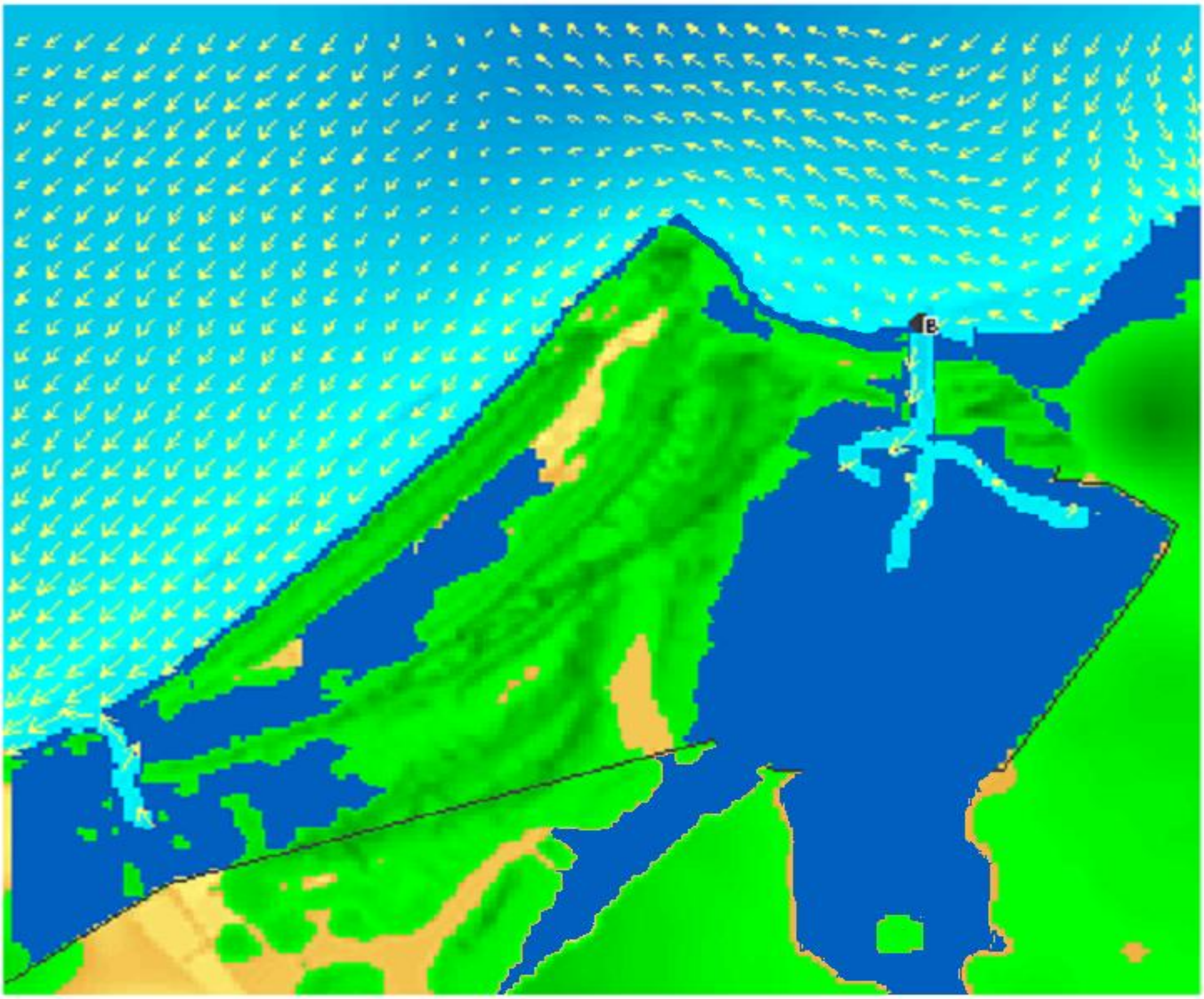

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Figure B3: Flooding in the Vicinity of Onslow & Beadon Creek at Flood Peak during TC Vance

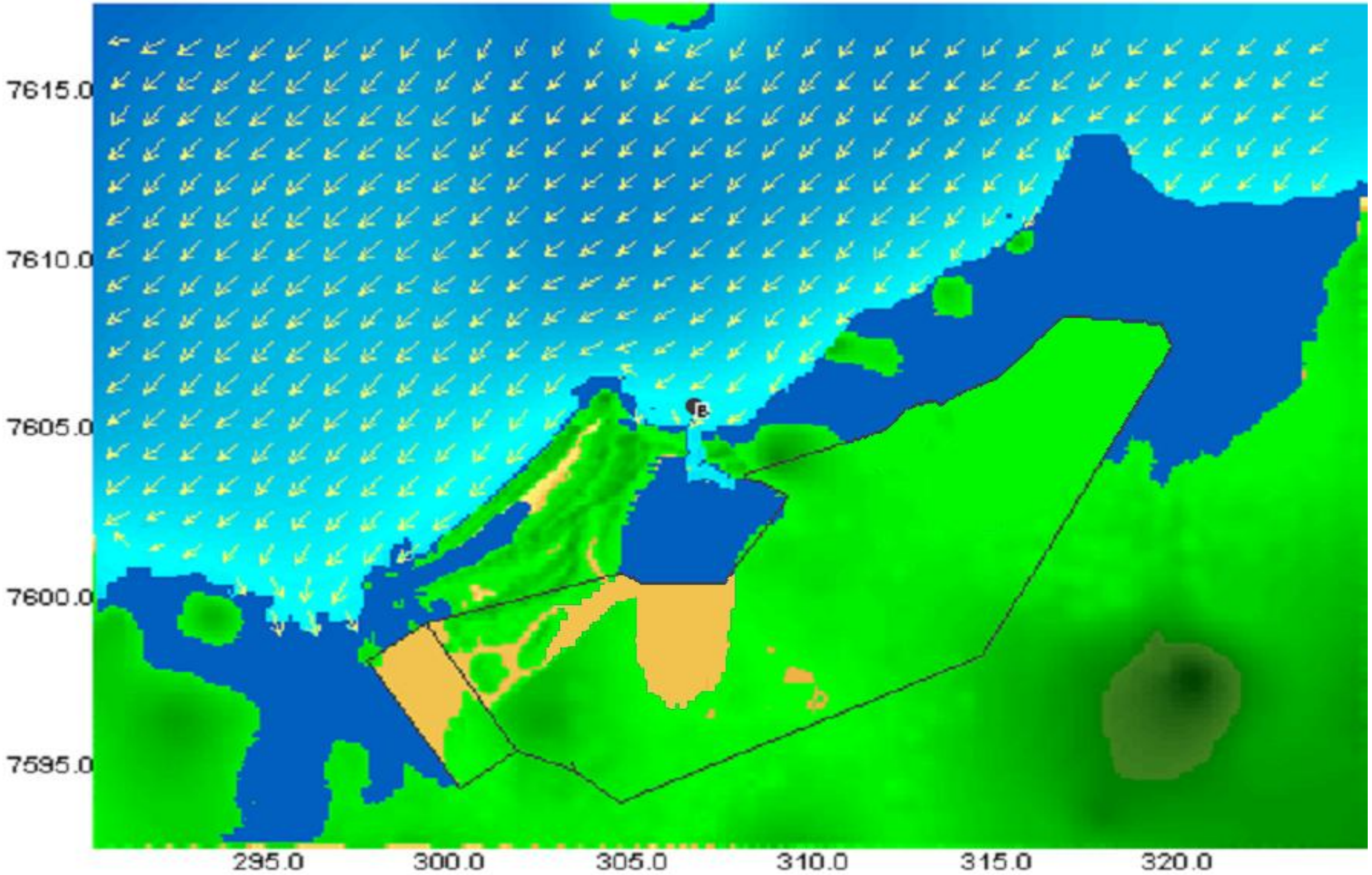

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Figure B4: Flooding around the Onslow Salt External Levees during the Redesign Program after Cyclone Vance

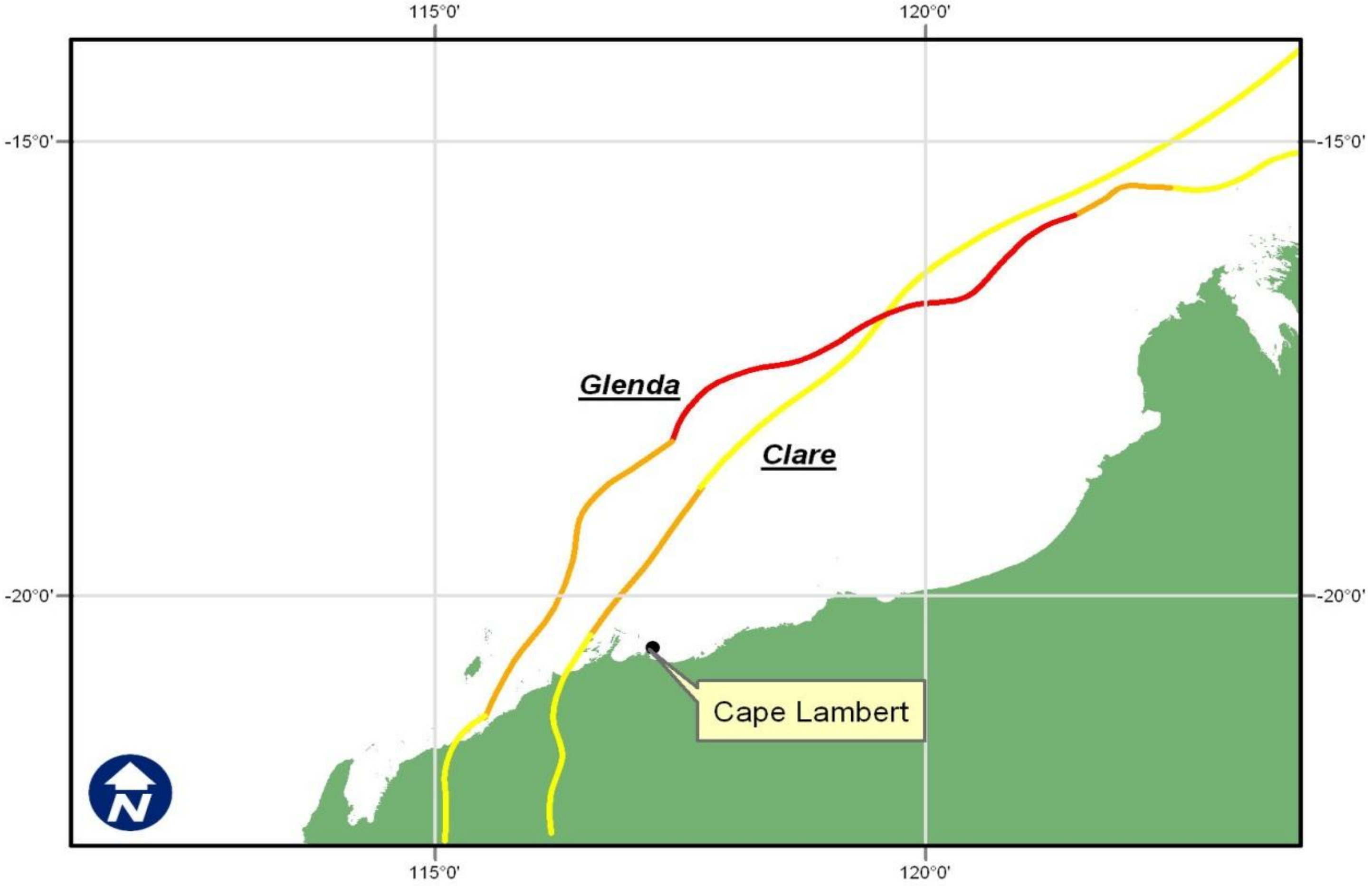

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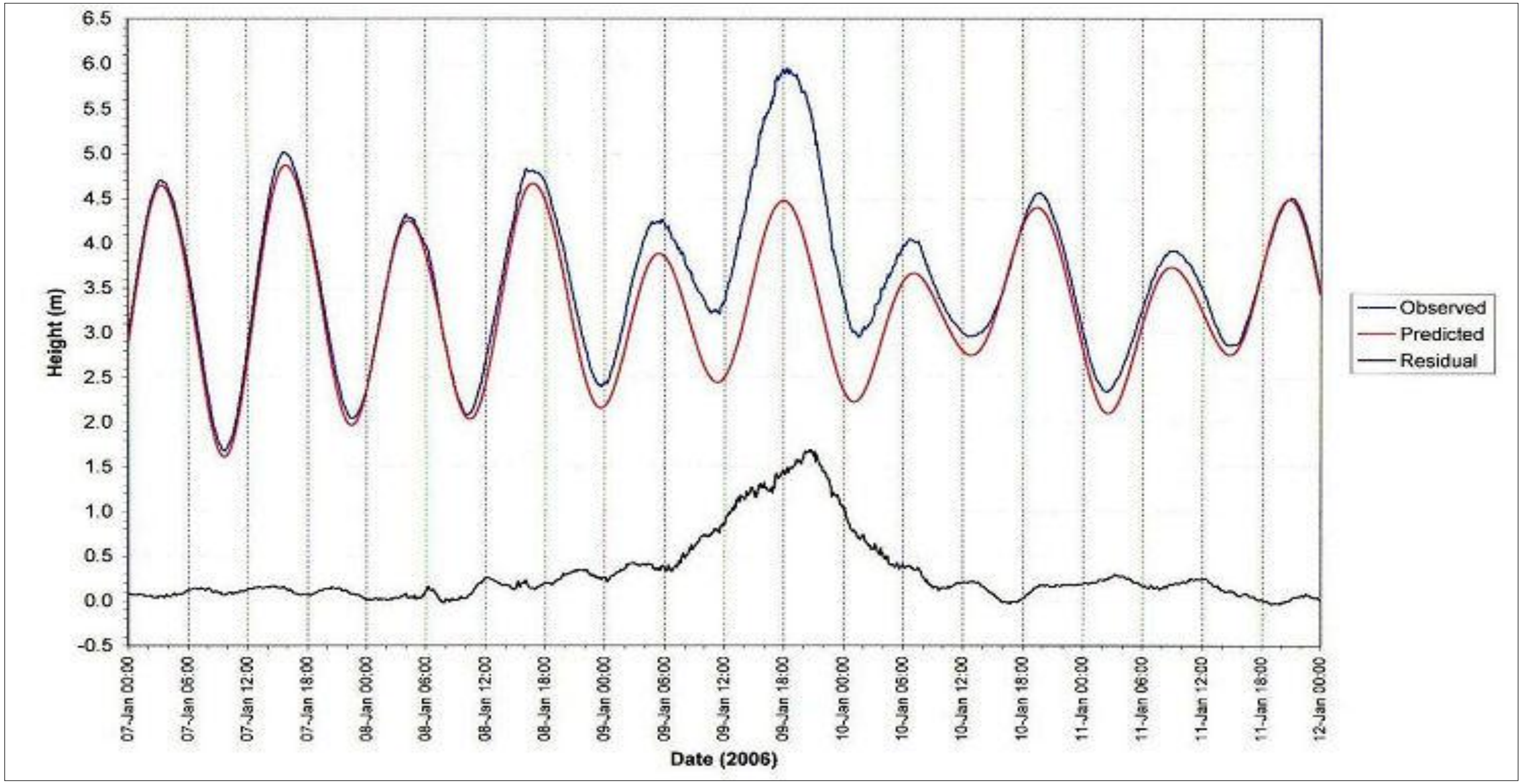
Figure B5: Tracks of TCs Glenda and Clare



Data Source: WA DPI

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Figure B6: Cape Lambert Tide Gauge and Residual during TC Clare

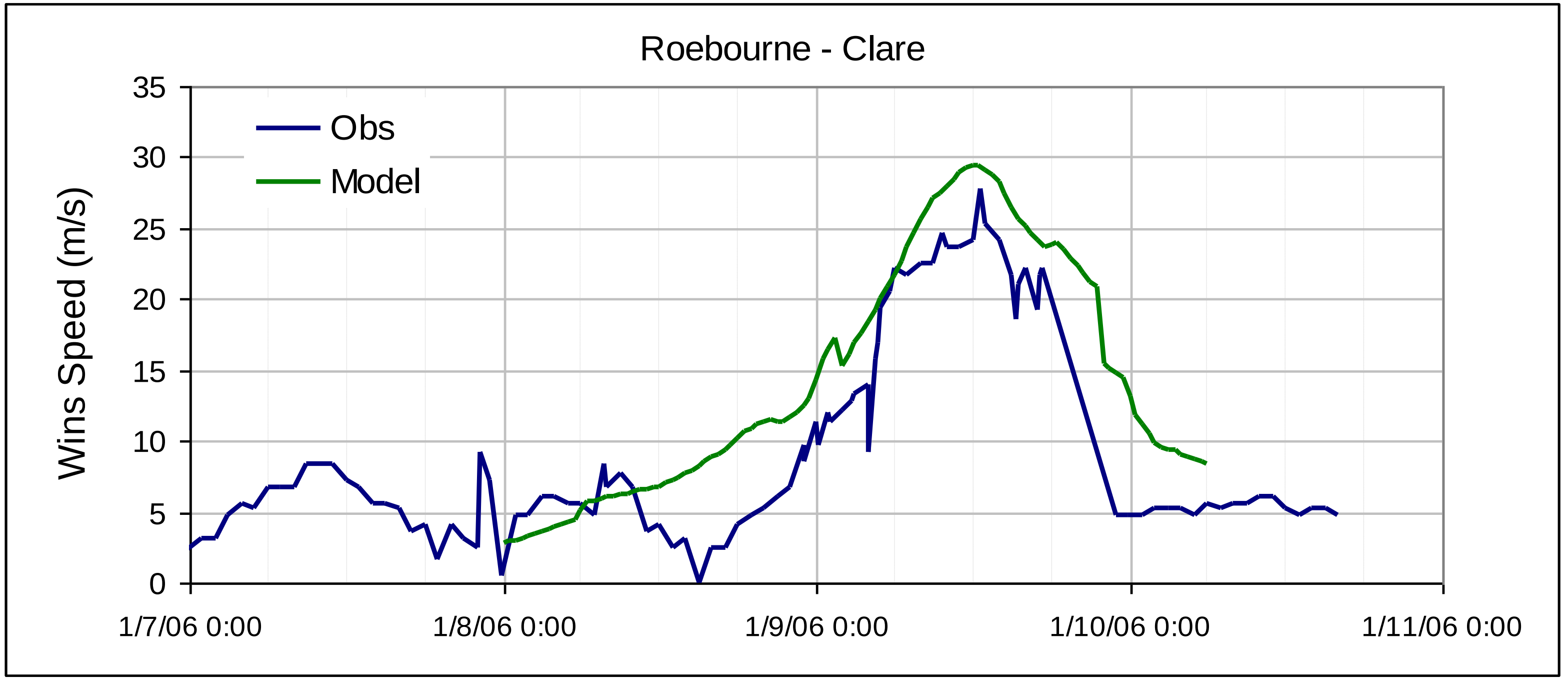

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Figure B7: Observed and Modeled Winds at Roebourne – TC Clare

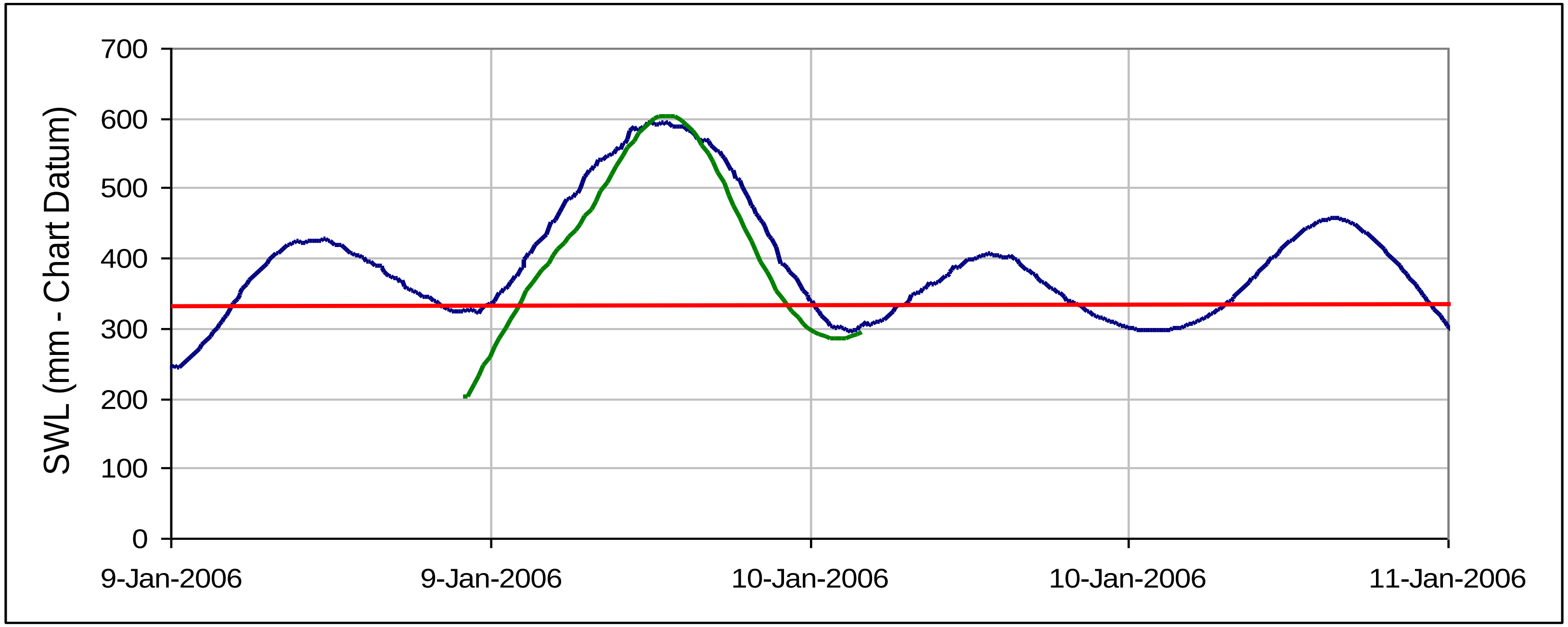

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Figure B8: Observed and Modeled Water Level at Cape Lambert Jetty during TC Clare

(a) During Normal Conditions

(b) During the Storm Surge generated by TC Glenda in March 2006

Figure B9: John's Creek Boat Harbour

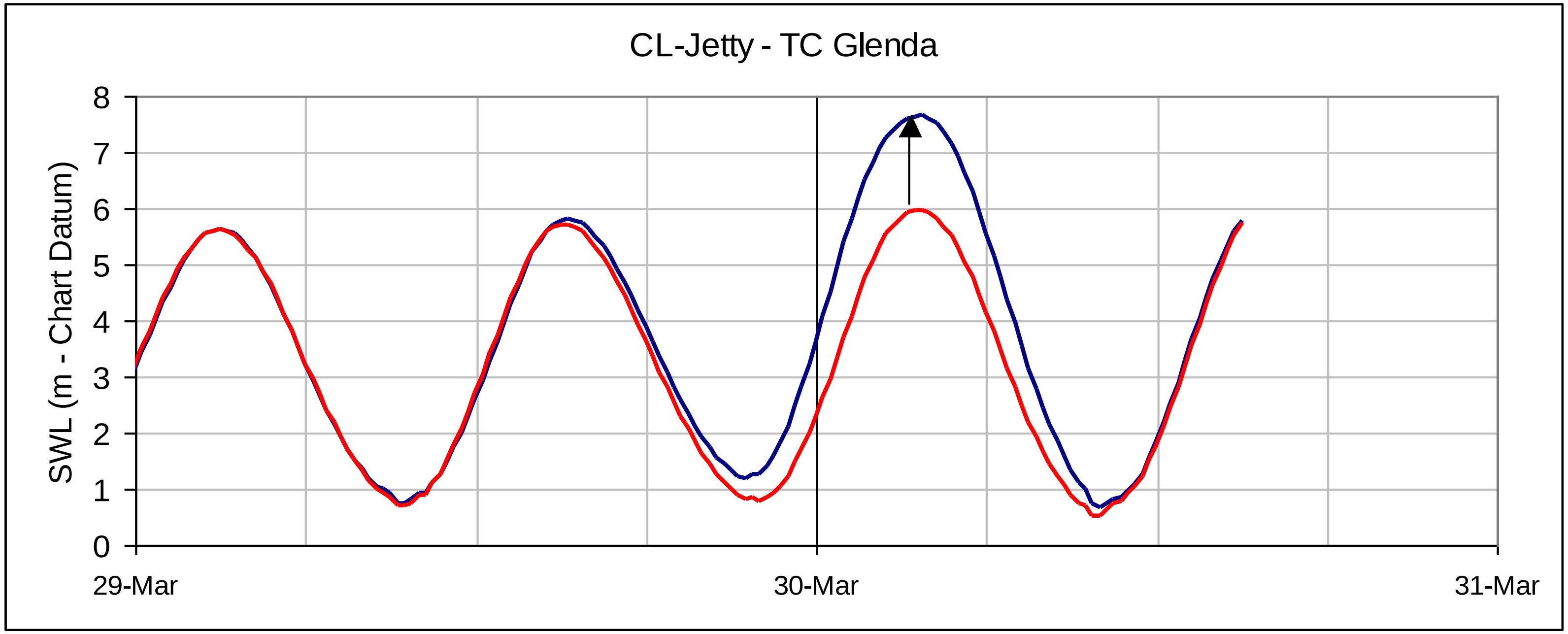

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Figure B10: Comparison of Modeled Peak Water Level for Glenda and Predicted Tidal Level

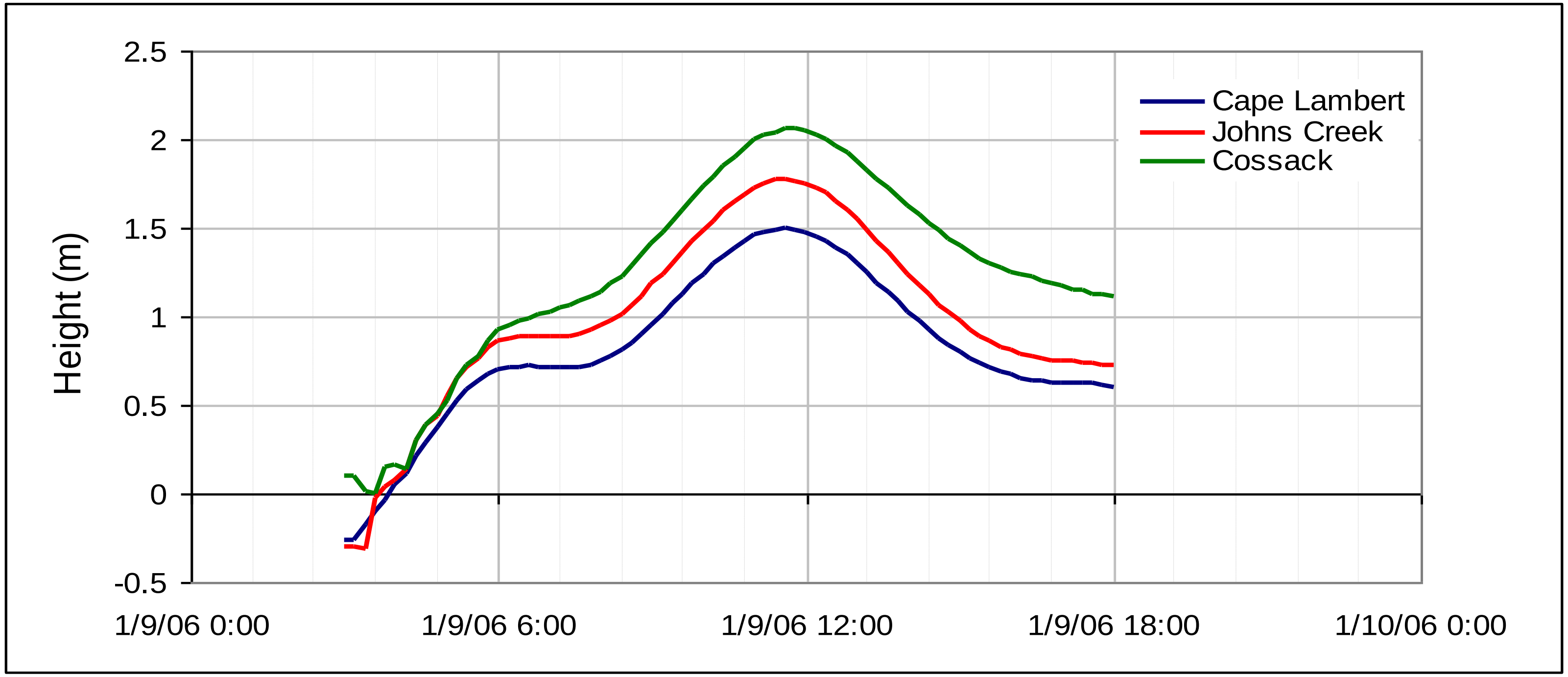

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Figure B11: Modeled Water Level for Cyclone Glenda Compared with Tidal Prediction at Cape Lambert

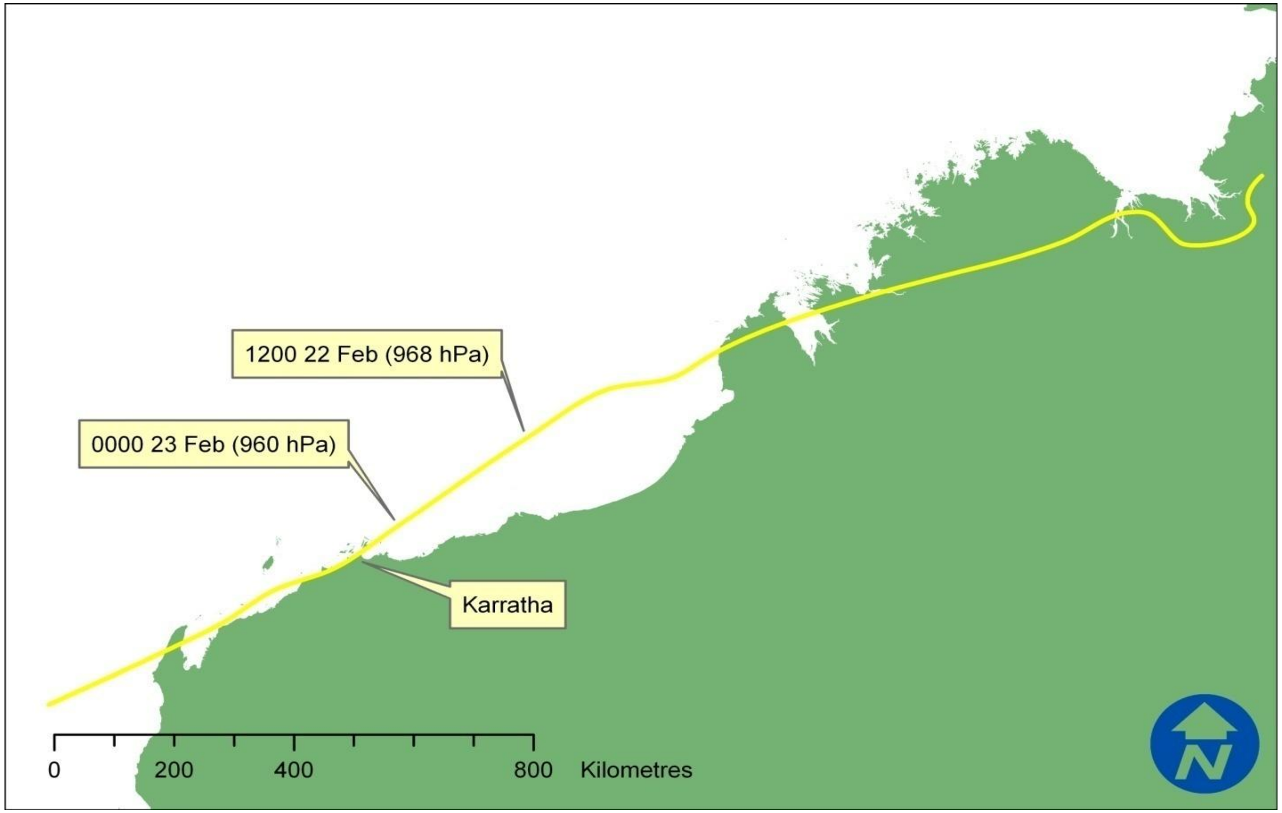

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Figure B12: Track of Cyclone Carlos

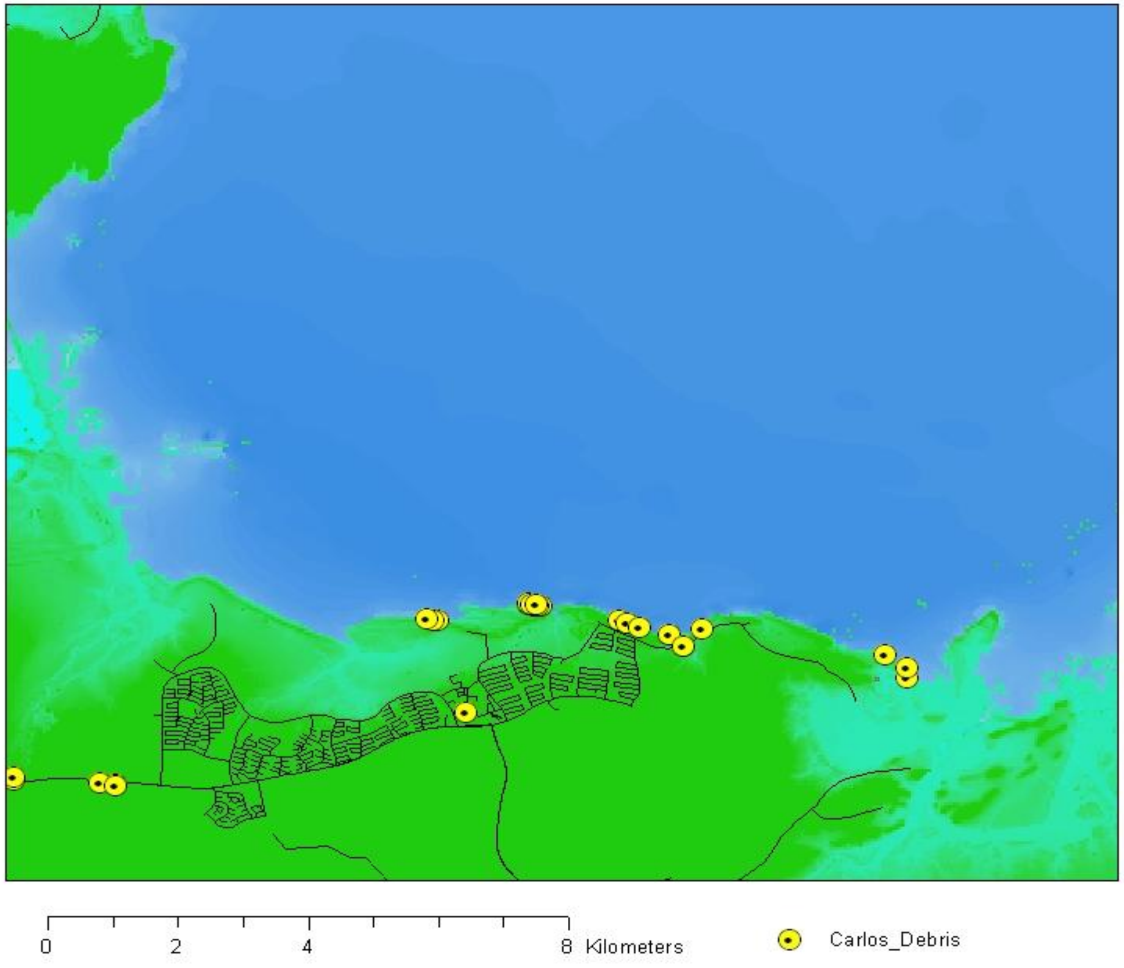

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Figure B13: Region of Modeled Maximum Inundation for TC Carlos and Observed Debris Locations

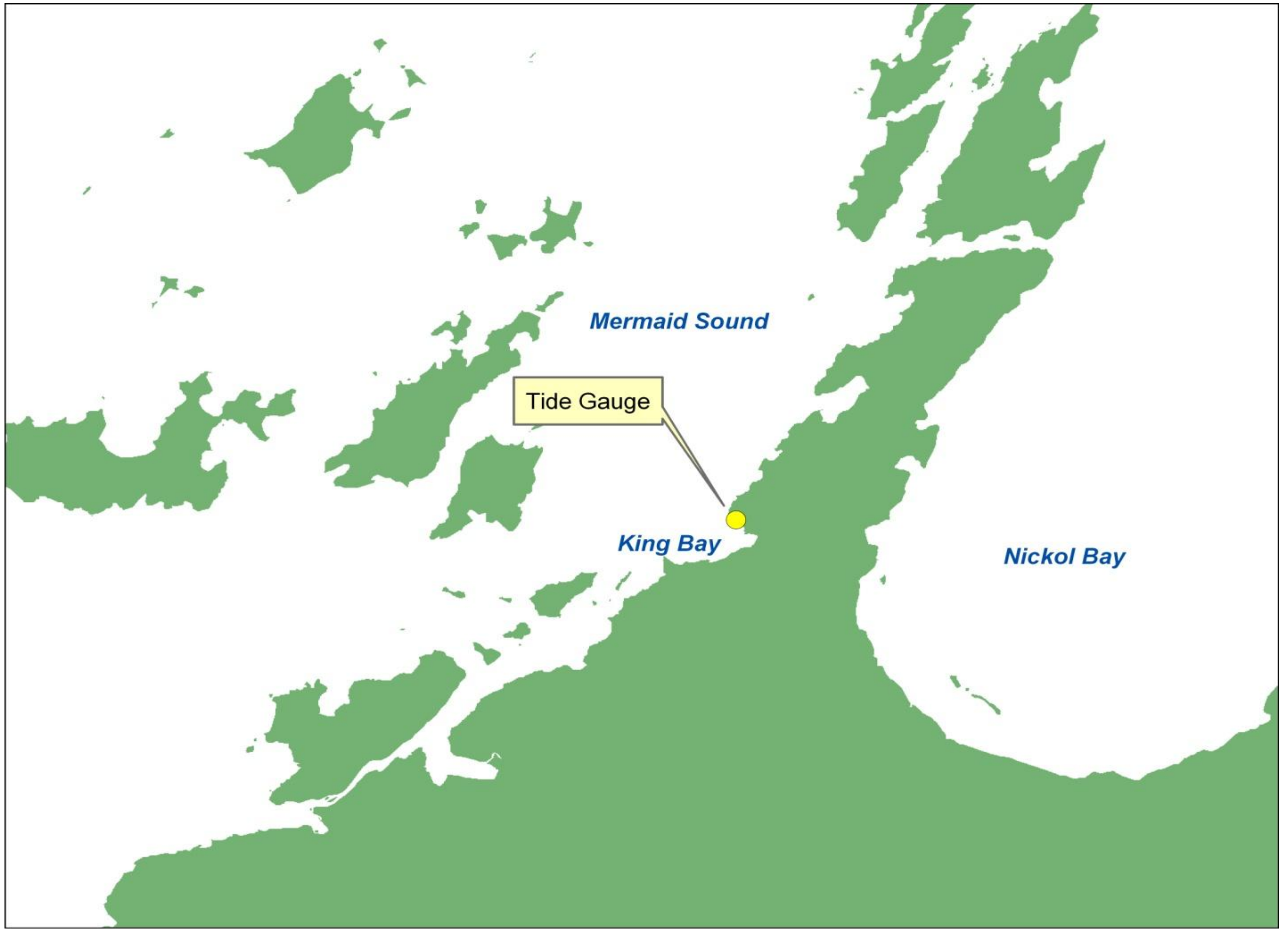

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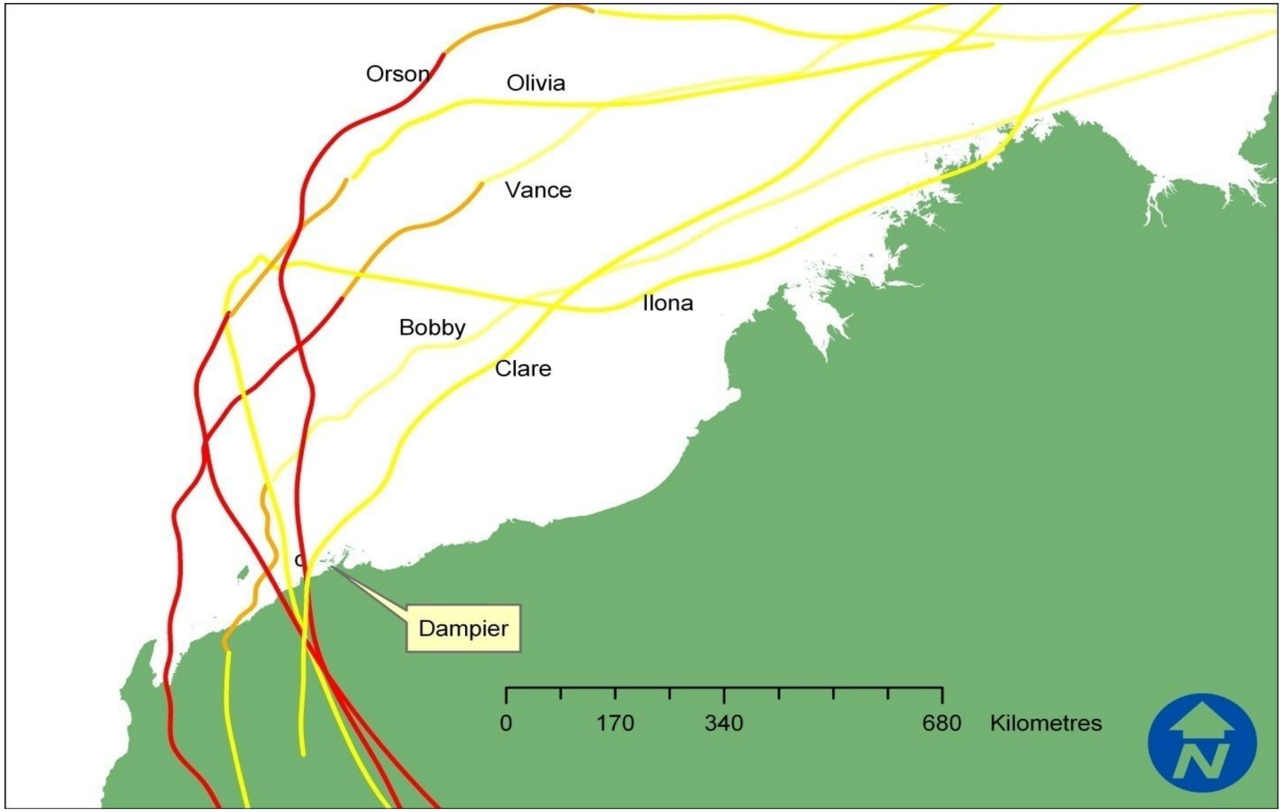
Figure B14: Location of King Bay Tide Gauge



Note: Colour indicates relative intensity – yellow weaker, red stronger

GEMS	Job No: J4812 	LandCorp Karratha Coastal Vulnerability Study Report IV: Storm Surge **Figure B15: Tracks of Cyclones Employed for Dampier Model validation Simulations**

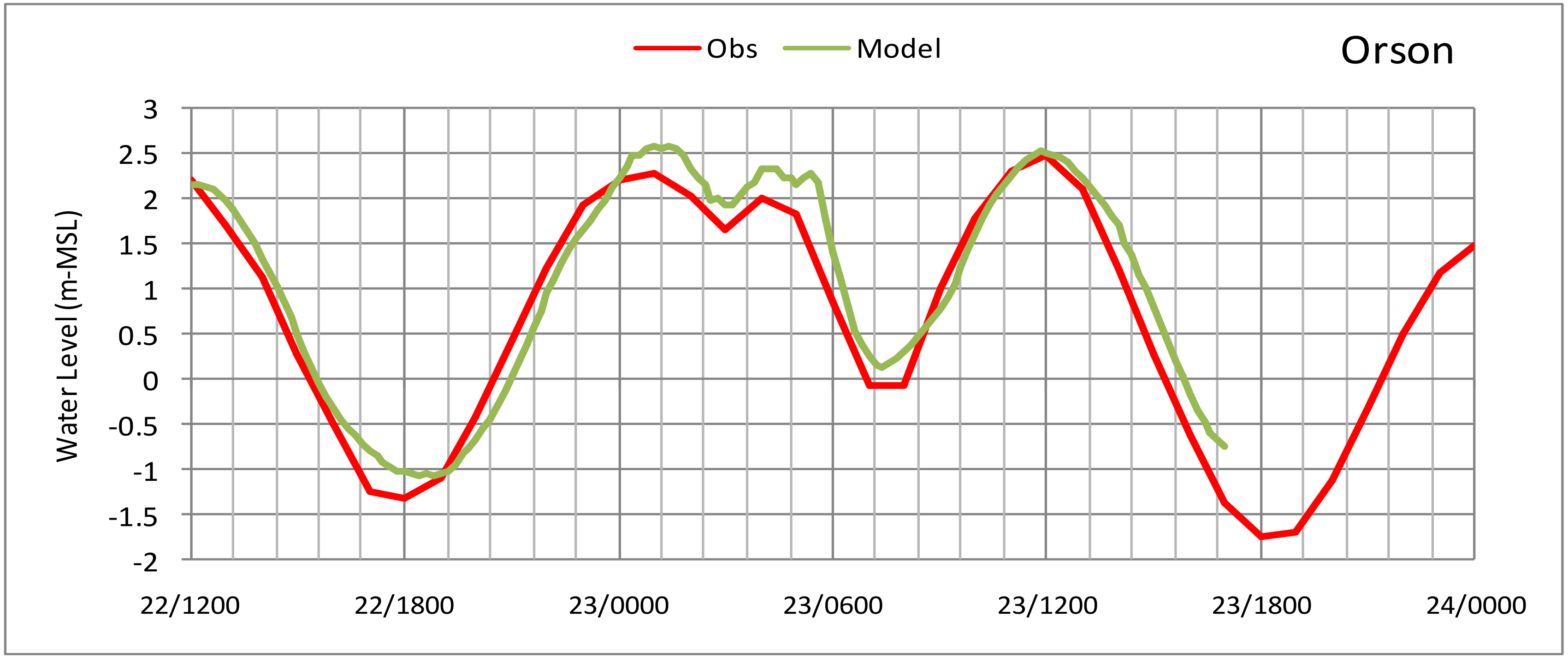


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Figure B16: Model Versus Observed Water Levels at King Bay Tide Gauge for Cyclone Orson

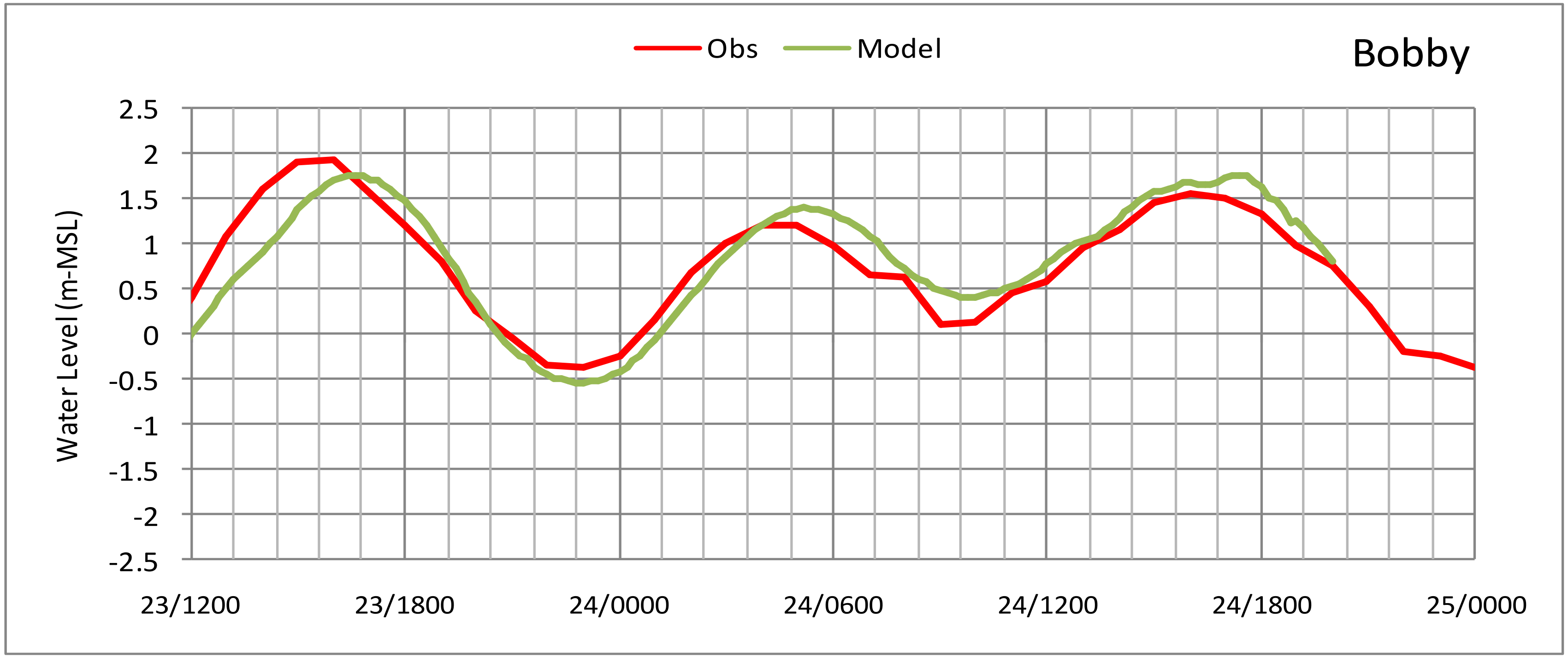

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Figure B17: Model Versus Observed Water Levels at King Bay Tide Gauge for Cyclone Bobby

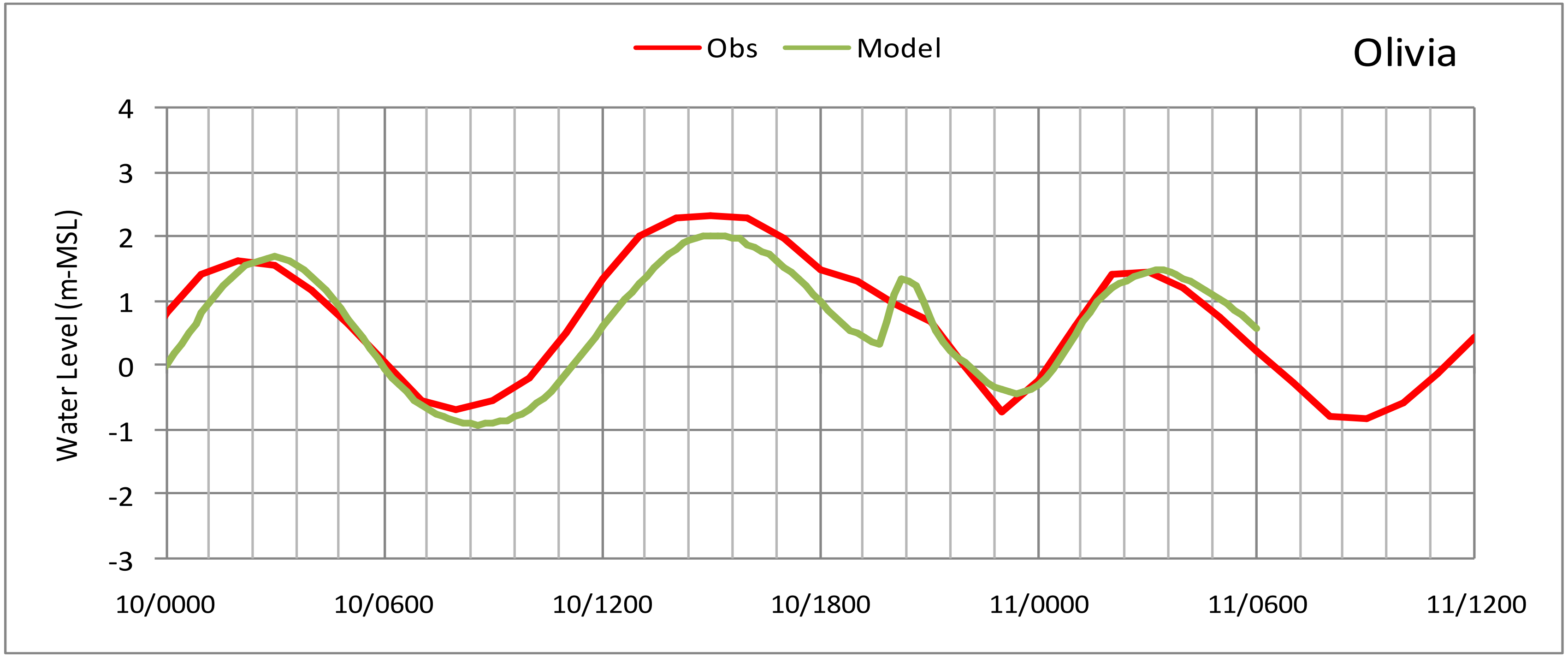

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Figure B18: Model Versus Observed Water Levels at King Bay Tide Gauge for Cyclone Olivia

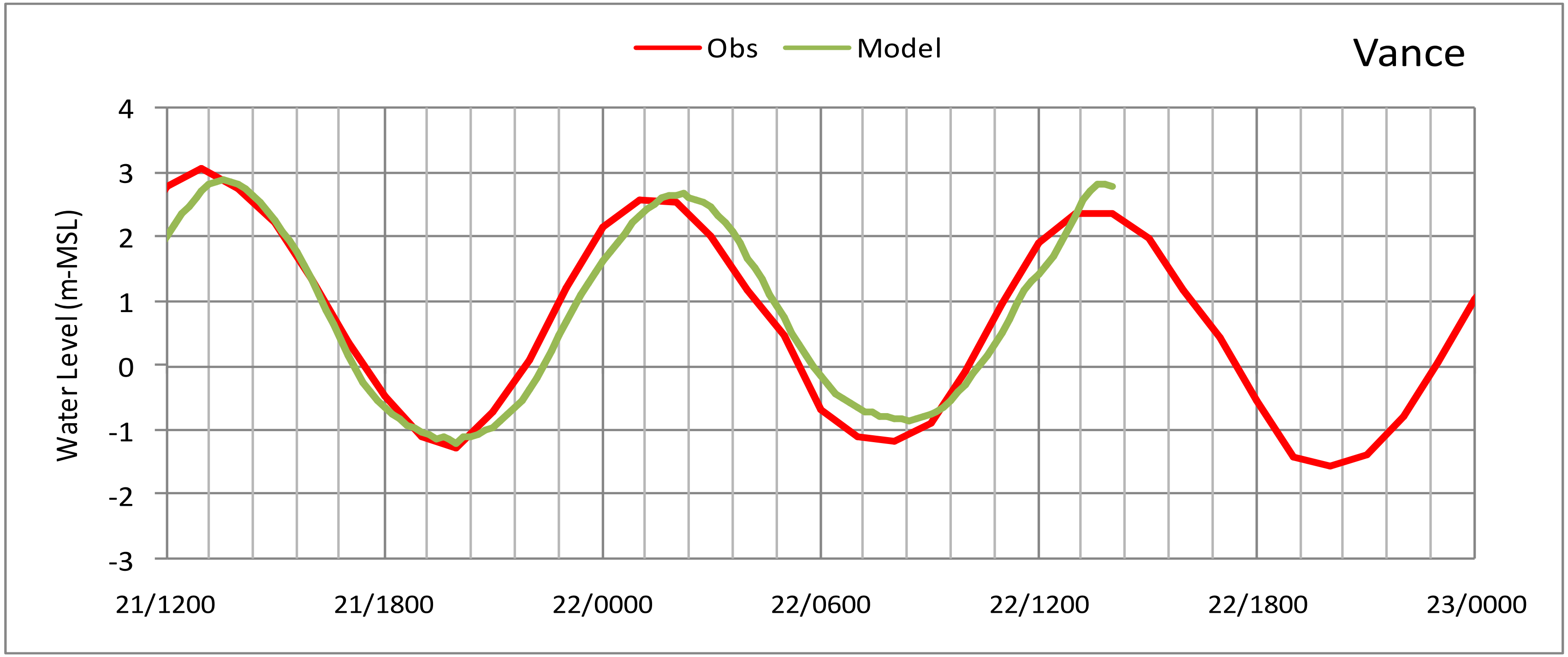

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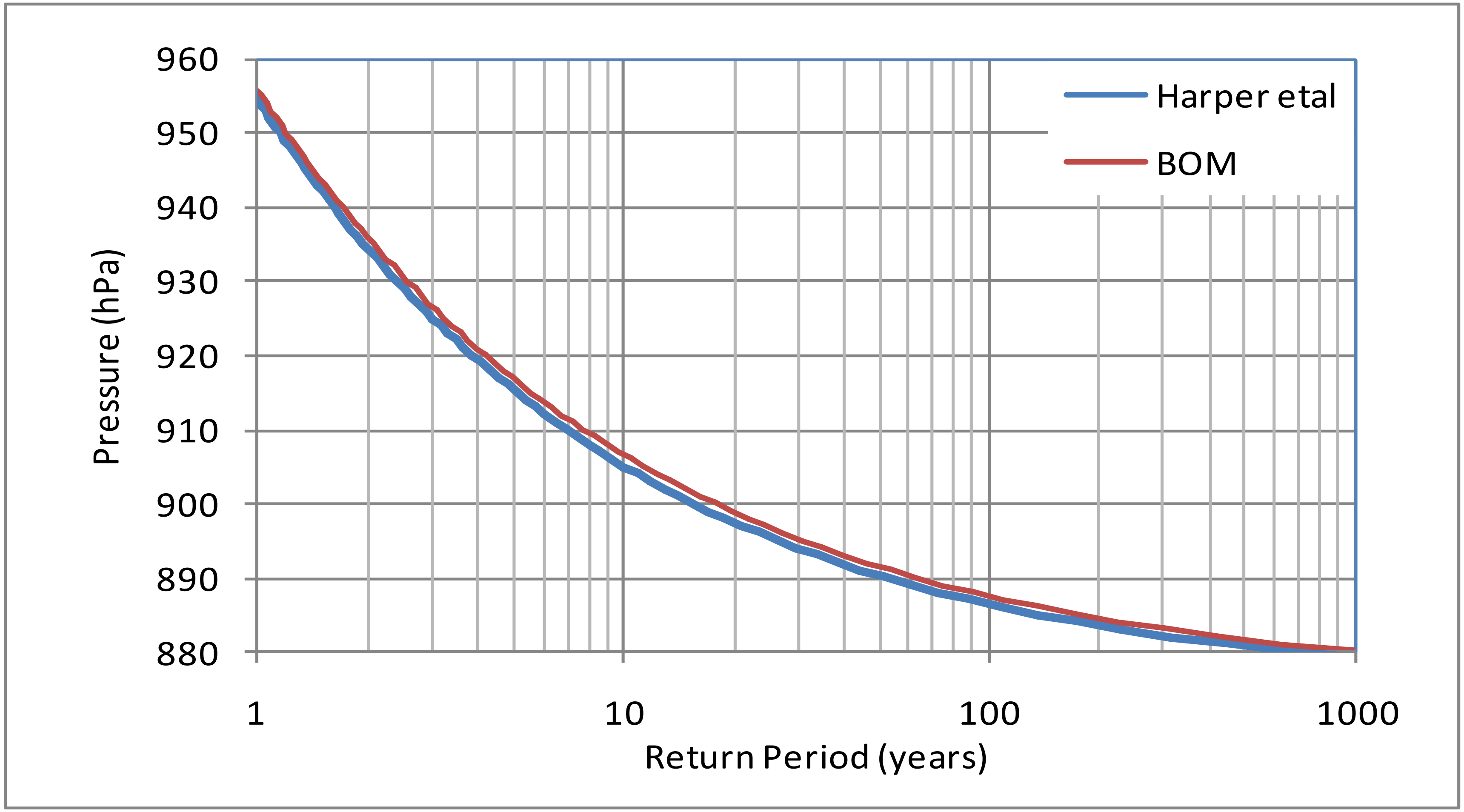
Figure B19: Model Versus Observed Water Levels at King Bay Tide Gauge for Cyclone Vance



Note: Comparison based on original BOM Data and modified storms from Harper et al

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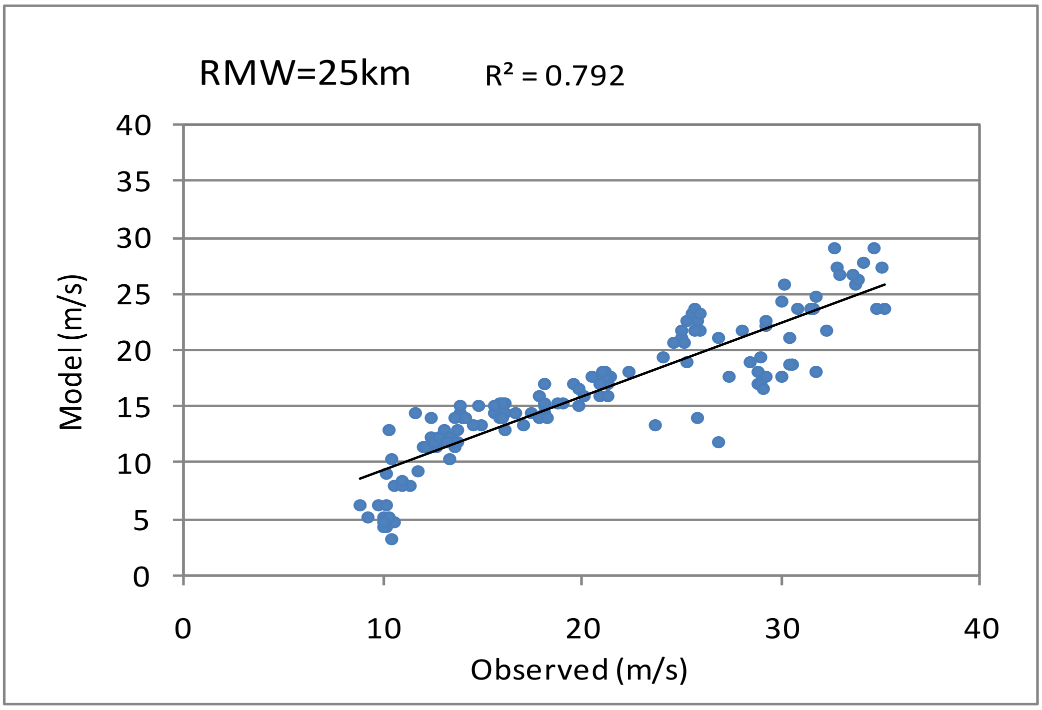
Figure B20: Comparison of Estimated ARIs for Regional Cyclone Minimum Pressure



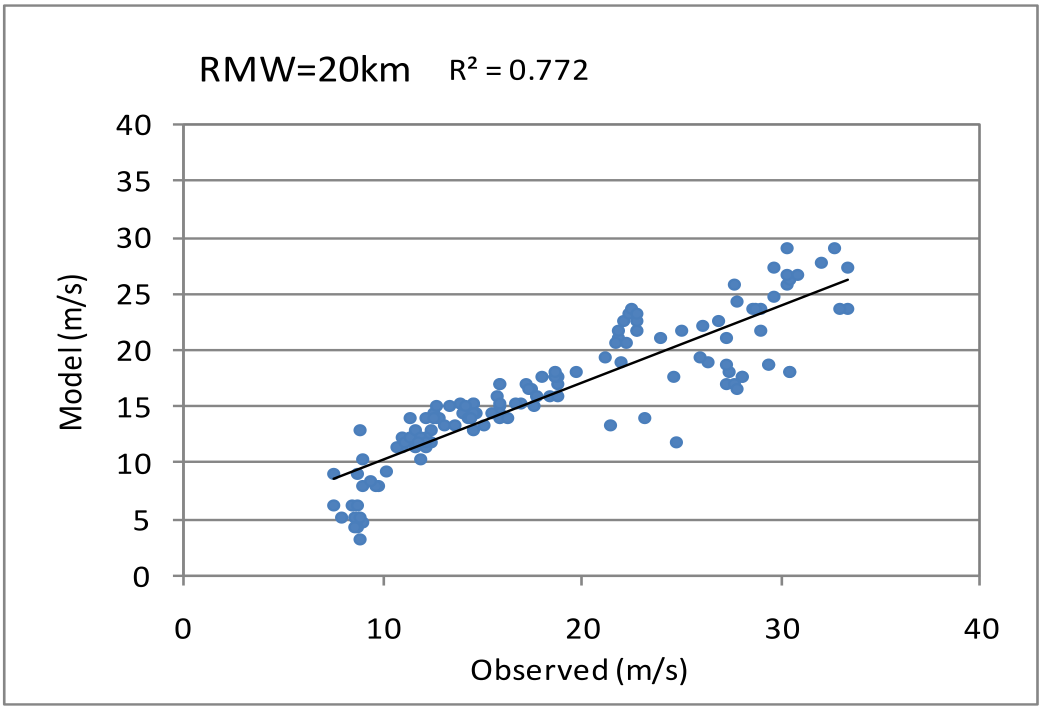


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Figure B21: Correlation of Measured & Modeled Wind Speeds at Karratha for selected Tropical Cyclones