Belongil Creek Flood Study

Final Report

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Byron Shire Council

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Foreword

The NSW Government's flood policy is directed at providing solutions to existing flooding problems in developed areas and to ensure that new development is compatible with the flood hazard and does not create additional flooding problems in other areas,

Under the policy the management of flood liable land remains the responsibility of local government. The State subsidises flood mitigation works to alleviate existing problems and provides specialist technical advice to assist councils in the discharge of their floodplain management responsibilities.

The Policy provides for technical and financial support by the Government through the following four sequential stages:

1.	Flood Study	Determines the nature and extent of the flood problem
2.	Floodplain Risk Management Study	Evaluates management options for the floodplain in respect of both existing and proposed development
3	Floodplain Risk Management Plan	Involves formal adoption by Council of a plan of management for a floodplain
4	Implementation of the Plan	Construction of flood mitigation works to protect existing development Use of Local Environmental Plans to ensure new development is compatible with the flood hazard.

The Belongil Creek Flood Study constitutes the first stage of the management process for the Belongil Creek catchment. It has been prepared for Byron Shire Council by SMEC Australia Pty Ltd to define flood behaviour under current conditions.

The study has been completed in accordance with the NSW Floodplain Development Manual, 2005.

Glossary of Technical Terms

Annual Exceedance Probability (AEP) - the chance of a flood of a given or larger size occurring in any one year, usually expressed as a percentage. For example, if a peak flood discharge of 500 m^3/s has an AEP of 5%, it means that there is a 5% chance (that is one-in-20 chance) of a peak flood discharge of 500 m^3/s or larger occurring in any one year (see average recurrence interval).

Australian Height Datum (AHD) - a common national surface level datum approximately corresponding to mean sea level.

Average Annual Damage (AAD) - depending on its size (or severity), each flood will cause a different amount of flood damage to a flood prone area. AAD is the average damage per year that would occur in a nominated development situation from flooding over a very long period of time.

Average Recurrence Interval (ARI) - the long-term average number of years between the occurrence of a flood as big as, or larger than, the selected event. For example, floods with a discharge as great as, or greater than, the 20 year ARI flood event will occur on average once every 20 years. ARI is another way of expressing the likelihood of occurrence of a flood event.

Catchment - the land area draining through the main stream, as well as tributary streams, to a particular site. It always relates to an area above a specific location.

Development - is defined in clause 4 of the Environmental Planning and Assessment Act (EP&A Act).

Disaster Plan (DISPLAN) - a step by step sequence of previously agreed roles, responsibilities, functions, actions and management arrangements for the conduct of a single or series of connected emergency operations, with the object of ensuring the coordinated response by all agencies having responsibilities and functions in emergencies.

Discharge - the rate of flow of water measured in terms of volume per unit time, for example, cubic metres per second (m^3/s). Discharge is different from the speed or velocity of flow, which is a measure of how fast the water is moving for example, metres per second (m/s).

Effective warning time - the time available after receiving advice of an impending flood and before the floodwaters prevent appropriate flood response actions being undertaken. The effective warning time is typically used to move farm equipment, move stock, raise furniture, evacuate people and transport their possessions.

Emergency management - a range of measures to manage risks to communities and the environment. In the flood context it may include measures to prevent, prepare for, respond to and recover from flooding.

Extreme event - an extreme flood is one which has a very low probability of occurrence and can be used to consider flood damages and emergency management within a floodplain.

Flash flooding - flooding which is sudden and unexpected. It is often caused by sudden local or nearby heavy rainfall. Often defined as flooding which peaks within six hours of the causative rain.

Flood - relatively high stream flow which overtops the natural or artificial banks in any part of a stream, river, estuary, lake or dam, and/or local overland flooding associated with major drainage before entering a watercourse, and/or coastal inundation resulting from super-elevated sea levels and/or waves overtopping coastline defences excluding tsunami.

Flood education, awareness and readiness

- **Flood education** seeks to provide information to raise awareness of the flood problem so as to enable individuals to understand how to manage themselves and their property in response to flood warnings and in a flood event. It invokes a state of flood readiness.
- **Flood awareness** is an appreciation of the likely effects of flooding and a knowledge of the relevant flood warning, response and evacuation procedures.
- **Flood readiness** is an ability to react within the effective warning time.

Flood fringe areas - the remaining area of flood prone land after floodway and flood storage areas have been defined.

Flood liable land - is synonymous with flood prone land (ie) land susceptible to flooding by the Probable Maximum Flood (PMF) event. Note that the term flood liable land now covers the whole of the floodplain, not just that part below the flood planning level, as indicated in the 1986 Floodplain Development Manual (see flood planning area).

Flood mitigation standard - the average recurrence interval of the flood, selected as part of the floodplain risk management process, that forms the basis for physical works to modify the impacts of flooding.

Floodplain - area of land which is subject to inundation by floods up to and including the Probable Maximum Flood event, that is, flood prone land.

Floodplain risk management options - the measures that might be feasible for the management of a particular area of the floodplain. Preparation of a floodplain risk management plan requires a detailed evaluation of floodplain risk management options.

Floodplain Risk Management Plan - a management plan developed in accordance with the principles and guidelines in this manual. Usually includes both written and diagrammatic information describing how particular areas of flood prone land are to be used and managed to achieve defined objectives.

Flood Plan (local) - A sub-plan of a disaster plan that deals specifically with flooding. They can exist at State, Division and local levels. Local flood plans are prepared under the leadership of the State Emergency Service.

Flood planning area - the area of land below the flood planning level and thus subject to flood related development controls. The concept of flood planning area generally supersedes the "flood liable land" concept in the 1986 Floodplain Development Manual.

Flood planning levels (FPL) - are the combinations of flood levels and freeboards selected for planning purposes, as determined in floodplain risk management studies and incorporated in floodplain risk management plans. The concept of flood planning levels supersedes the "standard flood event" of the first edition of the Floodplain Development Manual.

Flood proofing - a combination of measures incorporated in the design, construction and alteration of individual buildings or structures subject to flooding, to reduce or eliminate flood damages.

Flood prone land - is land susceptible to flooding by the Probable Maximum Flood (PMF) event. Flood prone land is synonymous with flood liable land.

Flood risk - potential danger to personal safety and potential damage to property resulting from flooding. The degree of risk varies with circumstances across the full range of floods. Flood risk in the Floodplain Development Manual is divided into 3 types, existing, future and continuing risks; these are described below.

- **Existing flood risk:** the risk a community is exposed to as a result of its location on the floodplain.
- **Future flood risk:** the risk a community may be exposed to as a result of new development on the floodplain.
- **Continuing flood risk:** the risk a community is exposed to after floodplain risk management measures have been implemented. For a town protected by levees, the continuing flood risk is the consequences of the levees being overtopped. For an area without any floodplain risk management measures, the continuing flood risk is simply the existence of its flood exposure.

Flood storage areas - those parts of the floodplain that are important for the temporary storage of floodwaters during the passage of a flood. The extent and behaviour of flood storage areas may change with flood severity, and loss of flood storage can increase the severity of flood impacts by reducing natural flood attenuation. Hence, it is necessary to investigate a range of flood sizes before defining flood storage areas.

Floodway areas - those areas of the floodplain where a significant discharge of water occurs during floods; they are often aligned with naturally defined channels. Floodways are areas that, even if only partially blocked, would cause a significant redistribution of flood flow, or a significant increase in flood levels.

Freeboard - a factor of safety typically used in relation to the setting of floor levels, levee crest levels, etc. It is usually expressed as the difference in height between the adopted flood planning level and the flood used to determine the flood planning level. Freeboard provides a factor of safety to compensate for uncertainties in the estimation of flood levels across the floodplain, such as wave action, localised hydraulic behaviour and impacts that are specific event related, such as levee and embankment settlement, and other effects such as "greenhouse" and climate change. Freeboard is included in the flood planning level.

Hazard - a source of potential harm or a situation with a potential to cause loss. In relation to this report the hazard is flooding which has the potential to cause damage to the community.

Isohyetal – refers to an isohyet or isohyetal line which joins points of equal precipitation on a map. A map with isohyets is called an isohyetal map.

Local overland flooding - inundation by local runoff rather than overbank discharge from a stream, river, estuary, lake or dam.

Local drainage - are smaller scale problems in urban areas. They are outside the definition of major drainage in this glossary.

Mainstream flooding - inundation of normally dry land occurring when water overflows the natural or artificial banks of a stream, river, estuary, lake or dam.

Merit approach - the merit approach weighs social, economic, ecological and cultural impacts of land use options for different flood prone areas together with flood damage, hazard and behaviour implications, and environmental protection and well being of the State's rivers and floodplains.

Minor, moderate and major flooding - both the State Emergency Service and the Bureau of Meteorology use the following definitions in flood warnings to give a general indication of the types of problems expected with a flood:

- **Minor flooding:** causes inconvenience such as closing of minor roads and the submergence of low level bridges. The lower limit of this class of flooding on the reference gauge is the initial flood level at which landholders and townspeople begin to be flooded.
- **Moderate flooding:** low-lying areas are inundated requiring removal of stock and/or evacuation of some houses. Main traffic routes may be covered.
- **Major flooding:** appreciable urban areas are flooded and/or extensive rural areas are flooded. Properties, villages and towns can be isolated.

Modification measures - measures that modify either the flood, the property or the response to flooding.

Peak discharge - the maximum discharge occurring during a flood event.

Pluviograph - a self-registering rain gauge typically measuring and recording hourly rainfall depths

Probable Maximum Flood (PMF) - the largest flood that could conceivably occur at a particular location, usually estimated from Probable Maximum Precipitation. Generally, it is not physically or economically possible to provide complete protection against this event. The PMF defines the extent of flood prone land, that is, the floodplain. The extent, nature and potential consequences of flooding associated with the PMF event should be addressed in a floodplain risk management study.

Probable Maximum Precipitation (PMP) - the theoretical greatest depth of precipitation for a given duration meteorologically possible over a given size storm area at a particular location at a particular time of the year, with no allowance made for long-term climatic trends (World Meteorological Organisation, 1986). It is the primary input to the estimation of the Probable Maximum Flood.

Probability - a statistical measure of the expected chance of flooding (see Annual Exceedance Probability).

Risk - chance of something happening that will have an impact. It is measured in terms of consequences and likelihood. In the context of this report it is the likelihood of consequences arising from the interaction of floods, communities and the environment. The risk of such an event occurring over a longer period is much higher.

Risk management - the systematic application of management policies, procedures and practices to the tasks of identifying, analysing, assessing, treating and monitoring flood risk. Flood risk management is undertaken as part of a Floodplain Risk Management Study. The Floodplain Risk Management Plan reflects the adopted means of managing flood risk.

Runoff - the amount of rainfall which actually ends up as streamflow, also known as rainfall excess.

Stage - equivalent to "water level". Both are measured with reference to a specified datum.

Stage hydrograph - a graph that shows how the water level at a particular location changes with time during a flood. It must be referenced to a particular datum.

Temporal pattern – refers to the overall pattern of the rainfall event over time and is specific to spatial location and storm duration.

1 Executive Summary

Belongil Creek is approximately 3km long and has a catchment of around 30km^2. The Byron Bay township is susceptible to flooding from both intense rainfall over the town catchment and elevated ocean levels.

The Belongil Creek flood study covers the following areas:

- The Belongil Creek Estuary, Union Drain and Clarkes Beach outlet
- Cumbebin Swamp and Nature Reserve
- Byron Bay township and town drain
- Byron Bay Industrial Estate and Sunrise Estate area drainage.

The flood study has been conducted in two phases. The first phase was the development and calibration of flood models to simulate flooding behaviour. The second phase was to apply these models to determine flood behaviour for "design" flood events and complete climate change sensitivity analysis. A hydraulic model of the Belongil Creek floodplain was established and calibrated to historic flood events. This model was then used to predict flooding behaviour across the Belongil Creek floodplain for a range of design flood events.

The design flood events incorporated climate change scenarios based upon IPCC and CSIRO models and DECC guidelines. These models suggest that ocean levels and rainfall intensities in Byron Bay are likely to increase over the next century in response to global climate change. Four climate change scenarios were examined during the course of this study (SMEC, February 2008).

- Scenario 1 – no sea level change, no increase in rainfall intensities
- Scenario 2 – lower bound IPCC sea level rise estimate with 20% increase in rainfall intensities
- Scenario 3 – mid range IPCC sea level rise estimate with 20% increase in rainfall intensities
- Scenario 4 – upper bound IPCC sea level estimate with 20% increase in rainfall intensities.

Following flood modelling and mapping of these four climate change scenarios using the calibrated TUFLOW model Byron Shire Council has resolved to adopt Scenarios 2 and 4 as the basis for planning decisions.

The flood models indicate that flooding of the Byron Bay township to the east of the North Coast Railway line is caused by inadequate trunk drainage system capacity, lack of a surface overland flow path to the Belongil Creek Estuary and insufficient change in elevation between the low lying portions of the town and the ocean to facilitate gravity flow. The Butler Street drain is the only means of drainage for the town centre and this drain was found to be deficient in capacity. However any upgrading of this drain may also allow greater quantities of sea water to reverse flow towards the town centre during times of elevated ocean levels and consideration would need to be given to the use of flood gates, levees and pump systems to protect the town east of the railway line.

In addition to the Butler Street drain, the Clarkes beach outfall was found to be deficient in capacity, resulting in flooding of Cowper Street and the surrounding area. The capacity to convey water from Cowper street either to Clarkes beach or to Belongil Creek would need to be increased, or additional flood storage provided, to reduce flooding at this location.

At the west of Byron Bay, in the Industrial Estate, a number of Lots in Brigantine Street, Bayshore Drive and Grevillea Street are flood affected. Flooding in this area could be reduced with upgraded drainage systems.

Provisional flood hazard categories based on the NSW Floodplain Development Manual (2005) indicate that while most flooding in the catchment can be categorised as low hazard, there are some areas of high hazard flooding within and adjacent to residential areas. Properties located along the Belongil Creek outlet reach, north of the North Coast

Railway line bridge are at particularly high risk with deep high velocity, floodwaters running in the creek immediately adjacent to these lots. In addition, these properties are vulnerable to coastal hazard. There a few options available to reduce flood hazard in this area, beside structural improvements to dwellings.

With the advent of climate change, the major impacts would occur near the Town Centre and Town Drain south and west of the railway line which would see existing low hazard flooding transformed to deeper high hazard flooding. In the south east, many lots that are currently flood free would become flood affected.

Properties along the Belongil Creek outfall channel are currently vulnerable to both coastal hazard and flood hazard and these hazards would increase with Climate Change.

The flood modelling undertaken for this study demonstrates that the climate change scenarios proposed by IPCC and CSIRO would see the transformation of flooding in the Belongil Creek Floodplain from low hazard to high hazard in many areas and significantly increase the number of flood affected lots.

The following actions should now follow this study:

- The flood mapping outputs for this study be incorporated in Councils GIS system and used to update Byron Shires Council's Flood Planning Level (FPL). Climate Change Scenario 2 has been modelled and mapped to obtain the "*Belongil Minimum Small Development Flood Planning Level",* while Climate Change Scenario 4 has been modelled and mapped to obtain the "*Belongil Large Development Flood Planning Level"* as defined in Chapter 10.
- Proceed to the preparation of a Floodplain Risk Management Study and Plan in accordance with the NSW Floodplain Development Manual (2005)
- Update s149 certificates for properties affected by flooding under this plan

2 Introduction

SMEC Australia Pty Ltd was commissioned by Byron Shire Council to prepare a flood study of the Belongil Creek Catchment. The purpose of the flood study is to determine the nature and extent of the flooding problem within the catchment. This information will be used to develop flood mitigation options to alleviate existing flooding problems and to ensure that future development is compatible with the floodplain.

Byron shire is located in a region of high annual rainfall with a pronounced wet season from December to April. During this season, the region is susceptible to the effects of cyclonic activity to the north which can bring torrential rain. The Byron Bay region has been subject to a regular pattern of intense rainfall and flooding throughout its history, with recurring falls in excess of 200 mm over 24 hours. Such falls are sufficient to cause severe flooding in the Byron Bay township, particularly when combined with high tide and storm surge conditions in the ocean as well as during times when the Belongil Creek entrance is closed by sand built-up. Some notable past flood events include:

- June 1945 which at the time resulted in unprecedented property damage
- 1954 during which cyclonic activity resulted in the loss of the Byron Bay jetty.
- March 1974 when it was reported that water entered shops in the northern end of Jonson St for the first time in living memory. Further flooding occurred in April 1974.
- April 1984 in which moderately heavy rainfall and high seas resulted in flooding of the estuary and town centre. It is believed that the Belongil Creek ocean entrance was closed, exacerbating flooding.
- February 1995 when moderately heavy rainfall resulted flooding of the township
- 1998 when heavy rainfall resulted in floods in April, May and September
- 2003 when a succession of moderate floods occurred in February, April and June.
- June 2005 which caused some flooding in Belongil Creek but severe flooding in other catchments to the north of Byron Bay.

The Belongil Creek catchment was the subject of an earlier flood study completed by NSW Public Works Department in 1986. This earlier study was based on a “cells” hydraulic model which simulated the movement of water through interconnected storages to the catchment outlet. The “cells” model has now been superseded by superior hydrodynamic models which are capable of much finer model resolution and hence greater accuracy. Other developments that have taken place since 1986 included the release of updated design rainfall patterns in 1987 which superseded the rainfall patterns adopted in the 1986 study.

In response to these developments, Byron Shire Council commissioned a new flood study to provide updated flooding information for the management of flood liable land in the Belongil Creek catchment. These models are based upon more accurate survey data, design rainfall information and improved flood modelling software.

The Belongil Creek flood study covers the following areas:

- The Belongil Creek Estuary, Union Drain and Clarkes Beach outlet
- Cumbebin Swamp and Nature Reserve
- Byron Bay township and town drain
- Byron Bay Industrial Estate and Sunrise Estate area drainage.

The flood study has been conducted in two phases. The first phase was the development and calibration of flood models to simulate historical flooding behaviour. The second phase was to apply these models to determine flood behaviour for “design” flood events and complete climate change sensitivity analysis.

3 Catchment Description

Belongil Creek is approximately 3km long and has a catchment of around 30km^2. The township of Byron Bay is situated toward the eastern boundary of the catchment with most of the development on higher ground. The transport of catchment runoff to the estuary is influenced by numerous man made drains and infrastructure. These include the Union Drain, the Byron Bay town drain (or Butler Street Drain), the North Coast Railway line, Ewingsdale Road and numerous bridges and culverts.

Parts of the catchment area have undergone urban development, but over one-third of the catchment area is covered by Cumbebin Swamp. Large areas of swamp near the town have been reclaimed and developed, reducing the storage within the catchment. Despite this, significant portions of the catchment area are below 2 m Australian Height Datum (AHD).

Areas of the catchment most vulnerable to flooding are located along the estuary outlet in the north of the catchment and on the eastern side of the catchment in the Byron Bay township and adjoining areas. These areas are impacted by high ocean elevations in combination with high flood flows from the estuary. Intermittent closure of the creek outlet through sand buildup can also exacerbate flood levels throughout the catchment under heavy rainfall. However closure of the creek may reduce ocean induced flooding during times of elevated ocean levels.

The Byron Bay township is susceptible to flooding from both intense short duration storms over the town catchment and elevated ocean levels. The Belongil Creek entrance condition can directly affect flood levels in the town. The lowest portions of the township are below RL 2.0 m AHD and elevated ocean conditions can rise to this level under cyclonic conditions. There is no direct overland escape route for flood waters in the township, which is separated from the estuary by the railway line. The town centre is drained to the estuary via the town drain, which receives water from the Byron Street drains under the railway line. The capacity of this drain is limited by a lack of hydraulic gradient between the low lying township and the Belongil Creek outlet. A separate study is currently underway to assess the adequacy of the piped drainage system and to determine options for improvements. This study has found that the Byron Bay township drainage system has a capacity equivalent to less than a 1 year ARI flood.

Low lying properties located adjacent to the town drain, are also susceptible to flooding due to the limited capacity of the town drain, and the proximity to the ocean.

The estuary mouth is intermittently open, with catchment flooding and sand transport being the main factors that influence the opening and closing of the mouth. The entrance condition will depend on the relative magnitudes of the littoral drift transporting sand to the inlet which acts to close the entrance and the channel discharge which acts to keep the channel open. Channel discharge is generated by both ebb tides and precipitation on the catchment. Council has an interim license for mechanically opening the channel when deemed necessary to relieve flooding. The interim license allows Council to mechanically open the creek entrance when the gauged water level at Ewingsdale Road Bridge reaches 1.0 m AHD.

The Belongil Creek catchment area is shown on Figure 1.

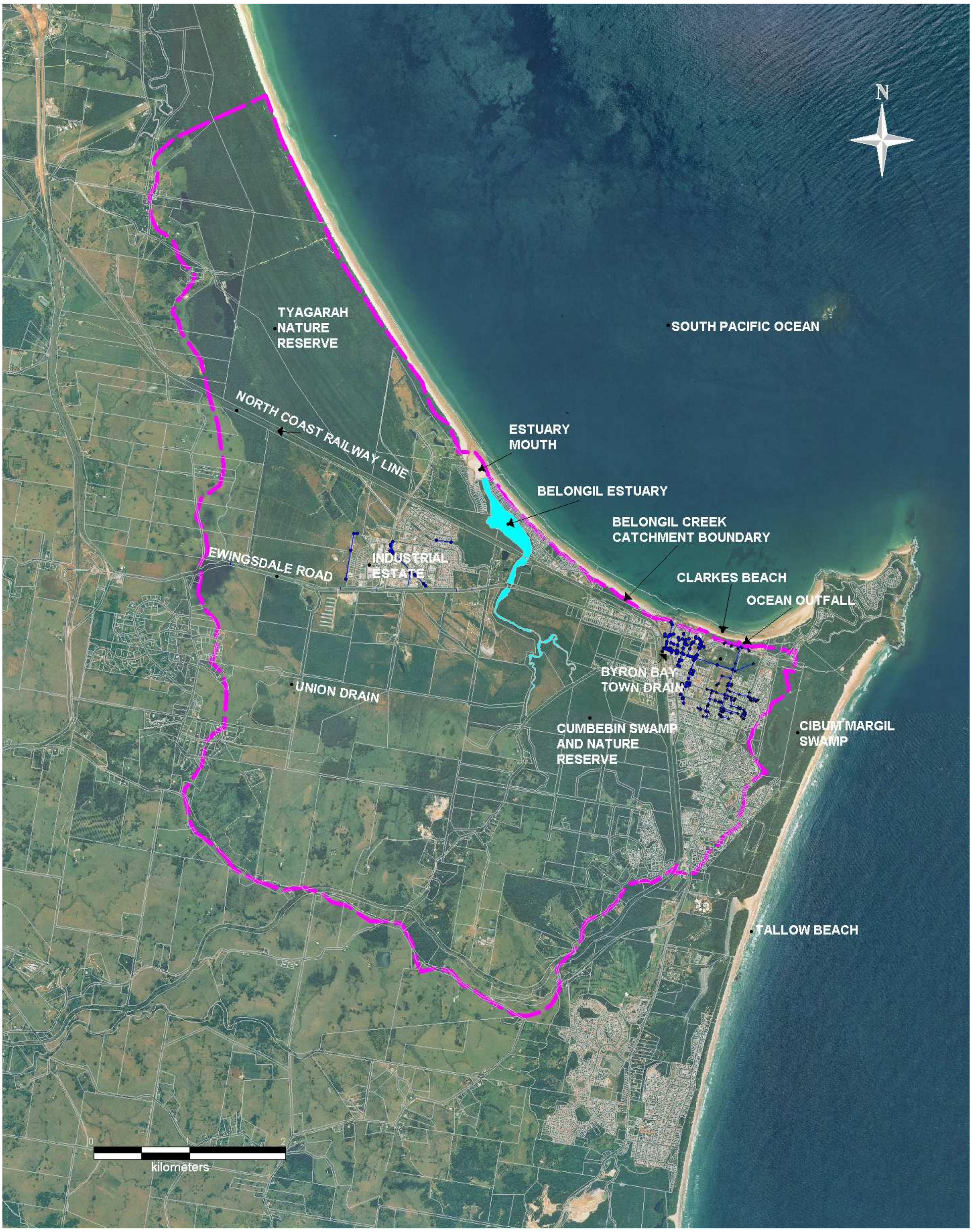


Figure 1

Locality Plan

4 Study Approach

The study was carried out in a series of sequential stages as described below

4.1 Data collection

The data collection stage included site inspections, resident interviews and collection of rainfall and water level data. The data collection stage provided the information necessary for the understanding of flooding history and for input to the numerical models.

The data collection stage is described in Chapter 5.

4.2 Selection of Calibration and Verification Events

Calibration and verification events are historic flood events for which there is accurate, reliable information on rainfall patterns and ocean conditions and observed flood levels. This information is used to calibrate the hydrologic and hydraulic models which are adjusted to best fit the observed data. The verification events are used to check the calibrated model without further adjustment of the model parameters. In this study, floods that occurred in 1974 and 1984 were used as calibration events. The flood that occurred in June 2003 was also selected as a verification event.

The event selection stage is described in Chapter 6.

4.3 Preparation of a Hydrologic Model.

The hydrologic model is used to determine catchment flood discharges. For this study "RAFTS", a rainfall runoff routing model was used to convert observed rainfall patterns to runoff hydrographs. The RAFTS input parameters include catchment areas, impervious proportions, soil loss rates and surface storage parameters.

The hydrologic modelling stage is described in Chapter 7.

4.4 Preparation of a Hydraulic Model

The hydraulic model is used to simulate flood levels and flow patterns, using the runoff hydrographs generated by the hydrologic model. There are a number of types of hydraulic model available. These include 1-dimensional (1D) models in which flow is assumed to follow predefined flow paths determined by the modeller and 2 dimensional (2D) models in which the floodplain surface levels are input as a "mesh" and flow may occur in any direction across the mesh, depending upon the topography of the surface and magnitude of the flow.

In the Belongil Creek floodplain, flow conditions will change during the rising stage of a flood. During the early stages during low flow conditions, water will follow the various natural and man made drainage channels. As water rises to inundate the floodplain, new flowpaths develop across the floodplain. 2D models are better able to model these complex flow patterns than 1D models, however they require much longer computation times, in some cases several orders of magnitude longer than 1D models.

The latest models combine 1D flowpaths within a 2D floodplain mesh. TUFLOW, which is an example of a combined 1D/2D model was used for this study. TUFLOW models 1D elements such as channels and pipes which are found in the urban areas, within a 2D representation of the floodplain.

The TUFLOW model input included surface topography, surface roughness, channel cross sectional information, and pipe network information. Time varying boundary conditions were then applied. These included inflow hydrographs at the upstream boundaries and ocean levels at the downstream boundaries.

The hydraulic modelling stage is described in Chapter 8.

4.5 Model Calibration and Verification

To ensure that the model is able to predict the flood behaviour of the catchment for the design events, it is necessary to calibrate the hydrologic and hydraulic models using historical flood events.

The only available information to calibrate the models was peak flood height data. Hence it was only possible to fit the model to peak flood heights.

To do this, the model parameters that included the RAFTS model infiltration losses, TUFLOW surface roughness and the geometry of the ocean outlet channel, which would vary according to sand deposition at the entrance, were adjusted to fit the observed peak flood levels.

The model calibration process is described in Chapter 9.

4.6 Design Event Modelling

The hydrologic and hydraulic models were then applied to the determination of design flood levels throughout the flood plain. Standard design rainfall patterns were derived and used to generate design flood discharges. Ocean boundary conditions were also derived with consideration of climate change impacts. The hydraulic model was then used to estimate flood levels, depths and velocities throughout the floodplain. This data was used to develop flood elevation maps and flood hazard maps. This information will be used by Byron Shire Council for both floodplain risk management and future land-use planning.

Further information on Climate Change is described in Chapter 10.

5 Available Data

The data available to gain an understanding of the catchment behaviour and to assist with the establishment and calibration of the hydrologic and hydraulic models is described below.

5.1 Previous Reports

There have been a number of hydraulic studies relating to the Belongil Creek catchment. The key reports produced on the catchment are described briefly below.

Belongil Creek Flood Study (PWD,1986)

In this report the then Public Works Department undertook a flood study of the Creek's floodplain using a quasi 2 dimensional model (CELLS). Upland inflow into the floodplain was simulated using the Cordery-Webb synthetic unit hydrograph method. Model calibration and verification was carried out using the 1974 and 1984 flood events.

Three creek entrance conditions were simulated, the entrance fully open (condition A), entrance closed until water levels reached 2.6 m AHD, when the entrance would scour open (condition B) and entrance closed to 2.6 m AHD until mechanically opened at the first low tide after a peak ocean level. (condition C).

Tidal hydrographs were synthesised with peak levels of 2.1 m AHD and 2.6 m AHD for the five percent and one percent design ocean levels. It was assumed that the ocean and storm events would occur with the same probability simultaneously. Thus the 5 percent events for storms and the 5 percent event for ocean levels would coincide.

The critical condition was identified during condition B when water levels reached 2.66 m AHD at the edge of the township during a one percent flood and 2.43 m AHD during a five percent event. The peak level during an extreme event was estimated at between 3.25 and 3.28 m AHD.

Belongil Creek Data Compilation Study (Willing & Partners, July 1996)

This report focussed on the collection of data for investigations into estuary management. Some data was collected on hydrological and flooding issues and also on hydrodynamic and marine processes. The major part of the study was directed into collection of data on environmental and river health issues.

The report noted that the previous flood study was over ten years old even at that stage and was in need of updating, using more recent modelling techniques. It did identify however that a lack of rainfall, water level and flow data remained a problem on this catchment.

Belongil Estuary Study and Management Plan (Parker and Pont, November 2001)

The Belongil estuary management plan (BEMP) was developed in accordance with the NSW Government's Estuary Management Manual (NSW Government, 1992) and was formally adopted by Council in November 2001. Opening of the mouth of the estuary is detailed under this Plan, however Council is still developing a final entrance opening strategy. The BEMP recommended the trigger for entrance opening be dropped to 1.0m AHD to alleviate the large draw down associated with a deep channel formed by a stronger rush out under the previous 1.2m opening trigger.

In regards to Belongil Creek entrance management and flooding of the Byron township the plan recommended the following high priority actions:

- The estuary mouth is to be kept open continuously at the interim benchmark level of one metre in conjunction with monitoring water quality parameters;
- Conduct further investigation into upper catchment remediation works (eg, trial drop-boards) in conjunction with an estuary opening strategy;

- Continue to liaise with DLWC (now DECC) regarding a Part 5 application for estuary opening;
- Monitor the protocol for entrance opening including such items as water quality, width of estuary and time and date of opening.

Byron Shire Council Draft Belongil Entrance Opening Strategy and REF on the Belongil Creek Entrance Opening Strategy (IERM, 2005)

BSC's Draft Belongil Entrance Opening Strategy (2005) provides the guidelines for the sustainable management of the creeks entrance. The opening activity is licensed by the NSW Department of Lands, which owns the land at the mouth of the Belongil Estuary.

Byron Shire Council has a temporary license from NSW Department of Lands to periodically open the Belongil Creek Entrance by mechanical means. To open the entrance, an excavator is used to dig a channel which allows the trapped water to escape to the ocean, scouring an opening through the sand. This allows for tidal exchange for several weeks to months before the sand re-accumulates closing the entrance.

The trigger for opening the entrance is the gauged water level at the Ewingsdale Road Bridge. Prior to 2001, the trigger for opening the entrance was when the water level reached 1.2 m AHD at Ewingsdale Road. In 2001, the trigger level was lowered from 1.2 to 1.0 m AHD on the basis that more frequent opening would improve flushing and tidal exchange, reduce pollutant buildup in the estuary and improve fish migration.

The existing temporary license to open the estuary is conditional upon environmental monitoring including:

- monitoring vegetation communities to detect any change in the wetland / intertidal vegetation health or structure as a result of the lowering of the trigger from 1.2 to 1.0 m AHD.
- monitoring water quality parameters in the estuary and tributaries before, during and following opening to help improve catchment management techniques.
- Council must inform a number government departments and community members prior to each opening.

Council employs a consultant to prepare six monthly entrance opening reports which describe the opening activities over the reporting period and which describe the water quality monitoring results, and ecological health (flora and fauna observations and vegetation monitoring) observed during the reporting period.

A Review of Environmental Factors has been prepared (IERM, 2005) to determine the environmental impacts of adopting the Draft Belongil Creek Entrance Opening Strategy. The REF considered potential impacts to a range of biotic and abiotic variables. IERM concluded that artificial opening of the entrance over the past 47 years had resulted in significant environmental changes, and that reducing the trigger value from RL 1.2m to 1.0m AHD would further contribute to these.

Some of the impacts identified by IERM (2005) include:

- Potential lowering of groundwater levels;
- Reduction of areas inundated by floods;
- Increased transport of ASS product from soil profile to estuary; and
- Increased oxidation of PASS.

Council have considered the REF, a Technical Review of the REF and a staff recommendation to adopt the recommendation in the technical review to employ a range for opening triggers based on tide and rainfall predictions. After consideration of the staff recommendation (in alignment with the recommendations in the technical review), Council resolved to complete a scoping statement for an EIS, with a view to completing an EIS on the entrance management regime.

Byron Council, Drainage Strategy Study (Toby Fianders and Associates, 1994)

This study used an ILSAX model to analyse the Cowper and Byron Street drainage networks to assess the capacity of these systems. The purpose of this study was to:

- develop a drainage policy
- investigate flood mitigation works and
- Prepare a Section 94 Contributions Plan.

This study focussed on the Byron Bay drainage systems. An ILSAX model was developed and used to model the drainage system. The 1 hour duration storm was found to be critical in the Byron Bay town centre, assuming no backwater flooding from downstream of the town centre.

The study noted that many pits are partially or fully blocked with debris and are difficult to gain access to for cleaning. The study determined that although individual pipes within the system may have inadequate capacity, there are generally adequate overland flow paths to cater for excess runoff. The study made the assumption that Belongil Creek, which forms the receiving waters for the town drainage system would not be likely to reach high water levels during the 1 hour flood and therefore it was assumed that the underground pipe system would operate unconstrained by any downstream water level in Belongil Creek or at the ocean. Longer duration storms or high ocean levels were not considered.

Draft Byron Bay CBD Stormwater Strategic Plan, Feb 1998

The draft Byron Bay CBD Stormwater Strategic Plan outlined drainage upgrading works in the Byron St and Cowper St catchments. The adopted strategy was to generally provide piped system capacity for the 5 year ARI with overland flow paths to prevent flooding of properties for the 100 year ARI. The report highlighted a lack of overland escape routes in the areas of Lawson St, Byron St and Marvel St. The report concluded that the existing level of development in the Byron St catchment would preclude options other than upgrading the piped drainage system. The Cowper St system was found to be adequate for only a 1 in 2 year ARI event downstream of Carlyle St. If the Clarkes Beach outfall is blocked, the report found that the Cowper St catchment would overflow to the Byron catchment in a 2 year ARI event.

5.2 Site Inspections and Resident Survey

To gain an understanding of the catchment behaviour, site inspections and resident interviews were conducted. The tasks undertaken included:

- Consultation with residents and interested groups;
- Inspection of the town drainage networks, in particular the Byron St and Cowper St drainage networks;
- Inspection of existing railway drainage in the Byron Bay vicinity including walking the railway line to inspect bridge openings;
- Inspection of the Belongil Creek ocean outlet in a closed and open condition; and,
- Inspection of the overall catchment including major channels and culverts.

A questionnaire was prepared to obtain information of historic floods and distributed to residents of Byron Bay. Those residents that replied to the flood questionnaire with specific flooding problems at their abode or business as well as those with knowledge of historical floods were contacted for a more in depth consultation. The information from the questionnaire was reviewed and from this information a list of historic flood marks was compiled. The flood marks were then surveyed by Byron Shire Council. The surveyed marks are provided in Appendix 2.

A site visit to the Union Drain was also undertaken with local volunteers. The site inspection included an overall view of the catchment from Bangalow Road (on the ridge) and an inspection of the many large open channels.

5.3 Survey And Mapping Data

Byron Shire Council and various other agencies have provided electronic data that has been used to create a GIS database (using the computer program MapInfo) of the catchment, this includes:

- 10m Contours;
- Permanent Marker and State Survey Spot Heights;
- Aerial Photography;
- Cadastral Data;
- Road reserve layout;
- Water Infrastructure;
- Sewer Infrastructure;
- Drainage Infrastructure;
- Geotechnical Survey;
- SEPP Zones; and,
- LEP Zones.

A comprehensive ground survey, based on a combination of photogrammetry and ground-truthing, was carried out by FUGRO Spatial Solutions Pty Ltd, in order to develop a Digital Terrain Model (DTM) for the catchment. The survey information included breaklines, stream cross-sections, structure invert and obvert levels as well as information about the various structures in the catchment area. Additionally Byron Shire Council undertook additional survey in the vicinity of the Industrial Estate to provide additional information on the drainage in this location.

The purpose of developing the DTM was for use in the TUFLOW hydraulic model to prepare a ground model to represent the floodplain surface. The previous modelling by Public Works in 1986 was based primarily on topographic maps which are only generally available at a 2m contour interval and do not cover the entire catchment. The FUGRO survey data, based on photogrammetry was ground truthed using ground survey control and the overall accuracy is claimed to be +/- 0.15m vertically and +/- 0.5m horizontally.

The DTM created from the photogrammetry and other data sources is shown on Figure 1A.

5.4 Flood Heights

Limited historical flood data has been obtained; however, feedback from community consultation has indicated critical areas of flooding. Flood levels for the 1974 and 1984 floods are published in Public Works (1986).

As discussed above, Byron Shire Council conducted a survey of flood marks that were identified by residents. These surveyed flood heights are reproduced in Appendix 2.

5.5 Rainfall Data

Rainfall pluviograph and daily data were obtained from weather stations data operated by the Bureau of Meteorology. These are shown in Table 1 and Figure 2.

TABLE 1. RAINFALL STATIONS

Number	Name	Longitude °E	Latitude °S	Type	Start Date	End Date
558066	Belongil Ck	153.6	28.65	Operational	16/10/02	
58103	Brunswick Heads Bowling Club	153.547	28.551	Daily	01/06/64	
58007	Byron Bay (Jacaranda Drive)	153.588	28.637	Daily	01-Dec-1892	
58009	Cape Byron Lighthouse	153.636	28.639	Daily	01/10/48	
58009	Cape Byron Lighthouse	153.636	28.639	Synop	01/10/48	
558005	Lacks Ck (Middle Pocket)	153.485	28.494	Operational	13/05/99	
558025	Mullumbimby (Chincogan Repeater)	153.479	28.525	Operational	05/08/99	
58040	Mullumbimby (Fairview Farm)	153.495	28.545	Daily	01-May-1898	
558034	Mullumbimby (Upper Main Arm)	153.388	28.506	Operational	05/08/99	
58072	Federal Post Office	153.454	28.6533	Pluviometer	01/11/65	02/01/98
58131	Alstonville Tropical Fruit Research Station	153.456	28.8521	Pluviometer	01/02/63	
58216	Cape Byron AWS	153.636	28.639	Pluviometer	01/01/94	
58127	Clunes (Main Rd)	153.405	28.7322	Daily	1/01/1962	
58133	Corndale (Willow Vale)	153.3619	28.7178	Daily	1/09/1938	
58019	Doon Doon (McCabes Rd)	153.3153	28.5311	Daily	27/11/1998	
58129	Kunghur (The Junction)	153.2632	28.4658	Daily	1/10/1965	
58070	Repentance Ck	153.4122	28.64	Daily	1/02/1957	
58060	Whian Whian (Rummery Park)	153.3783	28.5988	Daily	1/09/1943	
58165	Upper Coopers Ck	153.409	28.6217	Daily	1/06/1975	
58210	Commissioners Ck (Blue Ridge)	153.3347	28.5041	Daily	1/04/1995	

5.6 Ocean Water Levels

Manly Hydraulics Laboratory (MHL) operates a tide recorder at Brunswick Heads. This station commenced operation in 1986.

MHL also collects wave heights and period at a directional wave rider buoy located off shore east of Byron Bay. This commenced operation in 1976.

6 Selection of Model Calibration Events

The study brief stipulated that the model was to be calibrated to the flood events of April 1974 and April 1984. In the 1986 report, Public Works indicated that these events had a recurrence interval of 6% (17 yr ARI) and 10% (10 yr ARI) respectively. Recorded flood heights for these events are shown in Public Works report (1986).

There were two major flood events in 1974, one occurring in March and the other in April. While the event of March 1974 was more destructive due to the accompanying heavy seas, the April 1974 flood also caused extensive flooding in the town centre and has more available surveyed flood marks than the March event. A number of these marks are located in the Byron Bay township where some buildings were inundated. Hence the April 1974 flood is an important flood for model calibration.

The April 1984 event was a moderate flood which has a peak observed flood height available downstream of the railway line in the outfall reach, as well as several spot heights in the estuary upstream of Ewingsdale Road. As this flood has reasonable coverage of spot heights in the floodplain, it was considered to be a good event for calibration.

In addition to these events, a more recent event was selected. After reviewing the resident questionnaires, a flood height survey was completed by Byron Council. This survey yielded a number floods covering a range of flood events including 1995, 1997, 1998, 2003, 2005 and 2006. Generally there were only 1 or 2 marks per event. The resident survey seemed to indicate that the 1998 event was perhaps the largest flood event in the last 10 years that occurred in the Byron Bay township, however there were no accurate flood marks available for this flood. Following a review of all the available flood marks, it was decided that the 2003 event would be an appropriate event to model because it provided a reliable flood level in the town centre which is a critical flooding location.

In summary, the events selected for model calibration were:

- April 1974
- April 1984
- June 2003

The available historic flood heights for these events are shown on Figure 3.

The daily recorded rainfall at the Byron Bay (Jacaranda Drive) rainfall gauge (STN 58007) for the period 1900 to 2008 is shown in Appendix 3. Individual daily rainfall totals do not directly indicate the severity of flooding, which is also dependent on ocean conditions and the pattern of rainfall intensity during the storm. However high daily rainfall totals do indicate days when heavy flooding was likely to have occurred. The daily rainfall totals indicate that 1974 and 1984 events were significant rainfall events compared to historical events over the period following the 1954 flood event. Since 1984 there have been a number of events where very high daily rainfall totals were recorded, the most significant of which was on 11 May 1987 when 358 mm was recorded. When compared to daily rainfall totals for other events since 1984, the 2003 event was a moderate event but as stated above it was the only event for which a reliable flood height in the town centre was available.

7 Hydrologic Model Development

7.1 Modelling Approach

The hydrology of the catchment was modelled using RAFTS-XP software. RAFTS-XP is a comprehensive rainfall-runoff routing model that includes several infiltration loss options, separate routing of runoff from impervious and pervious catchments and provision for the modelling of weirs and basins. RAFTS uses Laurenson's non-linear runoff routing method (Laurenson, 1964) to estimate subcatchment runoff hydrographs.

The purpose of the RAFTS modelling was to generate inflow hydrographs for the hydraulic model, described in Chapter 8. Input data to the RAFTS model includes catchment area, impervious fraction, catchment slope, stream lag data and soil infiltration loss rates. Observed spatial and temporal patterns of rainfall are modelled by entering rainfall data for each subcatchment.

7.2 RAFTS Hydrologic Model

The catchment was subdivided into 43 subcatchments, representing the key variations in catchment slope and land use, as shown on Figure 4. The stream routing procedures available in RAFTS were not used as the purpose of the model was to derive individual sub catchment hydrographs which were then routed using the 2 dimensional hydraulic model described in Chapter 8.

Impervious percentages were estimated from aerial photographs, while catchment slopes were determined from topographic maps.

As there is no stream gauging within the catchment, it was necessary to use assumed loss rates, based on the recommendations in Australian Rainfall and Runoff (ARR), (1987, 1998). For eastern NSW, median values of 2.5 mm/hr continuing loss and 10 to 35 mm initial loss are recommended where actual data is not available.

A review of soil types was carried out to assess the likely magnitude of continuing loss rates that would be expected in the Belongil Creek catchment. Soils classifications provided by Byron Shire Council indicate that a large portion of the catchment is covered by Aeolian soils. These are well drained sandy soils that are deposited by wind action and originate from the coastal dunes. Soils of metamorphic origin lie in the mid to upper reaches, while soils of basaltic origin lie to the south west of the catchment ridges. These basaltic soils have reduced permeability compared to the sandy soils in the lower reaches. The catchment soil types are shown on Figure 5.

The loss rate values were that were selected are shown in Table 2. The selected continuing losses ranged from 3.5 to 10 mm per hour. These values are higher than the NSW median loss rates and are considered to reasonably represent the well drained soils within the catchment.

TABLE 2. RAFTS MODEL LOSSES

	Initial Loss	Continuing Loss
Impervious Surfaces	1 mm	0 mm/h
Pervious Surface	10 mm	3.5 to 10 mm/h (varied)

7.3 Rainfall Data

The rainfall data input to the RAFTS model was derived from daily recording stations, which provide an indication of the spatial variation in total depth across the catchment at a daily interval, and pluviometers which record rainfall at short time intervals and indicate the variation in rainfall intensity during the days of the event.

The availability of daily rainfall data for the calibration events is shown in Table 3. Daily rainfall isohyets showing the regional variation in daily rainfall depths, plotted using the daily station data, are shown in Appendix 3.

TABLE 3. DAILY RAINFALL DATA AVAILABILTY

Number	Name	1974	1984	2003
558066	Belongil Ck[1.]			X
58103	Brunswick Heads Bowling Club	X	X	X
58007	Byron Bay (Jacaranda Drive)	X	X	X
58009	Cape Byron Lighthouse	X	X	X
558005	Lacks Ck (Middle Pocket)			X
558025	Mullumbimby (Chincogan Repeater)			X
58040	Mullumbimby (Fairview Farm)	X	X	X
558034	Mullumbimby (Upper Main Arm)			X
58072	Federal Post Office[1.]	X	X	X
58131	Alstonville Tropical Fruit Research Station[1.]	X	X	X
58216	Cape Byron AWS[1.]			X
58127	Clunes (Main Rd)	X	X	X
58133	Corndale (Willow Vale)	X	X	X
58019	Doon Doon (McCabes Rd)			X
58129	Kunghur (The Junction)	X	X	X
58070	Repentance Ck	X	X	X
58060	Whian Whian (Rummery Park)	X	X	X
58165	Upper Coopers Ck		X	X
58210	Commissioners Ck (Blue Ridge)			X

Note [1.] rainfall station is also a pluviometer (data availability shown for daily data only)

The daily rainfall isohyets were used to determine the total amount of rainfall falling on each RAFTS model subarea on each day of the historic storm events.

To derive the temporal patterns for the historic events, the nearest available pluviometers were used.

For the 1974 and 1984 events, data was available from four stations:

- Alstonville (station number 58131)
- Federal (station number 58072)
- Nimbin (station number 58044)
- Kunghur/The Junction (station number 58129)

Of these stations, Federal (58072) is geographically the closest to Byron Bay followed by Alstonville (58131). For this reason, for the 1974 event, the Federal pluviograph was adopted as providing the best available representation of the temporal pattern.

During the 1984 event the Federal pluviometer malfunctioned and therefore the next closest available pluviograph, the station at Alstonville (58131), was used to provide the temporal pattern for the RAFTS model.

For the 2003 event, the Cape Byron AWS pluviometer (58216), which was installed in 1994, was functional and data from this station was used to provide the temporal pattern for the RAFTS model.

The temporal patterns adopted for modelling the 1974, 1984 and 2003 storms are shown in Appendix 3.

Hydrographs were calculated using the RAFTS hydrological model. The adopted temporal pattern was applied to each sub-catchment based on the daily isohyetal maps, and the average rainfall intensity was calculated for each sub-catchment to determine the inflow hydrographs for the hydraulic model.

8 Hydraulic Model Development

8.1 Introduction

The flood behaviour within Belongil Creek catchment was modelled using the two-dimensional hydraulic model, TUFLOW, with a nested one-dimensional model, ESTRY used to schematise the major hydraulic structures within the catchment. The objectives of the modelling exercise were:

- to define flood behaviour in the Belongil Creek catchment, for a full range of flood events under existing floodplain conditions;
- to update the findings of the previous Public Works Department (1986) Belongil Creek Flood Study;
- To consider the impact of climate change on flooding in Belongil Creek.

8.2 Model Selection

The study area has differing drainage characteristics which are broadly described as follows

- The estuary and swamp areas have slow moving floodwaters which rise and fall slowly. The floodplain flow directions can change during the passage of a flood and are 2-dimensional in nature. The outflow is controlled by the geometry of the creek outlet to the ocean, the ocean water level and ocean wave heights.
- The Byron Bay township and urban areas, which drain through open channels and underground pipes, discharges through a box culvert under the railway line at Butler St towards Belongil Creek and through a pipe at Clarkes Beach.
- The industrial area which drains via open channels and pipes under Ewingsdale Road into the estuary.

These characteristics require a hydraulic model capable of modelling both 2-dimensional floodplain flows and 1-dimensional piped and channelised flows. The TUFLOW software has this capability and was selected for this study.

TUFLOW was developed by WBM Pty Ltd. It is a two-dimensional (2D)/ one-dimensional (1D) flood and tide simulation software program. TUFLOW is a hydrodynamic model designed for the simulation of two-dimensional flood flow patterns in estuaries and floodplains.

Nested within the TUFLOW is a one dimensional mode known as ESTRY. ESTRY is a network dynamic flow program which is used to simulate a wide variety of 1D and quasi 2D situations including complex drainage system and river geometries associated with floodplains and estuaries.

Further information on TUFLOW and ESTRY is provided in Appendix 5.

8.3 Development of the Model

The grid resolution used for the hydraulic model was 20 meters and the grid extended over an area 5.6 km x 6 km, covering the area of interest and encompassing the creek entrance. Adopting a 20 m grid resolution, it is expected that approximately 20,000 cells will be wet (i.e. flooded) during a major flood such as the 1974 event. The grid was selected by considering the following items:

- The sensitivity requirement of the model;
- The time step requirement to provide a stable model;
- The capacity of the computer hardware to run the simulation;

The final survey information was compiled using the 12D terrain modelling software package and a combined, fine-resolution DTM of the catchment was developed. The DTM was then used to create the 2D model grid.

Data describing the geometry of structures including channel invert levels; and culvert sizes, diameters and invert levels was input to the ESTRY model. Additionally, information on bridge pier geometry and spacing collected by the surveyor was incorporated into the TUFLOW model. The main structures that were thought to have a significant influence on the flows and were therefore included in the model were:

- Bridge over Belongil Creek at Ewingsdale Road
- Railway line bridges
- Byron Street and Cowper Street drainage networks.
- Culvert under Butler Street
- Culvert under creek tributary at Ewingsdale Road at the industrial area near Melaleuca Drive
- Drainage channels at Byron Bay's Industrial Estate
- Culverts in Ewingsdale Road, to the north of the Industrial Estate.

Of the above structures, the bridge over the main creek at Ewingsdale Road is thought to have a significant influence over flooding in Belongil Creek as it provides a flow constriction, while the combination of culverts at the railway line and Butler Street and the Clarkes Beach ocean outfall are thought to have greatest significant influence on flooding within the town. In addition to these structures, the deposition of sand at the ocean entrance has a major impact on flood levels under heavy rainfall. The impact of sand buildup would diminish during the course of a major flood as scour would commence once the bar is overtopped by flood waters. However this scouring process may take many hours and depending upon the magnitude of the flood. For this study, the bar elevation has been assumed to be fixed during the period of the flood.

The model structure is shown on Figures 6 and Figure 7.

Frictional resistance is represented in the model using Manning's "n", a dimensionless parameter which is commonly used to model the frictional resistance of stream beds, floodplains and conduits. Manning's 'n' resistance parameters were chosen based on aerial photography and site reconnaissance, as well as from calibration and verification of the model. Figure 8 shows the designated land use areas applied in the model.

The Manning n parameters are summarised in Table 4.

TABLE 4. MANNING 'n' VALUES

Land use	Manning 'n'
Swamp Area	0.04
Forested Area	0.15
Medium Grass floodplain	0.055
Urban area	0.10
Water Body	0.025
Ocean outfall	0.025
Pipes	0.013
Grass lined channels	0.03

8.4 Boundary Conditions

8.4.1 Model Inflows

Inflows to the hydraulic model were calculated using the RAFTS hydrologic model. The adopted temporal pattern was applied to each sub-catchment based on the daily isohyetal maps, and an average rainfall intensity was calculated for each sub-catchment to determine the inflow hydrographs for the hydraulic model. These inflow time-series were then applied into the TUFLOW/ESTRY model, at the various locations corresponding to the locations of the RAFTS sub-catchments.

8.4.2 Tailwater Boundary

Tailwater conditions for the Belongil Creek estuary during a storm event consist of the following components:

- Tidal forcing at the estuary entrance;
- Wave setup caused by ocean waves and depending on the incident wave height and condition of the creek entrance;
- Barometric setup caused by the passage of a low pressure system.

Consultation with the Department of Commerce, Manly Hydraulics Laboratory revealed that offshore tidal gauge data were not available for the nearest gauges at Tweed Heads and Coffs Harbour, for the periods covering the calibration storm events. As such, predicted tides at Ballina, using the program WXTIDE, were adopted in calculating the downstream water level boundary. For the 2003 event, tidal data was available from the Brunswick Heads recorder.

Consultations with the community indicated that major flooding in the catchment has been, in the past, caused by a combination of high tides and torrential cyclonic rain. Photos of the 1974 flood show high seas and significant flooding in the town centre. However, a search of Bureau of Meteorology records and coastal storm event records from Blain, Bremmer and Williams (1985) and Lawson and Treloar (1986) found that the high seas (offshore *significant* wave heights above 6m) and passage of Cyclone Zoe near Byron Bay occurred in March of 1974, which preceded the recorded flooding event of April 1974 by several weeks. As such, these two events occurred in isolation. If the high rainfall event were to occur simultaneously with the crossing of the cyclone at Byron Bay, the tailwater conditions would have been more severe, leading to more severe flooding than was actually recorded.

As no coastal wave events were recorded during the period covered by the 1974 storm, it has been assumed that the influence of barometric and wave setup on water levels at the entrance were negligible. Similarly, no coastal storm events or low barometric pressure events were recorded for the period covered by the 1984 storms at Byron Bay, though a high significant wave event (6.2m) was recorded at the Coffs Harbour waverider buoy on April 8, 1984.

As such, the ocean tide levels at Ballina for the period 20-27 April 1974 and the period 5 – 12 April 1984 were adopted for the downstream water level conditions.

Peak significant wave heights up to 3.5 m were recorded off Tweed Heads during the event of June 2003. To assess the potential amount of wave setup that may have occurred, reference was made to Nielsen and Adamantidis (2002) who carried out an ocean tailwater control study for Crooked River, on the NSW south coast using wave transformation modelling. Crooked River is geographically similar estuary to Belongil Creek, in that both estuaries have a broad sheltered lagoon in their lower reaches, and both are intermittently closed or open depending on the transport of littoral sand drift from the beaches at their entrances. Based on this study, a wave setup of approximately 0.1 to 0.2 m would be expected for a 3.5 m significant wave height, once the creek entrance is open.

Tidal data was also available for Brunswick Heads for the June 2003 event. A wave setup component of 0.2m was applied to the recorded tide levels for this period.

9 Model Calibration and Verification

9.1 Introduction

The TUFLOW/ESTRY model was calibrated against the measured spot-height data from the April 1974 flood event, April 1984 event and verified against the June 2003 event. It is important to note that the data available for calibration and validation consisted of spot heights of maximum flood levels at various locations for the flood events (as reported by the Public Works 1986 flood study and obtained from Byron Shire Council). There were no streamflow gauging stations available to validate the model in terms of water level and discharge time-series.

The calibration process was carried out by adjusting the following main parameters:

- Rainfall loss parameters;
- Manning 'n' parameters
- Belongil Creek estuary condition;

9.2 Model Calibration – 1974 Event

The 1974 event was the largest of the three events used in this study. This event had the most historic levels against which the model could be calibrated.

Rainfall loss parameters were adjusted using the RAFTS model, the hydrographs from which were then integrated into TUFLOW as point inflows into the model. During the process of calibration, the rainfall losses were applied and adjusted to obtain a reasonable fit with the recorded flood levels. During the initial calibration phase, flood levels in the town centre were over estimated. The RAFTS model infiltration losses in this area were then increased and the fit was improved. The adoption of higher losses is considered reasonable, given the sandy soils in this area and flat open space opportunities for infiltration to the east of the township. The impervious fraction was also significantly lower in 1974 than at the present level of development and therefore it is expected that infiltration losses would have reduced since 1974.

Using surveyed outfall channel bathymetry (NSW Public Works, 1997), the model initially over-estimated flood levels throughout the study area. The assumed Manning's "n" roughness parameter for the outfall of 0.025 is considered to be a reasonable estimate for a sandy channel and it was not considered reasonable to reduce this value. Upstream of the outfall channel, where floodwater was found to be relatively slow moving, the Manning's parameter made minimal difference to the modelled flood levels and no adjustments were made to the assumed parameters.

The outfall channel bathymetry was then assessed. The surveyed bathymetry showed a relatively shallow outfall channel with the presence of a sand bar at the channel outlet. The channel then deepened upstream of the bar. It was considered to be a reasonable assumption that the bar would have been removed during the passage of the preceding flood in March, with additional scour during the modelled event. The outlet channel was progressively deepened and widened to account for scour and the fit was improved. A final scoured bed level of RL-2.0 m AHD was adopted.

Following the parameter adjustment, the calibration results are presented in Figures 9 and a comparison between the observed levels and calibrated levels is presented in Table 5.

TABLE 5. CALIBRATION RESULTS – 1974 EVENT

Observed Level (mAHD)	Modelled Level (mAHD)	Difference (m)	Location
2.24	*	*	Lot 184 Butler Street
2.45	2.89	0.44	Lot 444 Carlyle Street
2.14	2.17	0.03	Lot 6 Fletcher Street
2.41	2.47	0.06	Lot 1 Lawson Street
2.06	2.30	0.24	Lot 1 Jonson Street
1.97	1.86	-0.11	Lot 1 Butler Street
1.93	1.86	-0.07	Lot 388 Butler Street
2.07	*	*	Lot 2 Byron Street
1.91	1.86	-0.05	Lot 331 Byron Street
1.85	1.86	0.01	Shirley Street
1.97	1.86	-0.11	412 Ewingsdale Road
1.83	1.85	0.02	Upstream Ewingsdale Road Bridge
1.82	1.85	0.03	Upstream Ewingsdale Road Bridge
1.38	1.39	0.01	Downstream Ewingsdale Road Bridge

Note: * Modelled flood does not extend to the observed point

The modelled and observed levels were generally within an average error of 0.05m, excluding the points described below:

- Lot 184 Butler Street

  Flooding at this location is suspected to be a localised flood. It is observed that ground elevation is at RL2.12m which is slightly higher than the regional flood level near this location.

- Lot 444 Carlyle Street

  The ground surface level at this location is 2.87m AHD, while the observed flood level was only 2.45m AHD. This point is located at the existing playing fields which are believed to have been filled since the 1974 flood and therefore the DTM may not accurately represent the 1974 ground surface at this location.

- Lot 1 Jonson Street

  The exact location of the observed level is not accurately known and the error of 0.24 m may be due to a location error.

- Lot 2 Byron Street

  The observed flood level at this location is higher than some observed flood levels further upstream and it is not consistent with the surrounding observed flood levels. The observed level may have resulted from localised flooding. The model matches other levels in this portion of the estuary reasonably well.

9.3 Model Calibration – 1984 Event

During the initial model calibration, the results indicated an underestimation of the depth of flooding in 1984 compared to the observed flood levels. It was observed that the 1984 flood levels in the outfall reach were reportedly higher than for the 1974 flood, despite the discharges being significantly lower than the 1974 discharges.

As for the 1974 flood event, the RAFTS model rainfall losses, the Manning's 'n' parameters and the outfall bathymetry were reassessed. It was decided that the rainfall losses and Manning's 'n' values should initially be kept the same as for the 1974 event while the bathymetry should be re-examined.

Public Works (1986) had similar calibration problems for the 1984 event and attributed this to the likely presence of a sand bar at the entrance in 1984. Therefore a sandbar was introduced to the TUFLOW model topography across the ocean entrance and the model fit was improved significantly. No adjustment was made to the rainfall losses or Manning's "n" values. The presence of a sandbar is considered to be feasible explanation for the initial calibration difficulties. The results of calibration are shown on Figure 10 and comparison between the observed level and the modelled levels is presented in Table 6.

TABLE 6. CALIBRATION RESULTS – 1984 EVENT

Observed Level (mAHD)	Modelled Level (mAHD)	Difference (m)	Location
1.93	1.73	*	Lot 331 Byron Street
1.74	1.72	-0.02	Lot 396 Ewingsdale Road
1.74	1.72	-0.02	Lot 350 Ewingsdale Road
1.67	1.70	+0.03	Lot 1 Childe Street

Note: * Modelled flood does not extend to the observed point

The modelled and observed levels were generally within an average error of 0.03m, excluding the point at Lot 331 Byron Street. The flood level at Lot 331 Byron Street was modelled at RL1.73m AHD which is consistent with the surrounding observed flood levels. The observed flood level at this location may have been the result of localised flooding.

9.4 Model Verification – 2003 Event

The 2003 event was used as a verification event. No adjustment to the model parameters was carried out. The entrance was assumed to be open as for the 1974 flood. The result of the verification is presented in Figure 11 and a comparison between the observed levels and calibrated levels is presented in Table 7.

TABLE 7. VERIFICATION RESULT – 2003 EVENT

Observed Level (mAHD)	Modelled Level (mAHD)	Difference (m)	Location
3.47	*	*	Lot 1 Burns Street
4.32	3.76	-0.56	Lot A Kingsley Street
2.61	2.57	-0.04	Lot 2 Marvell Street

Note: * Modelled flood does not extend to the observed point

For the 2003 verification event, while three historic levels were observed, two of these were significantly higher than the modelled levels and are believed to be due to localised flooding which is beyond the scope of this study. The reported flood level at Marvel Street is considered by Council to be a reliable level and the model fit at this location is good (within 0.04m). There were no other observed levels available outside of the town centre and the model fit in other areas cannot be verified.

9.5 Conclusions

Apart from the several exceptions described above, the model calibration is considered to be good. It is considered that the hydrologic and hydraulic models adequately represent the flood behaviour of Belongil Creek and Byron Bay township.

The results of the model calibration phase were presented to the Committee at a meeting held on 20 June 2007 and to the community at an open meeting in Byron Shire Council's training rooms on 5 July 2007. No issues were raised and the calibration results were supported.

10 Design Events

10.1 Design Flood Events

Following the establishment and calibration stage, the models were then applied to the prediction of flooding behaviour for various probability design flood events. The following design flood events were modelled:

- 5 year ARI
- 10 year ARI
- 20 year ARI
- 100 year ARI
- Probable Maximum Flood (PMF)

10.2 Climate Change Consideration

The IPCC 2007 Fourth Assessment report describes the current understanding of the global climate system and provides estimates of its projected future evolution and the uncertainties inherent in these projections. IPCC (2007) provides estimates of the projected rise in sea level between the present (1980–1999) and the end of this century (2090–2099) under various scenarios and using a spread of Atmosphere-Ocean General Circulation Models (AOGCMs) results.

In conjunction with the IPCC modelling, research undertaken by the CSIRO in Australia, published in 2007 ("Climate Change in Australia - Technical Report 2007") provides current regional climate change projections specific to the Australian continent. CSIRO (2007) indicates that precipitation intensities may increase in future as a result of increased atmospheric moisture and increased cyclonic intensity.

The ranges of climate change effects at Byron Bay over a 100 year period may include:

a) temperature increases of 0.7 to 5.6 degrees C by 2070;

b) global average sea-level rises of 18 – 91 cm by the end of this century;

c) increases in rainfall intensities of 5 - 40% by the end of this century;

d) increase in cyclone intensities by 2050 of 10% to 20%, with peak wind speeds 5% to 10 % faster, increases in maximum rainfall of 20% to 30% and storm surge increases of 20cm to 40cm.

The NSW Government Department of Environment and Climate Change (DECC) have developed the Floodplain Risk Guideline document "Practical Consideration of Climate Change" (October 2007), to be used as the basis for the examination of climate change in projects undertaken under the State Floodplain Management Program and 2005 Floodplain Development Manual.

The DECC Guideline is divided into 4 sections which are summarised as follows:

- Section 1. Assessment of climate change impacts through development of scenarios, modelling and sensitivity analysis. A range of specific sea level rise and rainfall intensity increases are suggested for sensitivity analysis. The following scenarios are suggested:

  Sea level, increase of:
  - 0.18m (Low Level Ocean Impacts)
  - 0.55m (Mid Range Ocean Impacts)
  - 0.91m (High Level Ocean Impacts)

  Rainfall Intensities, increases of:
  - 10% in peak rainfall and storm volume
  - 20% in peak rainfall and storm volume
  - 30% in peak rainfall and storm volume

- Section 2. Determining whether climate change is a key issue at a particular location. The potential for greater areas of inundation, increased flood hazard and increased flood damages are examined. The preparedness of the community to cope with climate change impacts and the need for mitigation strategies is reviewed.
- Section 3. Incorporating climate change in floodplain risk management plan development considerations, and in new and current works projects and planning strategies.
- Section 4. Managing vulnerability of options and decisions. This section outlines some potential climate change management strategies for existing and future development and associated practical issues.

Byron Shire Council has applied the DECC Guidelines in developing a new planning policy known as the "*Byron Shire Council Climate Change Strategic Planning Policy"* which sets out Byron Shire Council's policy position relating to climate change.

The Policy objects are stated as follows:

- To set out Council's accepted climate change parameter's to inform the decision making process for strategic, infrastructure and operational planning
- To mitigate impacts associated with climate change on future generations through commitment to the precautionary principle.
- To review climate change parameters as further information becomes available from leading government organisations.

In 2008, during development of the climate change planning policy, four Climate Change scenarios were considered by Council as indicated in Table 8. Sensitivity modelling of these scenarios was carried out in a separate study (SMEC 2008).

TABLE 8. CLIMATE CHANGE SCENARIOS – 2008 SENSITIVITY ANALYSIS

Scenario	Global Sea Level rise (m)	Additional Local Sea Level Rise (m)	Accelerated Ice Melt (m)	Total Sea Level Rise (m)	Increase in Rainfall Intensities	Comment
1	0	0	0	0	0	Existing Climate Conditions
2	0.18	0.12	0.10	0.40	20%	Lower Bound Climate Change Estimate
3	0.43	0.12	0.15	0.70	30%	Mid Range Climate Change Estimate
4	0.59	0.12	0.20	0.91	40%	Upper Bound Climate Change Estimate

Following flood modelling and mapping of these scenarios using the calibrated TUFLOW model, Byron Shire Council resolved, in 2008, to adopt Scenarios 2 (modified to allow for an increase in rainfall intensities of 10%, rather than 20%) and Scenario 4 as the basis for planning decisions. Council's 2008 resolution is summarised as follows:

- *For the production of the Belongil Flood Study flood mapping all annual recurrence interval events will use the conditions stipulated for the lower bound Climate Change, i.e. Scenario 2, with the addition of model runs for the 100 year event and Probable Maximum Flood using scenario 4.*
- *Pending completion and then adoption of the Belongil Creek Flood Study and Floodplain Management Plan, for properties located in the Belongil Creek Flood Plain:*

  (i) When considering land use planning, large scale developments, major infrastructure upgrades, new land releases, rezonings and subdivisions, the flood level results from the 100 year scenario (scenario 4) will be used, resulting in the addition of 0.5 metre freeboard. This will be named the 'Belongil Large Development Flood Planning Level'.

  (ii) When considering infill development within existing residential and commercial/industrial zones, the results from the 100 year event under scenario 2, plus 0.5 metre freeboard will be used as a minimum Flood Planning Level. This will be named the 'Belongil Minimum Small Development Flood Planning Level'. In addition, the results from the 100 year scenario (scenario 4) be considered, however, the surrounding floor levels, building adaptability, building flood protection requirements and/or proposals will also be considered before setting any floor levels above the 'Belongil Minimum Small Development Flood Planning Level'.

Consequently, Climate Change Scenario 2 has been adopted as the basis for flood modelling in this study for events up to the 100 year ARI. An additional 100 year ARI model run has also been carried out with Climate Change Scenario 4. For the Probable Maximum Flood, Climate Change Scenario 4 has been adopted. The adopted climate change components are listed in Table 9.

TABLE 9. CLIMATE CHANGE SCENARIOS ADOPTED FOLLOWING 2008 COUNCIL RESOLUTION

Scenario	Global Sea Level rise (m)	Additional Local Sea Level Rise (m)	Accelerated Ice Melt (m)	Total Sea Level Rise (m)	Increase in Rainfall Intensities	Comment
1	0	0	0	0	0	Existing Climate Conditions
2	0.18	0.12	0.10	0.40	10%	Lower Bound Climate Change Estimate
3	0.43	0.12	0.15	0.70	20%	Mid Range Climate Change Estimate
4	0.59	0.12	0.20	0.91	40%	Upper Bound Climate Change Estimate

10.3 Hydrology

Design storms from 5 year ARI to 100 year ARI were derived using the rainfall intensities and temporal patterns published in Australian Rainfall and Runoff (1987). Storm durations from 2 hours to 24 hours were modelled.

As indicated in Table 9, a 10% increase was applied to these intensities to account for future climate change Scenario 2. In addition, both 10% and 40% increases were applied to the 100 year ARI intensities for the modelling of climate change Scenarios 2 and 4.

The magnitude of the PMF event was estimated for the 6 hour, 12 hour and 24 hour duration events, based on the methodology given by the Bureau of Meteorology (2003a, 2003b).

To estimate the 6 hour duration PMF, the Bureau of Meteorology's Generalised Short Duration Method (GSDM) was used. The method uses a standard Depth-Duration-Area nomogram for probable maximum precipitation, which is subject to elevation and moisture adjustment factors that are based on catchment location. A standard temporal distribution is then applied to the rainfall.

For the 12 hour and 24 hour duration PMF, the Bureau of Meteorology's Generalised Tropical Storm Method (GTSMR) was used. This method is based on an annual Probable Maximum Precipitation (PMP) depth, which is adjusted by a topography factor, decay factor and moisture adjustment factor, these factors being dependent on catchment location. The rainfall is then distributed spatially according to the variation in Topographical Adjustment Factor (TAF) across the catchment. A temporal pattern that depends on the area of the catchment is then applied to the rainfall.

The RAFTS hydrologic model was then used to calculate the inflows for the two-dimensional hydraulic model (TUFLOW). The TUFLOW model was then used to determine the critical duration for the catchment which is dependent upon hydraulic factors such as the ocean level and the volume of flood plain storage in the system.

10.4 Hydraulic Modelling

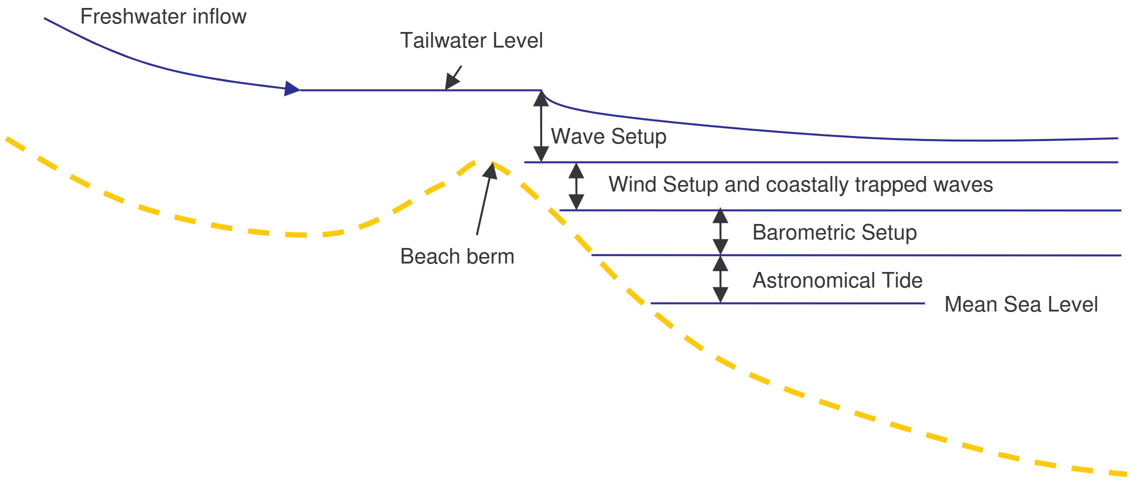
The calibrated TUFLOW model was used to model the design storms. Inflow hydrographs from the RAFTS model were applied to the various model subcatchments. These were applied as distributed inflows over the subcatchments.

A water level boundary condition was applied at the ocean outlet. In order to correctly model the hydraulics of the creek and predict flood levels within the Belongil Creek catchment accurately, the downstream water level at the entrance to the creek needs to be accurately predicted.

The tailwater level for floods in Belongil Creek is determined by the nearshore ocean water level. This level may depend on several factors including:

1. the astronomical tide, which is the greatest contributor by far and is in the order of metres;
2. storm surge, comprising barometric setup and coast-wide wind setup, which is in the order of tenths of a metre;
3. the passage of coastally trapped waves, which can be in the order of tenths of a metre,
4. fresh water inflow, and
5. wave setup.

These components of tailwater level are illustrated below.



The downstream ocean boundary was developed using superposition of various components that are likely to occur during a storm event. In addition to the above components, climate change ocean level increases were also applied. The magnitude of the individual tailwater components are shown in Table 10.

TABLE 10. OCEAN BOUNDARY COMPONENTS FOR DESIGN FLOOD EVENTS

Component	Design Flood Event				
	5 year ARI (Scenario 2)	10 year ARI (Scenario 2)	20 year ARI (Scenario 2)	100 year ARI (Scenario 2)	100 year ARI and Probable Maximum Flood (Scenario 4)
Typical Spring Tide (m AHD)	0.87	0.87	0.87	0.87	
Possible High Tide (m AHD)	-	-	-	-	0.96
Barometric Setup (m)	0.35	0.40	0.45	0.60	0.60
Wind Setup (m)	0.40	0.40	0.40	0.40	0.50
Wave Setup (m)	0.42	0.45	0.47	0.55	0.65
Existing Ongoing Sea Level Rise (m)	0.12	0.12	0.12	0.12	0.12
Sea Level Rise (m)	0.18	0.18	0.18	0.18	0.59
Accelerated Ice Melt (m)	0.10	0.10	0.10	0.10	0.20
Total (m AHD)	2.44	2.52	2.59	2.82	3.62

The timing of the maximum storm surge, wave setup and astronomical tides were set to coincide with the time of maximum freshwater discharge, representing a conservative condition.

10.5 Flood Modelling Results

10.5.1 Flood Elevations, Depths and Velocities

Simulated flood levels at various locations throughout the floodplain, for the various design flood events, are shown in Table 11. The locations of these flood levels are shown on Figure 10.1. The critical duration for flood levels was found to be 12 hours at most locations within the floodplain. Flood elevation contours for the critical duration storm are illustrated in Figure 12 to 16.

Peak velocity and flood water depth maps are shown on Figures 17 to 21. These represent the maximum water depth values throughout the simulation and do not necessarily coincide with the maximum velocity in time.

10.5.2 Provisional Floodplain Hazard Mapping

Provisional Flood hazard categories in accordance with the Floodplain Development Manual (2005) are illustrated on Figures 22 to 26. These maps show indicatively the expected locations of high and low hazard areas during the passage of floods. The Provisional Flood Hazard is dependent upon a combination of flood water depth and velocity. In developing a more comprehensive floodplain risk management plan, other factors such as warning time, flood awareness and difficulty of evacuation will also need to be considered.

High Hazard areas are characterised by relatively fast moving and/ or deep flood waters which would endanger personal safety. In these areas, adults would have difficulty wading to safety and structural damage to buildings may occur. Evacuation by trucks would also be difficult.

In Low Hazard areas, flood water depths and velocities would be sufficiently low that able bodied adults would be able to walk to safety and evacuation by trucks would be possible.

The maps also show a “transition” zone. In this zone, the hazard may be low or high depending upon individual circumstances.

10.5.3 Hydraulic Categorisation

Hydraulic category mapping is illustrated on Figures 27 to 31. Hydraulic categories are divided into the following categories:

- **Floodway** - Areas that convey a significant portion of the flow. These are areas that, even if partially blocked, would cause a significant increase in flood levels or a significant redistribution of flood flows, which may adversely affect other areas.

- **Flood Storage** - Areas that are important in the temporary storage of the floodwater during the passage of the flood. If the area is substantially removed by levees or fill it will result in elevated water levels and/or elevated discharges.

- **Flood Fringe** - Remaining area of flood prone land, after Floodway and Flood Storage areas have been defined. Blockage or filling of this area will not have any significant affect on the flood pattern or flood levels.

TABLE 11. SIMULATED FLOOD LEVELS AT KEY LOCATIONS

Location		Flood Level (mAHD)					
		5 year ARI (Scen 2)	10 year ARI (Scen 2)	20 year ARI (Scen 2)	100 year ARI (Scen 2)	100 year ARI (Scen 4)	PMF (Scen 4)
Northern Floodplain Region							
1	Belongil Creek at Ocean	2.47	2.56	2.63	2.82	3.78	3.79
2	Belongil Ck d/s of Ewingsdale Road	2.24	2.31	2.38	2.59	3.33	3.62
3	Belongil Ck and Cumbebin Swamp u/s of Ewingsdale Road	2.10	2.20	2.30	2.56	3.32	3.62
Eastern Floodplain Region							
4	Byron Street Channel d/s railway line	2.10	2.20	2.31	2.56	3.33	3.63
5	Intersection Byron Street/Jonson Street	2.21	2.22	2.31	2.57	3.32	3.63
6	Lawson Street between Fletcher Street and Middleton Street	2.40	2.44	2.50	2.71	3.33	3.63
7	Intersection Marvel Street/Middleton Street	2.72	2.84	2.95	3.06	3.33	3.63
8	Cowper Street west of Recreation Grounds	2.77	3.00	3.12	3.20	3.33	3.64
Western Floodplain Region							
9	Industrial Estate d/s Ewingsdale Road	2.65	2.73	2.71	2.89	3.33	3.64
10	Industrial Estate u/s Ewingsdale Road	3.52	3.64	3.59	3.73	3.79	3.87
11	Industrial Estate at Bayshore Drive	3.92	3.94	3.95	3.95	3.95	3.94
12	Western Recreation Grounds d/s Ewingsdale Road	2.12	2.22	2.33	2.58	3.35	3.66
13	Western Recreation Grounds u/s Ewingsdale Road	2.75	2.77	2.81	2.87	3.35	3.66
Southern Floodplain Region							
14	Railway Line, near Lilli Pilli Drive	2.18	2.21	2.31	2.57	3.34	3.63
15	East Side Railway Line near Cumbebin Park	2.31	2.36	2.43	2.57	3.33	3.63
16	Ti Tree Road west of Cemetery Road	2.82	2.85	2.90	2.97	3.34	3.64

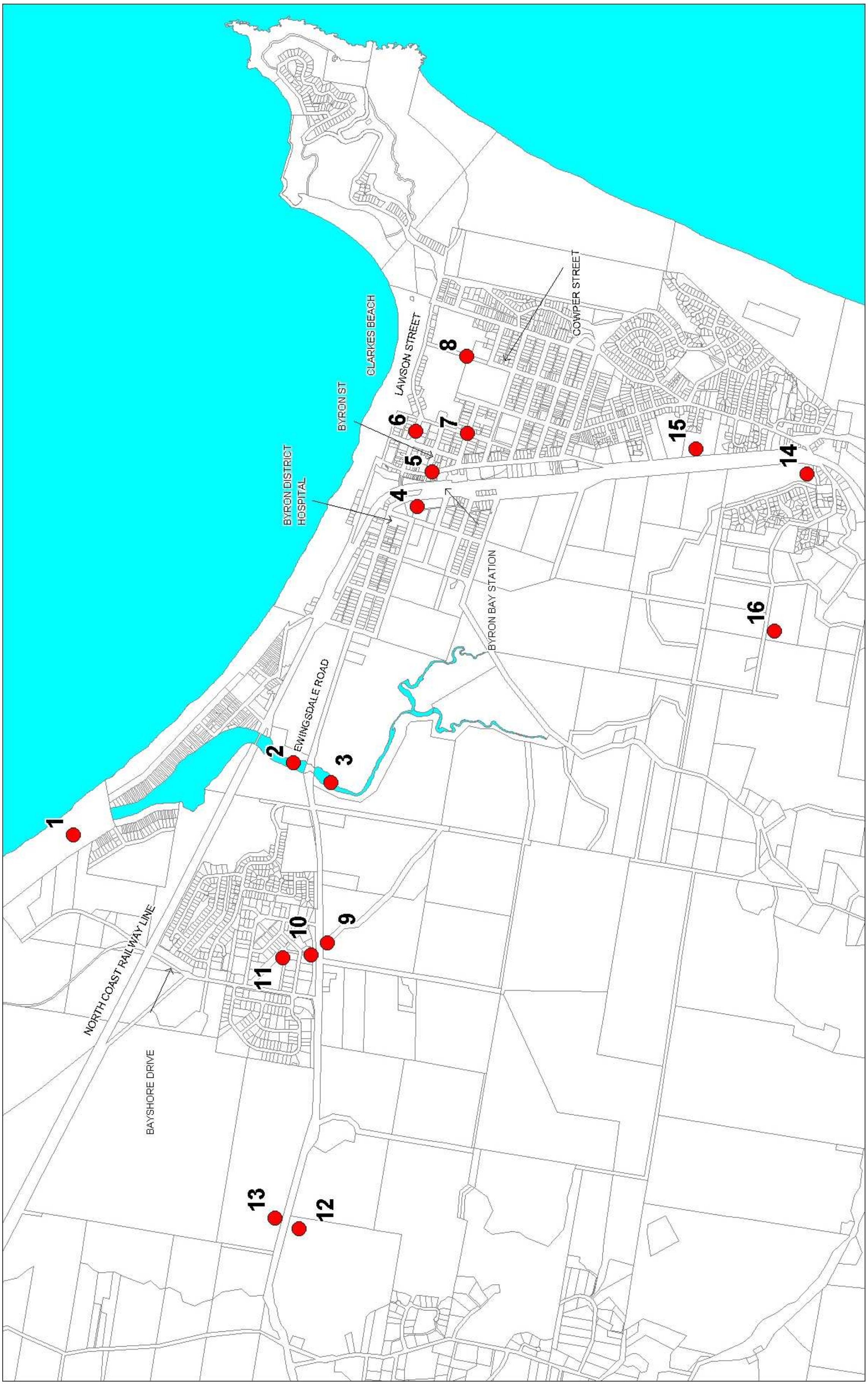


Figure 10.1 – Tabulated Flood Level Locations

10.6 Discussion on Flood Behaviour

10.6.1 General

In the lower reaches of Belongil Creek, the peak tidal component level is slightly damped through the railway bridge and Ewingsdale Road bridges. The Cumbebin Swamp area upstream of Ewingsdale Road forms an extensive level pool extending to the Byron Bay Town Centre to the east and the Industrial Estate outfall channel to the west.

The Byron Bay township has been constructed on low lying land which was, prior to construction of the town, a tributary of the Cumbebin Swamp and Belongil Creek. The lowest surface levels occur in Lawson Street, east of Fletcher Street, where the gutter pavement is at approximately RL 2.0 in the road lowpoint. The laneway opposite this low point falls to approximately 1.9 m AHD, between Lawson and Byron Streets. Byron Street generally falls from 3.0 m AHD at Middleton Street, to 1.9 m AHD near the railway line.

The natural flowpath toward Belongil Creek has been filled and drained to the west via the Byron Street Drainage system and to the north via the Clarkes Beach outfall. Any previous surface flow path through the township to the Cumbebin Swamp has been removed with the construction of the North Coast Railway Line and all flow leaving the town centre is through piped systems. The hydraulic gradient from the Byron Street drain to the ocean is almost flat and under high seas flows may reverse direction and flow from the ocean towards the town.

In assessing flooding behaviour in Belongil Creek, this study has considered the concurrence of both high rainfall and high ocean levels. Such conditions are typically linked with the occurrence of East Coast low pressure systems or tropical cyclones which bring heavy rainfall and high seas. In the event of high seas, the man made drainage components and other infrastructure that inhibit outflows from the catchment, such as the Byron Street drain and the North Coast Railway, may actually provide some protection to the town east of the railway by limiting the quantity of inflow from the ocean. However, in heavy rainfall events, with low or moderate ocean levels, these man-made constrictions do exacerbate flooding in the town. Intermittent closure of the creek outlet through sand buildup can also exacerbate flood levels throughout the catchment in the event of heavy rainfall. However the modelling shows that a closed entrance condition can also result in a reduction in ocean inflows during high seas.

10.6.2 Northern Floodplain

In the 100 year ARI flood event (with Climate Change Scenario 2) the peak flood level in the Cumbebin Swamp reached 2.56 m AHD, approximately 0.25 m lower than the peak ocean level. Peak velocities were generally below 0.1 m/s over most of the Belongil Creek Floodplain for all design events. Hence the primary hazard is water depth. In the ocean outfall reach, velocities are highest, reaching up to 1.5 m/s in the lower reaches. In the 100 year ARI flood, water depths in the outfall channel exceed 5 m adjacent to lots north of Childe Street.

Properties adjoining Belongil Creek, north of the railway line, are within a high hazard zone from both coastal hazard and flood hazard. Under the high velocities encountered along the creek, there is also a very high stream bank erosion risk for properties adjoining the creek, north of the Railway Line Bridge.

Properties adjacent to the north side Byron Street town drain reserve (west of the Town Centre) are currently inundated in the 100 year ARI flood. Properties near Kendall Street are in a high hazard flood zone under 100 year ARI conditions. In the Probable Maximum Flood, the high hazard region covers properties in Kendall Street, Dryden Street, Milton Street, Wordsworth Street and Shirley Street.

10.6.3 Eastern Floodplain

In the 100 year ARI flood, flood levels in the Byron Bay Town Centre at Lawson Street, east of the railway line are approximately 0.15 m higher than those on the west side. The railway line remains flood free. During the Probable Maximum Flood, the railway line is overtopped near Ruskin Street and peak flood levels in the Town Centre rise to the same level as those on the west side of the railway line. The peak flood level during the PMF is approximately 3.6 m AHD through much of the township, compared to 3.8 m AHD at the ocean. This would result in 1.8 m water depth in the lowest part of Lawson Street where the surface is at approximately RL 2.0 m AHD.

In the Town Centre, the deepest flooding occurs in properties located within the land bounded by Lawson Street, Byron Street, Fletcher Street and Middleton Street. Under current conditions, the 100 year ARI flood reached 2.71 m AHD at this location, with a maximum depth of approximately 0.5 m. This water would be slow moving and the hazard would be low. In the PMF, flood levels would reach up to 3.6 m AHD, with a depth of 1.4 m. The hazard category would be high, based on the flood depth.

East of the town centre, a large portion of the catchment drains to the Cowper Street piped outfall to Clarkes Beach This outfall replaces the natural flowpath toward the west to Belongil Creek which has been raised through filling for development. The limited capacity of this outfall causes significant flooding at the existing playing fields in Cowper Street as well as surrounding properties. In the flood events up to the 20 year ARI, all flow that leaves this part of the catchment flows through the ocean outfall to Clarkes Beach. In the 100 year flood event, flood waters reach sufficient depth that they overflow as surface flow to the west to the Belongil Creek system.

In the PMF, the flood level forms a level pool from the Ewingsdale Road bridge, upstream to the recreation grounds east of the Town Centre and reaches a peak flood level of 3.6 m AHD. A large portion of the Town Centre which would be classed as low hazard in the 100 year ARI event would be classed as high hazard in the PMF.

In Middleton Street, at the lowpoint immediately north of Marvell Street, the road would be flooded to 0.9 m depth in the 100 year ARI flood. Lots to the east of Middleton Street are currently vulnerable to similar flood depths.

10.6.4 Southern and Western Floodplain

On the west side of the railway line, in the south of the floodplain, properties along Lilli Pilli Drive are flood free in the 100 year ARI flood. The flood hazard category is low for properties in this area. In the PMF, properties along Lilli Pilli Drive are inundated by up to 1.0 m of water along the road reserve. The flood hazard would be high under these conditions, although the water would be slow moving.

In the Industrial Estate, the 100 year ARI flood level reached 3.95 m AHD at Bayshore Drive and Brigantine Street. A number of Lots in Brigantine Street, Bayshore Drive and Grevillea Street are inundated in the 100 year ARI flood event. In the PMF, most flooding remains low hazard although lots are inundated in Centennial Circuit, Grevillea Street, Bayshore Drive and Brigantine Street. Low hazard flooding would also occur in Cypress Circuit, Julian Rocks Drive, Sunrise Boulevarde and Belongil Crescent. High hazard flooding would be mainly confined to the open drainage channels in the industrial estate and water overtopping Ewingsdale Road.

In the south of the catchment, there are currently very few residential properties either side of the railway line that are inundated in the 100 year ARI or PMF.

10.7 Sensitivity Analysis

A sensitivity analysis was carried out to test the sensitivity of the modelled results to input parameters. The parameters tested included:

- Model Roughness +/- 20%
- Entrance Condition Open (scoured to -2.0m AHD) /Closed(sand bar at 0m AHD)
- High Tailwater (BCC Climate Change Scenario 4)

The results are shown in Table 12

The impact of changed roughness is minimal throughout the floodplain. It is interesting to note that the entrance closed condition results in slightly reduced flood levels. While under a low tailwater condition a closed entrance would be expected to constrict outflows and cause increased upstream flooding, in this case with a high ocean level a closed entrance results in reduced inflow of water from the ocean. This has the effect of slightly reducing upstream flood levels.

The Climate Change Scenario 4 flood levels are higher throughout the catchment as expected because the Belongil Creek catchment experiences ocean dominated flood events. While the ocean boundary level (tide level plus wind setup and wave setup) is increased by approximately 0.8 m compared to Scenario 2 (see Table 8 and Table 9), this resulted in a 0.6 m increase in the 100 year ARI flood level at Lawson Street in the town centre.

TABLE 12. SENSITIVITY ANALYSIS

Location		100 year ARI Flood Level (mAHD)				
		Base Case	Manning n-20%	Manning n+20%	Entrance Closed	Climate Change Scen 4
Northern Floodplain Region						
1	Belongil Creek at Ocean	2.82	2.82	2.82	2.82	3.78
2	Belongil Ck d/s of Ewingsdale Road	2.59	2.59	2.60	2.59	3.33
3	Belongil Ck and Cumbebin Swamp u/s of Ewingsdale Road	2.56	2.56	2.58	2.54	3.32
Eastern Floodplain Region						
4	Byron Street Channel d/s railway line	2.56	2.56	2.59	2.54	3.33
5	Intersection Byron Street/Jonson Street	2.57	2.57	2.59	2.55	3.32
6	Lawson Street between Fletcher Street and Middleton Street	2.71	2.68	2.67	2.68	3.33
7	Intersection Marvel Street/Middleton Street	3.06	3.02	3.02	3.02	3.33
8	Cowper Street west of Recreation Grounds	3.20	3.17	3.16	3.18	3.33
Western Floodplain Region						
9	Industrial Estate d/s Ewingsdale Road	2.89	2.80	2.81	2.79	3.33
10	Industrial Estate u/s Ewingsdale Road	3.73	3.78	3.77	3.78	3.79
11	Industrial Estate at Bayshore Drive	3.95	4.09	4.08	4.10	3.95
12	Western Recreation Grounds d/s Ewingsdale Road	2.58	2.58	2.61	2.56	3.35
13	Western Recreation Grounds u/s Ewingsdale Road	2.87	2.87	2.87	2.87	3.35
Southern Floodplain Region						
14	Railway Line, near Lilli Pilli Drive	2.57	2.57	2.60	2.55	3.34
15	East Side Railway Line near Cumbebin Park	2.57	2.58	2.59	2.57	3.33
16	Ti Tree Road west of Cemetery Road	2.97	2.97	2.92	3.02	3.34

11 Conclusions

A hydraulic model of the Belongil Creek floodplain has been established and calibrated to historic flood events. This model has been used to predict flooding behaviour across the Belongil Creek floodplain for a range of design flood events. The design flood events incorporated climate change scenarios based upon IPCC and CSIRO models and DECC guidelines. These models suggest that ocean levels and rainfall intensities in Byron Bay are highly likely to increase over the next century in response to global climate change.

The flood models indicate that flooding of the Byron bay township to the east of the North Coast Railway line is caused by inadequate trunk drainage system capacity, lack of a surface overland flow path to the Belongil Creek Estuary and insufficient change in elevation between the low lying portions of the town and the ocean to facilitate gravity flow. The Butler Street drain is the only means of drainage for the town centre and this drain was found to be deficient in capacity. However any upgrading of this drain may also allow greater quantities of sea water to reverse flow towards the town centre during times of elevated ocean levels and consideration would need to be given to the use of flood gates, levees and pump systems to protect the town east of the railway line. In addition to the Butler Street drain, the Clarkes beach outfall was found to be deficient in capacity, resulting in flooding of Cowper Street and the surrounding area. The capacity to convey water from Cowper Street either to Clarkes Beach or to Belongil Creek would need to be increased, or additional flood storage provided, to reduce flooding at this location.

To the west, in the Industrial Estate, a number of Lots in Brigantine Street, Bayshore Drive and Grevillea Street are inundated in the 100 year ARI flood event. Flooding in this area could be reduced with upgraded drainage systems.

Provisional flood hazard categories based on the NSW Floodplain Development Manual (2005) indicate that while most flooding in the catchment can be categorised as low hazard, there are some areas of high hazard flooding within and adjacent to residential areas. Properties located along the Belongil Creek outlet reach, north of the North Coast Railway line bridge are at particularly high risk with deep high velocity, floodwaters running in the creek immediately adjacent to these lots. In addition, these properties are vulnerable to coastal hazards. There are few options available to reduce flood hazard in this area, beside structural improvements to dwellings.

With the advent of climate change, the major impacts would occur near the Town Centre and Town Drain south and west of the railway line which would see existing low hazard flooding transformed to deeper high hazard flooding. In the south east, many lots that are currently flood free would become flood affected.

The model indicates that much of the Industrial Estate to the west would be less affected by climate change, than other parts of Byron Bay because much of this land has been filled to a level above the worst case scenario 4 ocean level and the climate change impacts are reduced.

The flood modelling undertaken for this study demonstrates that the climate change scenarios proposed by IPCC and CSIRO would see the transformation of flooding in the Belongil Creek Floodplain from low hazard to high hazard in many areas and significantly increase the number of flood affected lots.

12 Action Plan

The following actions should now follow this study:

Task Number	Action	Responsibility	Timing
1	Flood Planning Levels for the Belongil Creek Catchment should be updated as per Council's previous resolution which is summarised as follows: For the production of the Belongil Flood Study flood mapping all annual recurrence interval events will use the conditions stipulated for the lower bound Climate Change, i.e. Scenario 2, with the addition of model runs for the 100 year event and Probable Maximum Flood using scenario 4. Pending completion and then adoption of the Belongil Creek Flood Study and Floodplain Management Plan, for properties located in the Belongil Creek Flood Plain: (i) When considering land use planning, large scale developments, major infrastructure upgrades, new land releases, rezonings and subdivisions, the flood level results from the 100 year scenario (scenario 4) will be used, resulting in the addition of 0.5 metre freeboard. This will be named the 'Belongil Large Development Flood Planning Level'. (ii) When considering infill development within existing residential and commercial/industrial zones, the results from the 100 year event under scenario 2, plus 0.5 metre freeboard will be used as a minimum Flood Planning Level. This will be named the 'Belongil Minimum Small Development Flood Planning Level'. In addition, the results from the 100 year scenario (scenario 4) be considered, however, the surrounding floor levels, building adaptability, building flood protection requirements and/or proposals will also be considered before setting any floor levels above the 'Belongil Minimum Small Development Flood Planning Level'.	Council	September 2009
2	The flood mapping output for this study should be incorporated in Councils GIS system and used to update Byron Shires Council's Flood Planning Level (FPL).	Council	December 2009
3	Update S149 certificates for properties affected by flooding under this plan.	Council	December 2009
4	Proceed to the preparation of a Floodplain Risk Management Study and Plan in accordance with the NSW Floodplain Development Manual (2005).	Council	2010-2012

13 References

Byron Shire Council (1998), "*Draft Byron Bay CBD Stormwater Strategic Plan*", February 1998.

CSIRO-BoM (2007) "*Climate Change in Australia: Technical Report 2007*", Pearce K, Holper P, Hopkins M, Bouma W, Whetton P, Hennessy K, Power S (eds.), CSIRO Publishing, 2007

Department of Public Works and Services (1998), "*Belongil Creek – Hydrographic Survey of Belongil Creek and off-creek drains*". 1998

Department of Environment and Climate Change (2007) "*Practical Consideration of Climate Change*", Floodplain Risk Management Guidelines, Issued 25/10/2007

Department of Infrastructure Planning and Natural Resources (2004). "*Floodplain Management Guideline No. 5, Ocean Boundary Conditions*", Draft, 22 March 2004.

Gordon, A.D., Lord, D.B., Nolan, M.W. (1978), "*Byron Bay – Hastings Point Erosion Study*", Department of Public Works, NSW Report No. PWD 78026, November 1978.

Haradasa, D., S. Wylie & E. Couriel (1991). "*Design Guidelines for Water Level and Wave Climate at Pittwater*", Australian Water and Coastal Studies Pty Ltd Report 89/23, March, 1991.

IERM, 2005, REF on the Belongil Creek Entrance Opening Strategy.

The Institution of Engineers, Australia (1997), "*Australian Rainfall and Runoff – A Guide to Flood Estimation*" (ARR97).

IPCC (2007). "*Climate Change 2007 – The Physical Science Basis, Fourth Assessment Report of Working Group 1 of the Intergovernmental Panel on Climate Change*", Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 2007.

Kulmar, M., Lord, D. and Sanderson, B. (2005) *"Future Directions for Wave Data Collection in New South Wales"*, Proceedings of Coasts and Ports 2005 Australasian Conference, 20-23 September 2005, Adelaide, South Australia.

Nathan, R. J., & Weinmann, P. E. (1998) *"Australian Rainfall and Runoff, Book VI, Estimation of Large to Extreme Floods"*, revised 1998.

Nielsen, A.F. & Adamantidis, C.A. (2002), "*Crooked River Flood Study Ocean Tail Water Control*", Report prepared by SMEC Australia for Paterson Consultants on behalf of Perrens Consulting. Document Number 31333-018, October 2002.

Nielsen, P & DJ Hanslow (1995), "*Wave setup at river entrances*", preprints of papers presented at 12th Aust. Coastal & Ocean Engg. Conf., IEAust., Melbourne, May-June, 1995

NSW Government (1990), "*Coastline Management Manual*", 1990

NSW Government (2005), "*Floodplain Development Manual: the management of flood liable land*", April 2005.

Parker and Pont (2001),"Belongil Estuary Study and Management Plan", Report prepared for Byron Shire Council, November 2001.

Public Works Department (1986), "*Belongil Creek Flood Study*", 1986.

SMEC (2008), "*Belongil Creek Climate Change Assessment*". Report for Byron Shire Council, February 2008.

Toby Fiander and Associates (1994), "*Byron Council – Drainage Strategy Study", 1994*

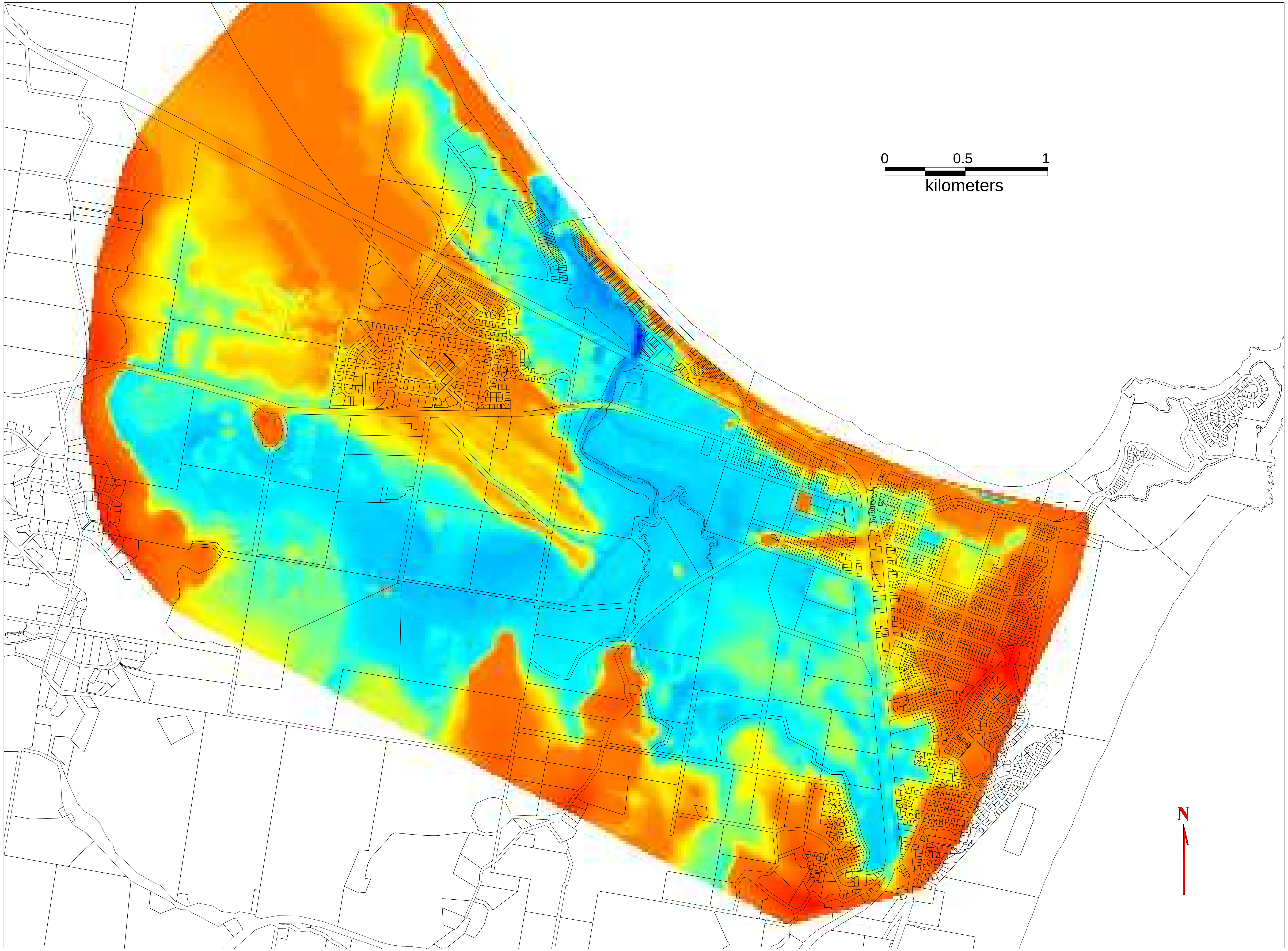
Willing and Partners (2000), "*Flood Impact Assessment, Development of Areas 1, 2 and 3*", 2000.

Willing & Partners (1996)," *Belongil Creek Data Compilation Study*", July 1996

WBM Oceanics (2006), "*TUFLOW USER MANUAL – GIS based 2D/1D Hydrodynamic Modelling*" (June 2006)

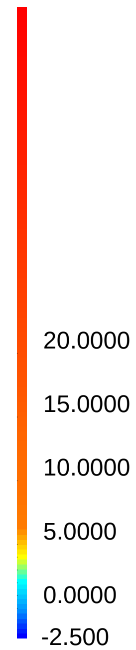
XP-RAFTS Software (2000). "*XP-RAFTS runoff analysis & flow training simulation with XP graphical interface user manual*", Belconnen ACT.

APPENDIX 1 : Figures



LEGEND

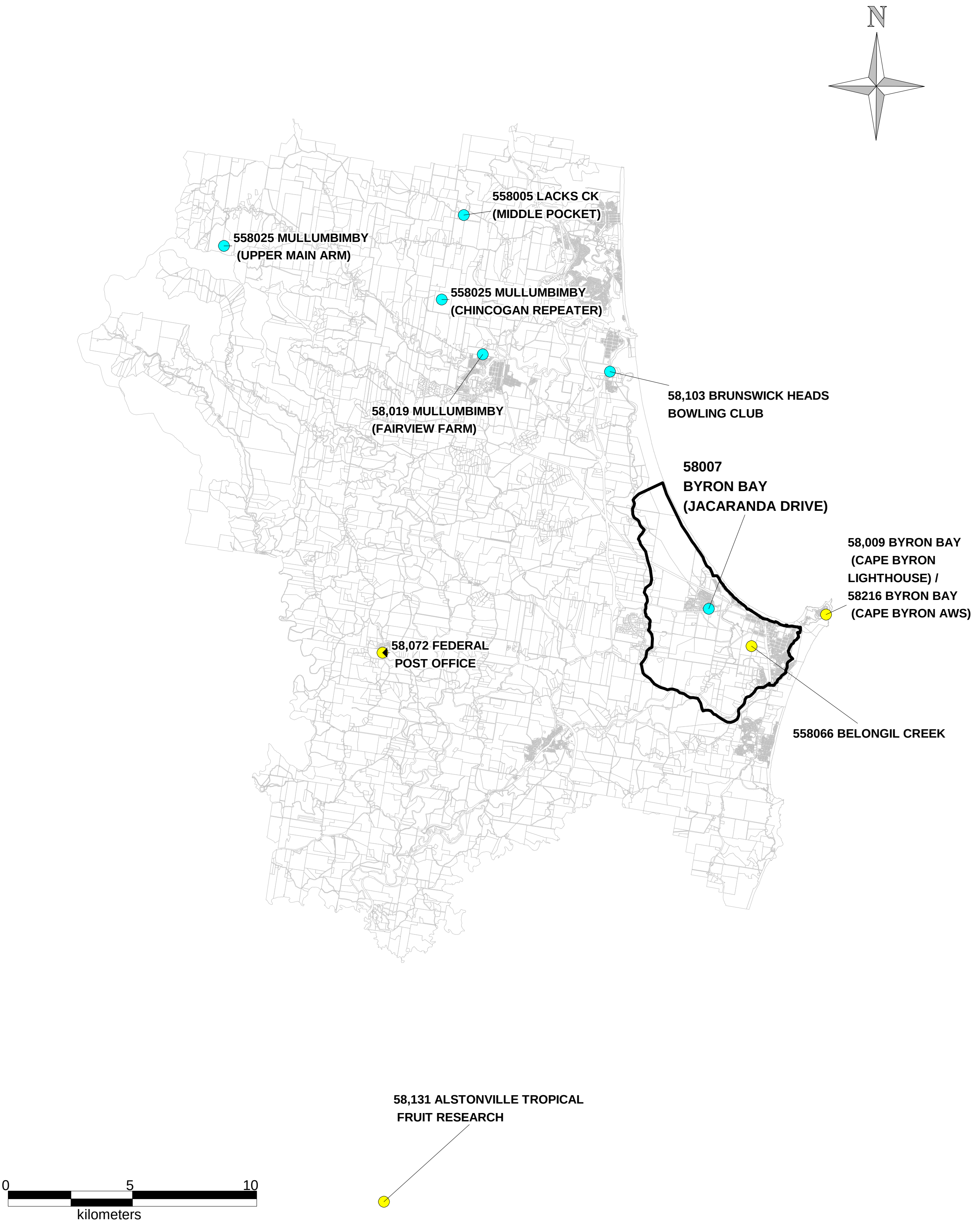
ELELEVATION (mAHD)



SMEC

BELONGIL CREEK FLOOD STUDY

FIGURE 1A SURVEY DTM



LEGEND

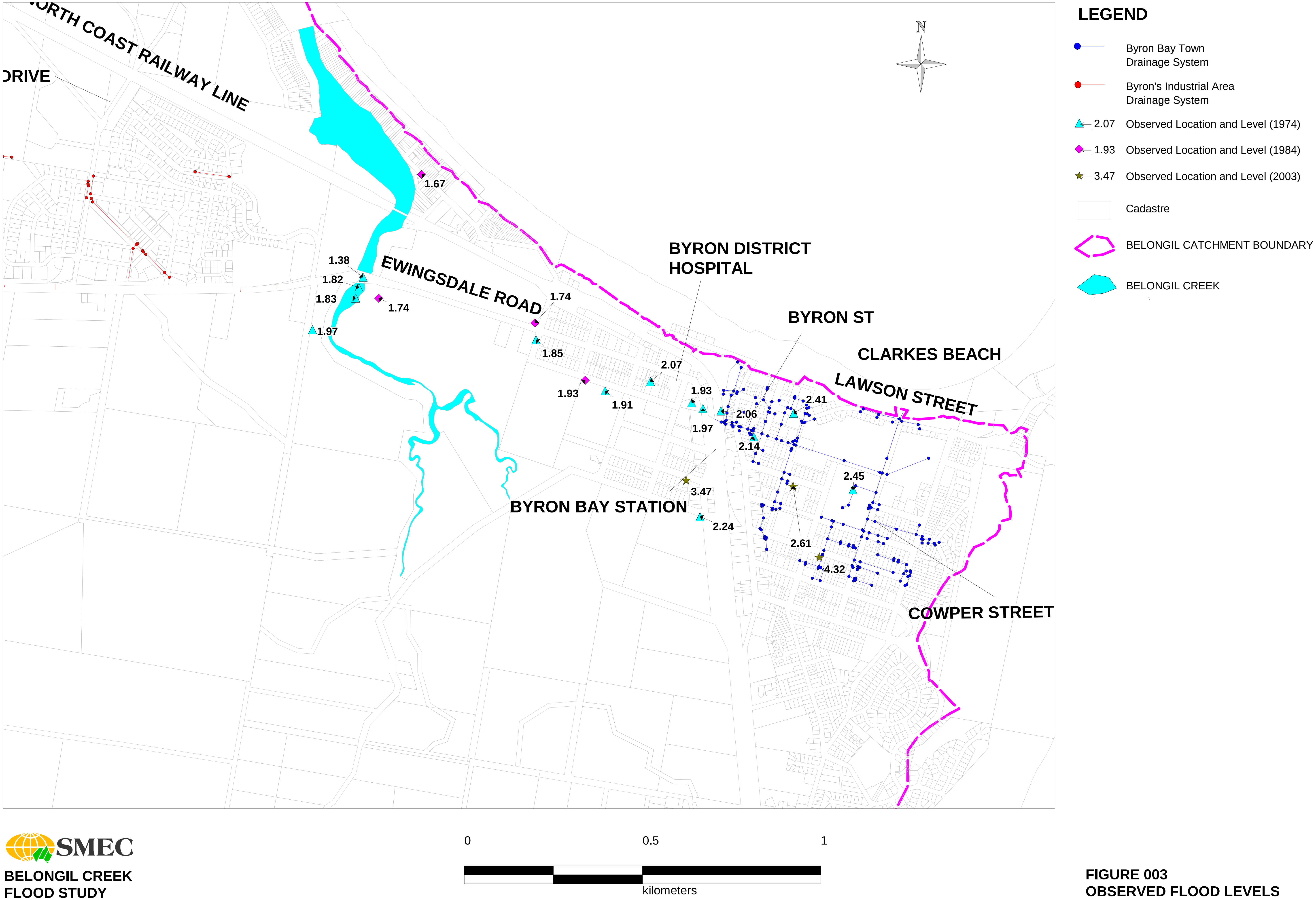
DAILY READ RAINFALL STATION

PLUVIOMETER

SMEC

BELONGIL CREEK
FLOOD STUDY

FIGURE 002
WEATHER STATION
LOCATIONS



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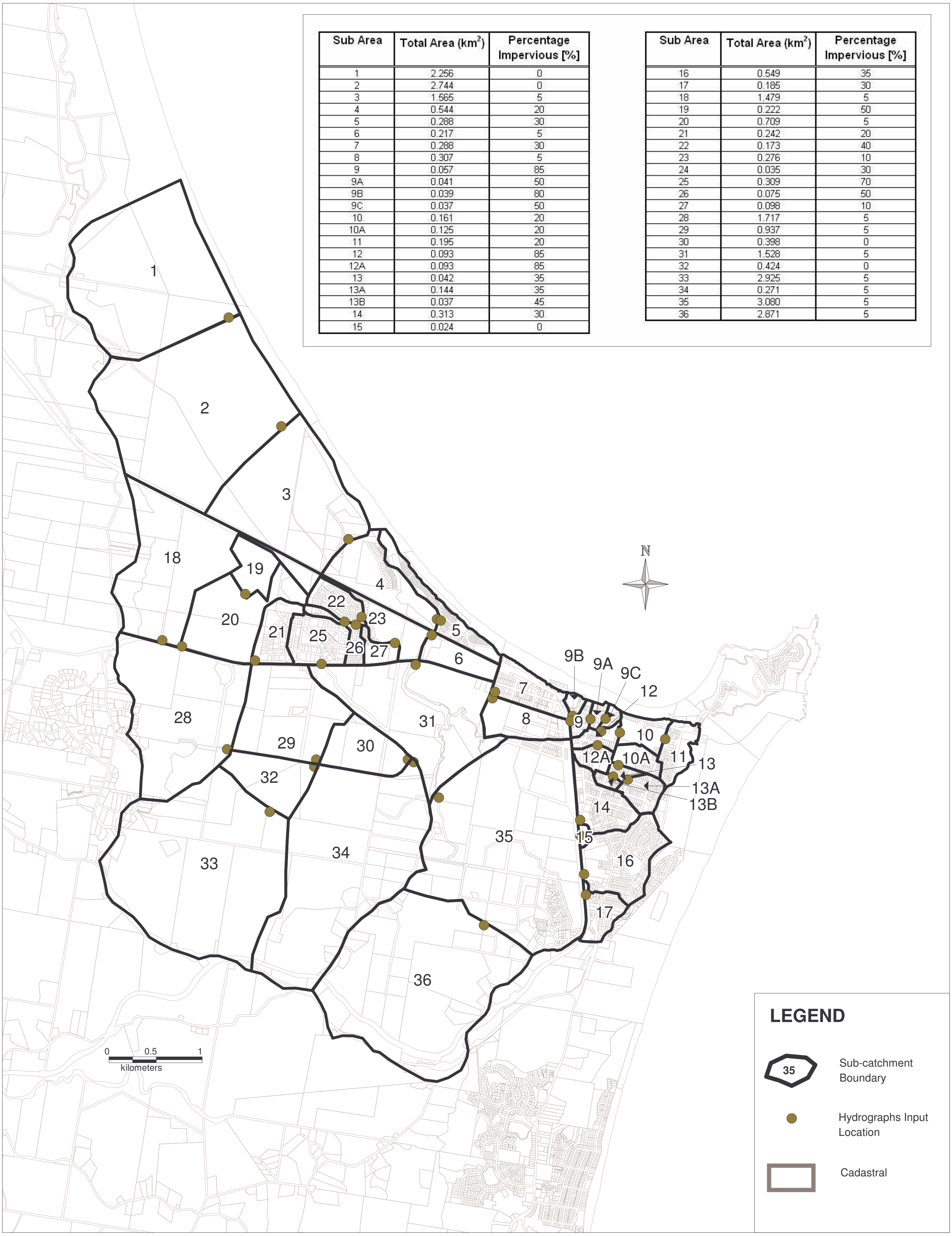
BELONGIL CREEK
FLOOD STUDY

FIGURE 003
OBSERVED FLOOD LEVELS

Sub Area	Total Area (km^2)	Percentage Impervious [%]
1	2.256	0
2	2.744	0
3	1.565	5
4	0.544	20
5	0.288	30
6	0.217	5
7	0.288	30
8	0.307	5
9	0.057	85
9A	0.041	50
9B	0.039	80
9C	0.037	50
10	0.161	20
10A	0.125	20
11	0.195	20
12	0.093	85
12A	0.093	85
13	0.042	35
13A	0.144	35
13B	0.037	45
14	0.313	30
15	0.024	0

Sub Area	Total Area (km^2)	Percentage Impervious [%]
16	0.549	35
17	0.185	30
18	1.479	5
19	0.222	50
20	0.709	5
21	0.242	20
22	0.173	40
23	0.276	10
24	0.035	30
25	0.309	70
26	0.075	50
27	0.098	10
28	1.717	5
29	0.937	5
30	0.398	0
31	1.528	5
32	0.424	0
33	2.925	5
34	0.271	5
35	3.080	5
36	2.871	5



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BELONGIL CREEK FLOOD STUDY

FIGURE 004 RAFTS MODEL LAYOUT

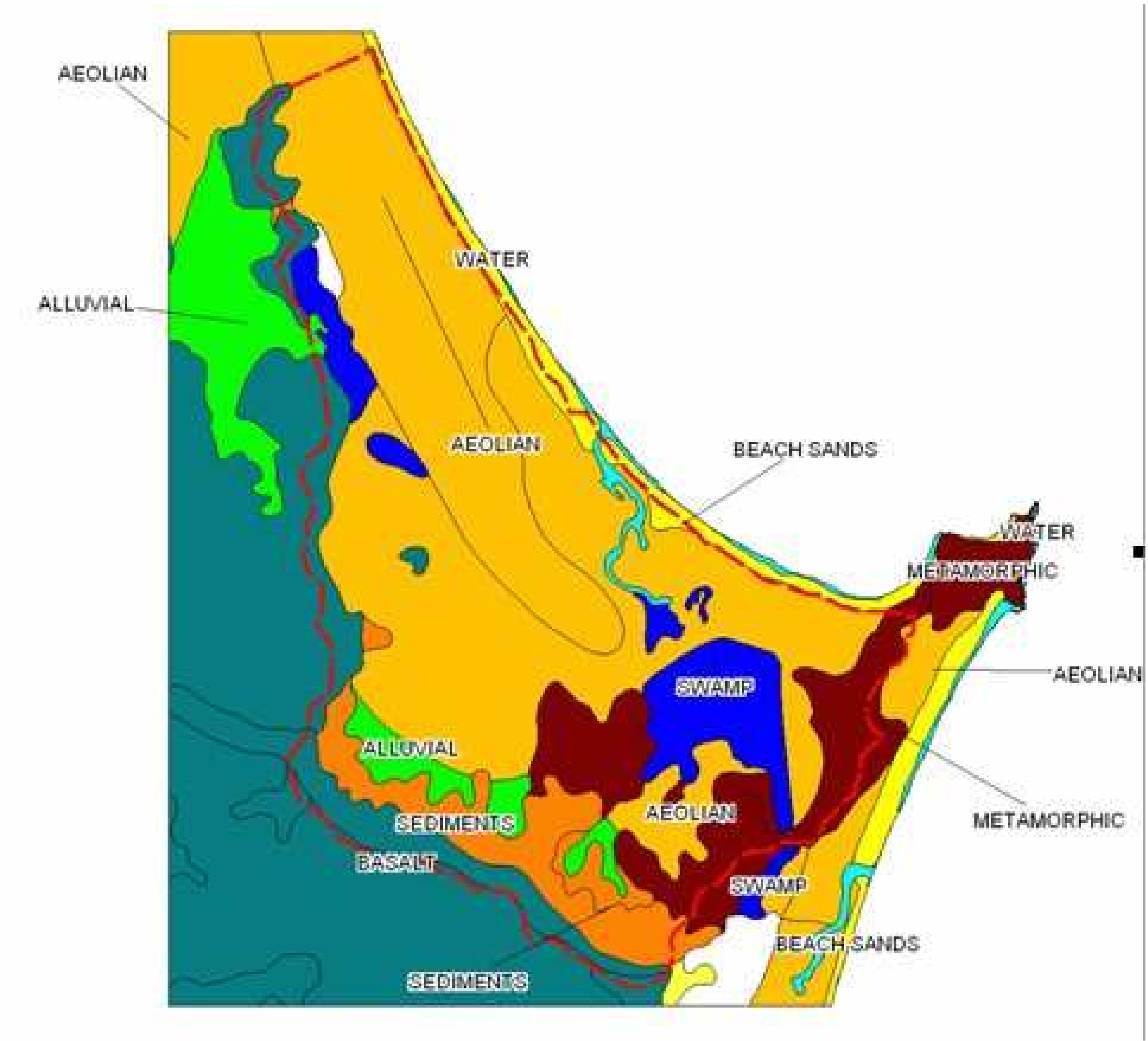
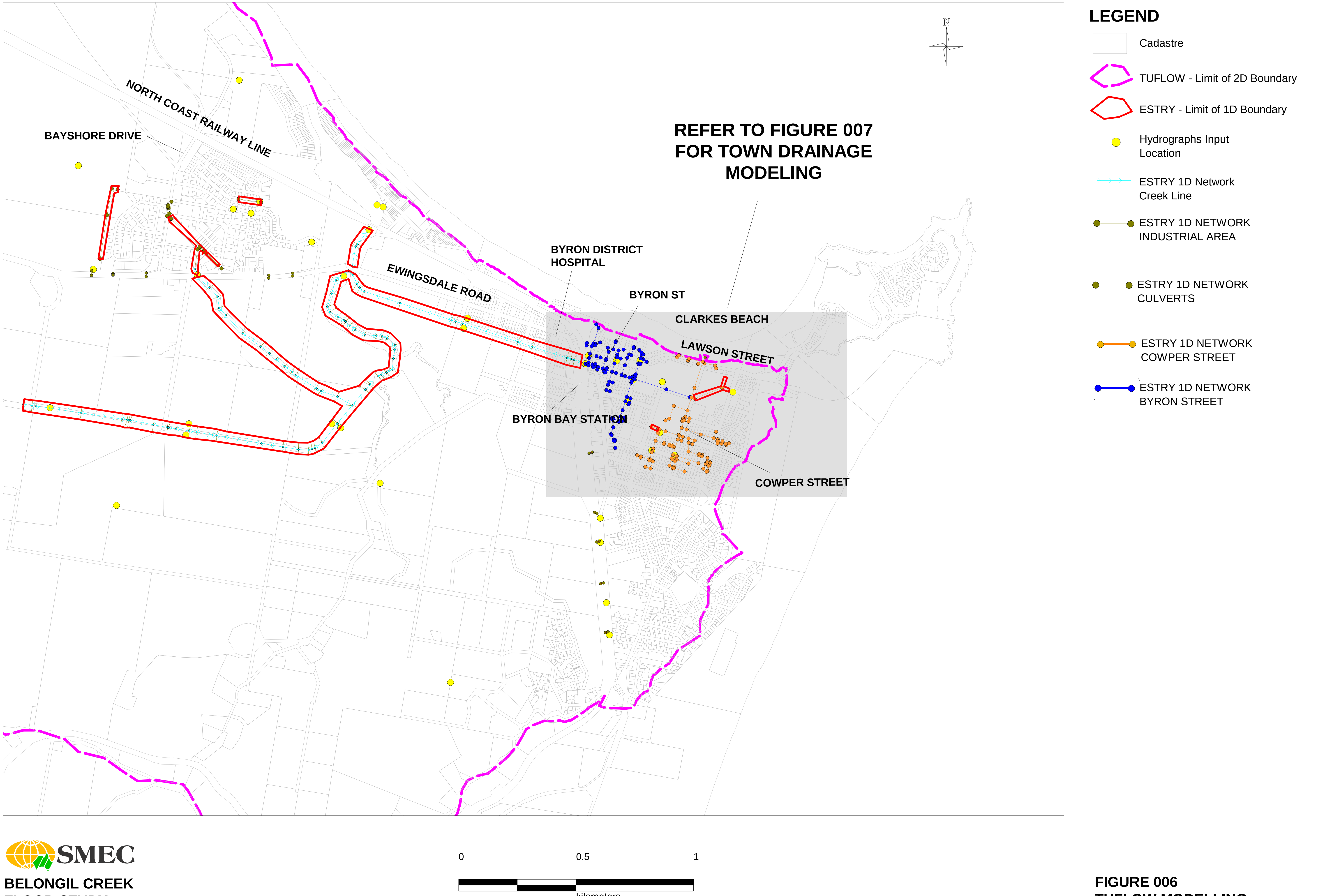


FIGURE 005
SOIL STRATA MAP



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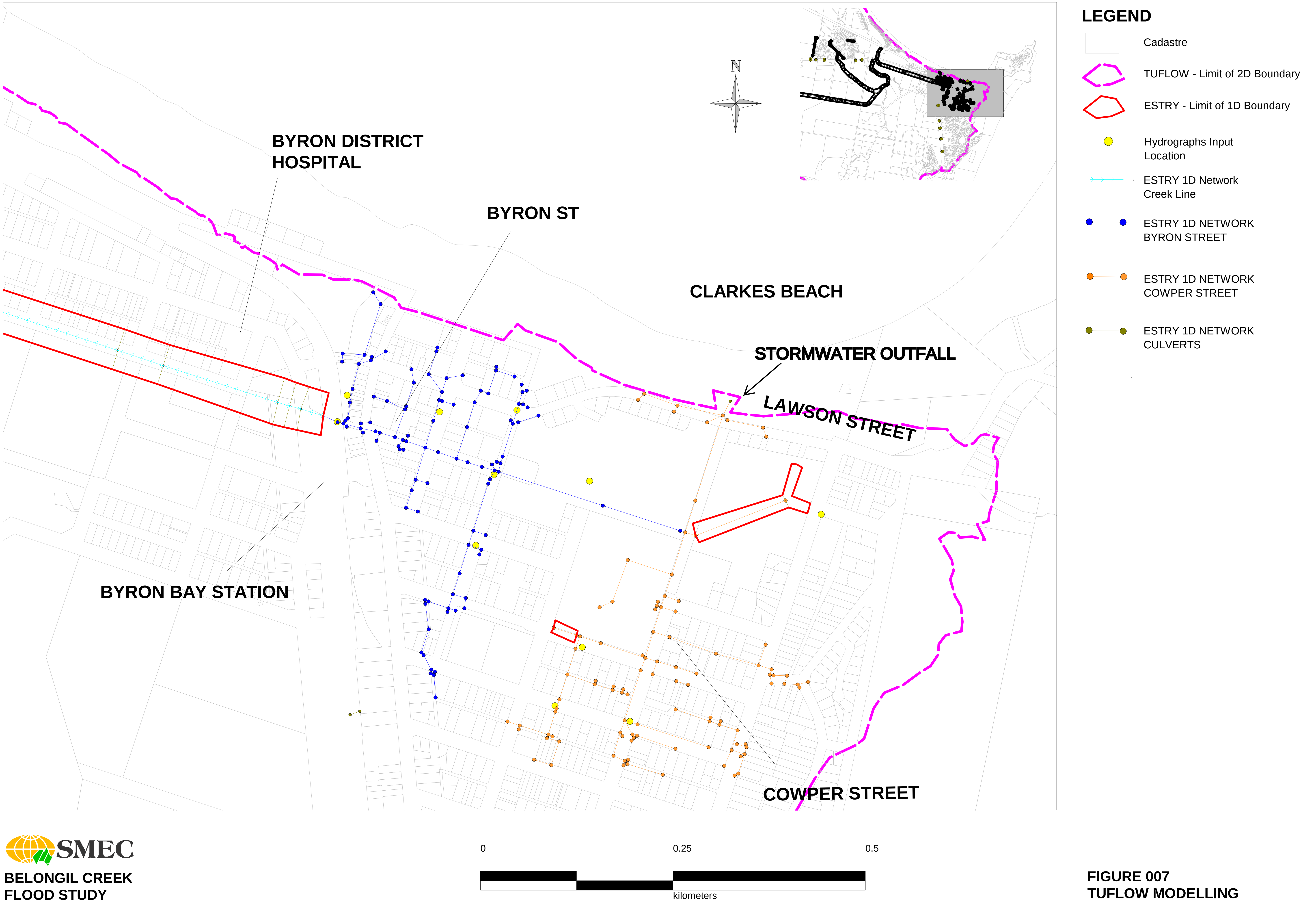
BELONGIL CREEK FLOOD STUDY

FIGURE 006
TUFLOW MODELLING
MODEL STRUCTURE OVERVIEW



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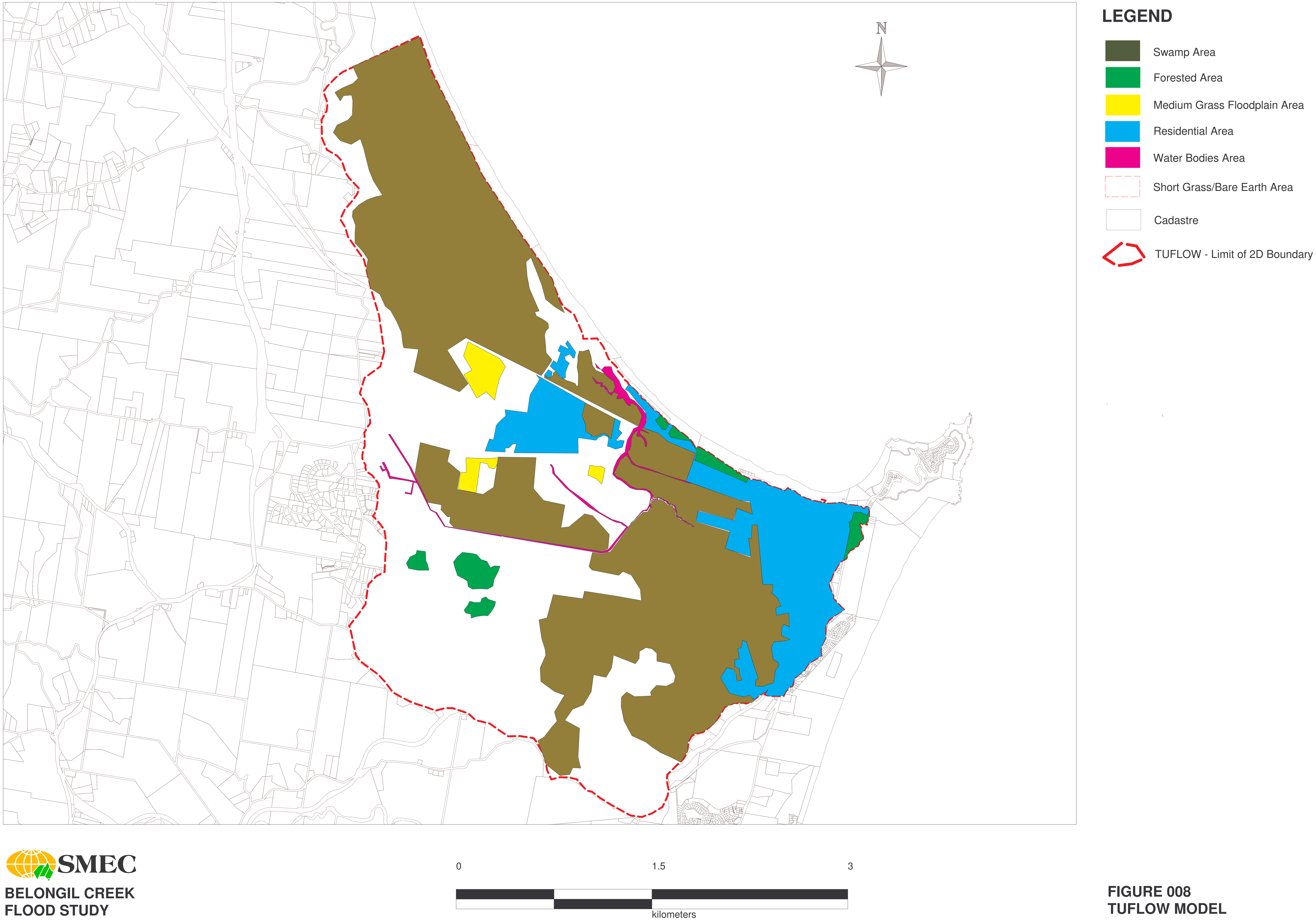
BELONGIL CREEK
FLOOD STUDY

FIGURE 007
TUFLOW MODELLING
TOWN MODEL STRUCTURE



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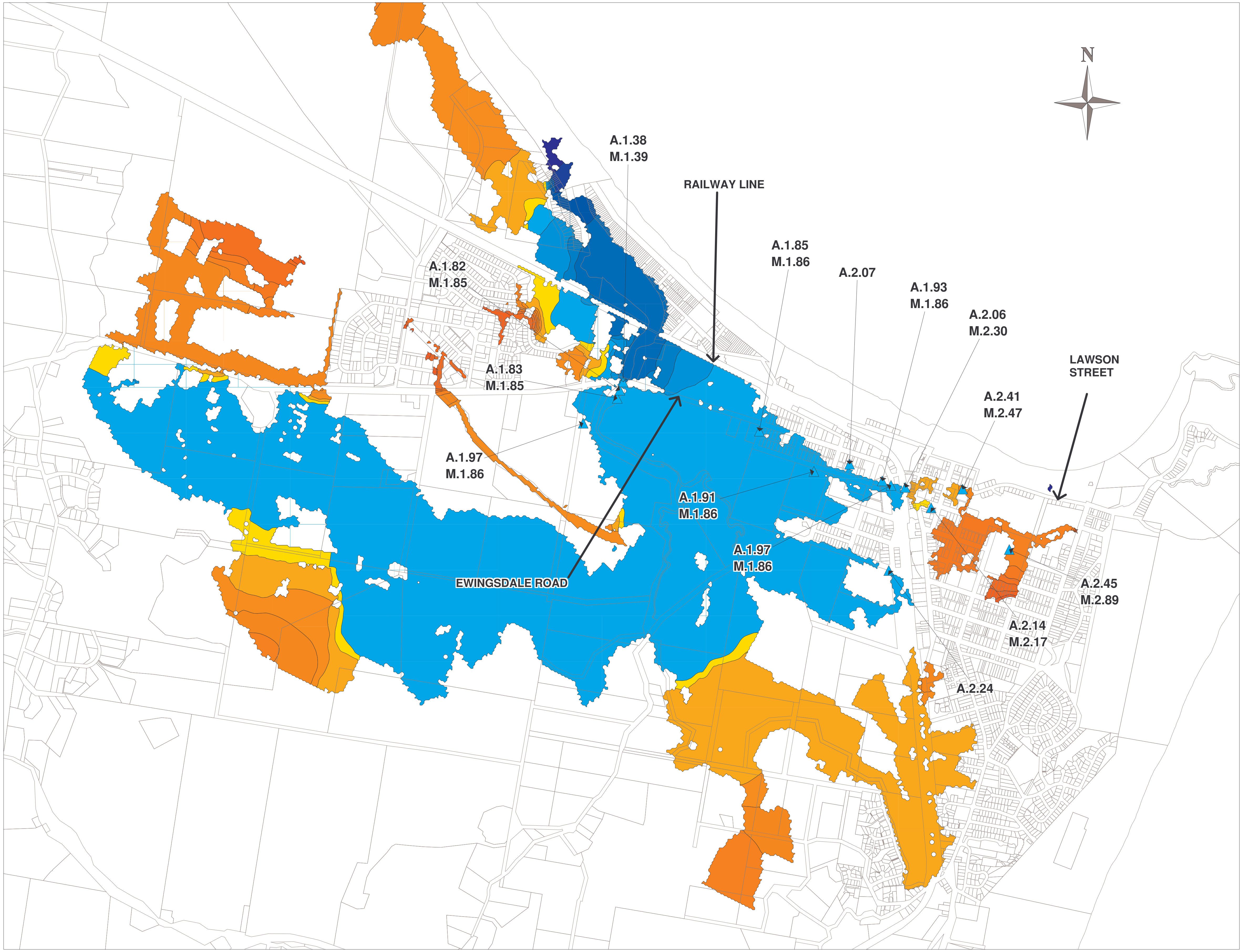
BELONGIL CREEK
FLOOD STUDY

FIGURE 008
TUFLOW MODEL
LAND USE MODELING



FLOOD LEVEL LEGEND (RL in metres AHD)

- 0.6000 to 0.8000
- 0.8000 to 1.0000
- 1.0000 to 1.2000
- 1.2000 to 1.4000
- 1.4000 to 1.6000
- 1.6000 to 1.8000
- 1.8000 to 2.0000
- 2.0000 to 2.2000
- 2.2000 to 2.4000
- 2.4000 to 2.6000
- 2.6000 to 2.8000
- 2.8000 to 3.0000
- 3.0000 to 3.2000
- 3.2000 to 3.4000
- 3.4000 to 3.6000
- 3.6000 to 3.8000
- 3.8000 to 4.0000

LEGEND

- A.1.97 — Observed Flood Level - 1974 (RL in m AHD)
- M.1.86 — Modelled Flood Level - 1974 (RL in m AHD)
- Cadastre

0 0.3 0.6

kilometers

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BELONGIL CREEK
FLOOD STUDY

FIGURE 009
TUFLOW MODELLING
1974 CALIBRATION RESULT
FLOOD EXTENT MAP

FLOOD LEVEL LEGEND (RL in metres AHD)

- 0.0000 to 1.2000
- 1.2000 to 1.4000
- 1.4000 to 1.6000
- 1.6000 to 1.8000
- 1.8000 to 2.0000
- 2.0000 to 2.2000
- 2.2000 to 2.4000
- 2.4000 to 2.6000
- 2.6000 to 2.8000
- 2.8000 to 3.0000
- 3.0000 to 3.2000
- 3.2000 to 3.4000
- 3.4000 to 3.6000
- 3.6000 to 3.8000
- 3.8000 to 5.0000

LEGEND

- A.1.74 — Observed Flood Level - 1984 (RL in m AHD)
- M.1.72 — Modelled Flood Level - 1984 (RL in m AHD)
- Cadastre

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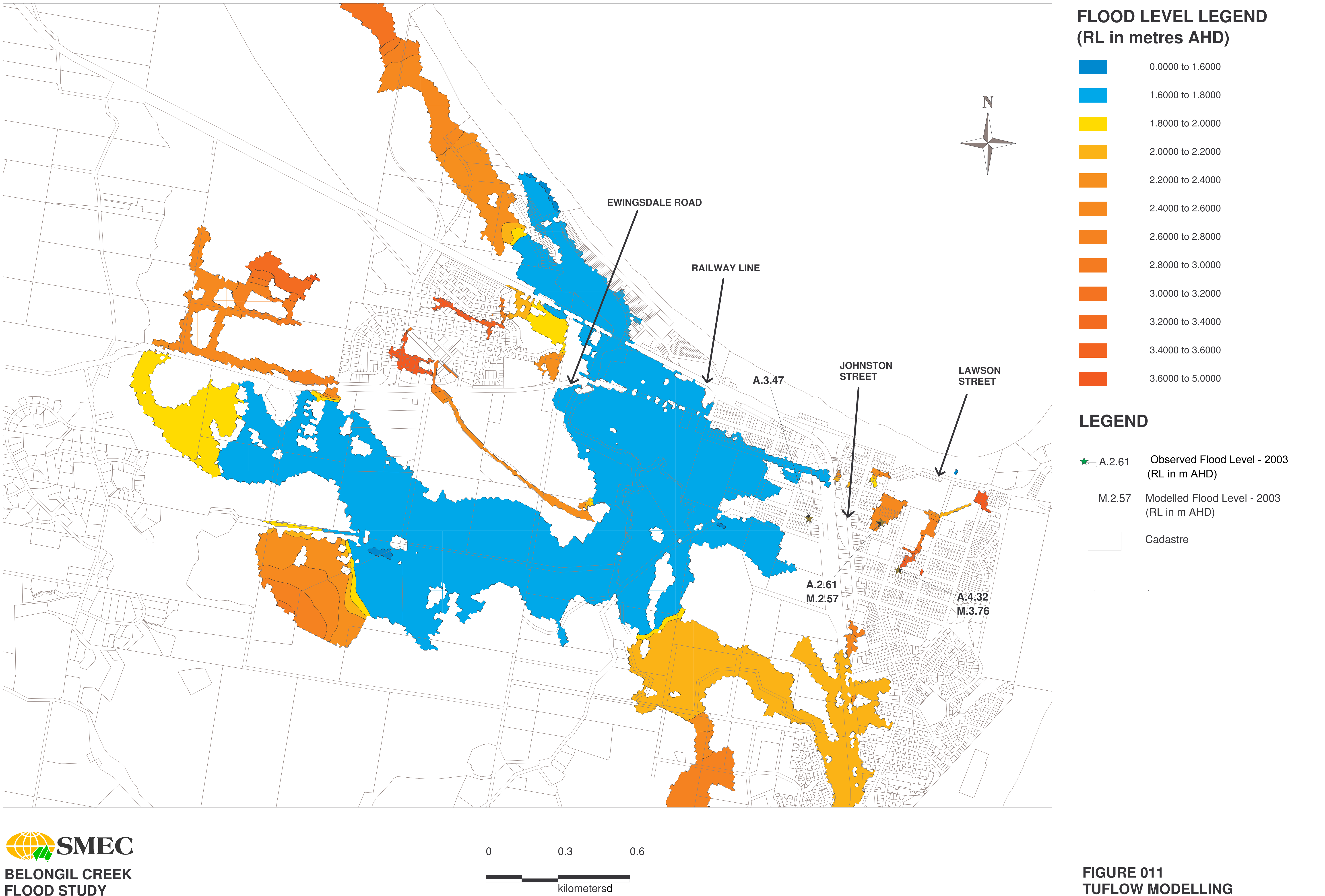
BELONGIL CREEK
FLOOD STUDY

FIGURE 010
TUFLOW MODELLING
1984 CALIBRATION RESULT
FLOOD EXTENT MAP



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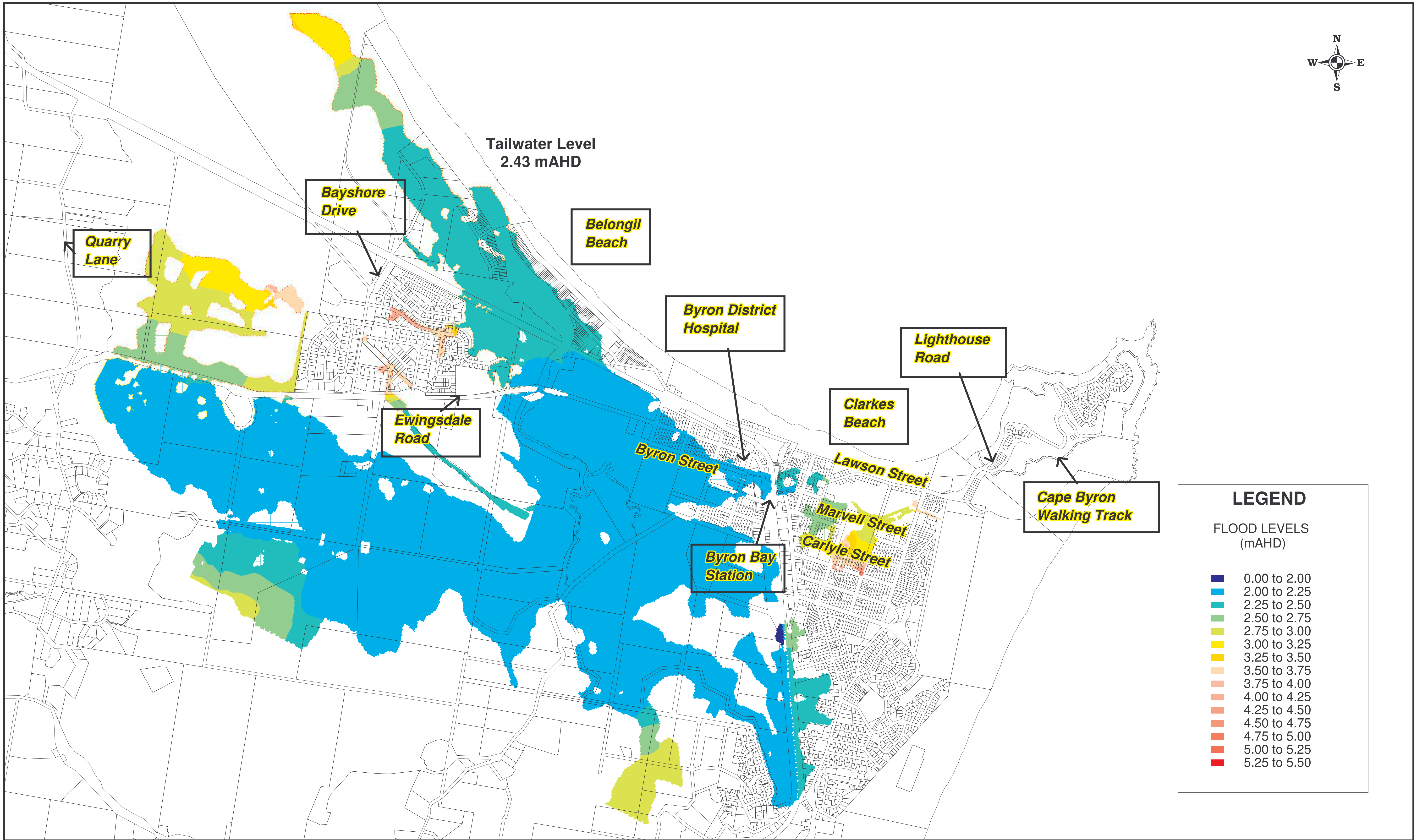
BELONGIL CREEK FLOOD STUDY

FIGURE 011
TUFLOW MODELLING
2003 CALIBRATION RESULT
FLOOD EXTENT MAP



For

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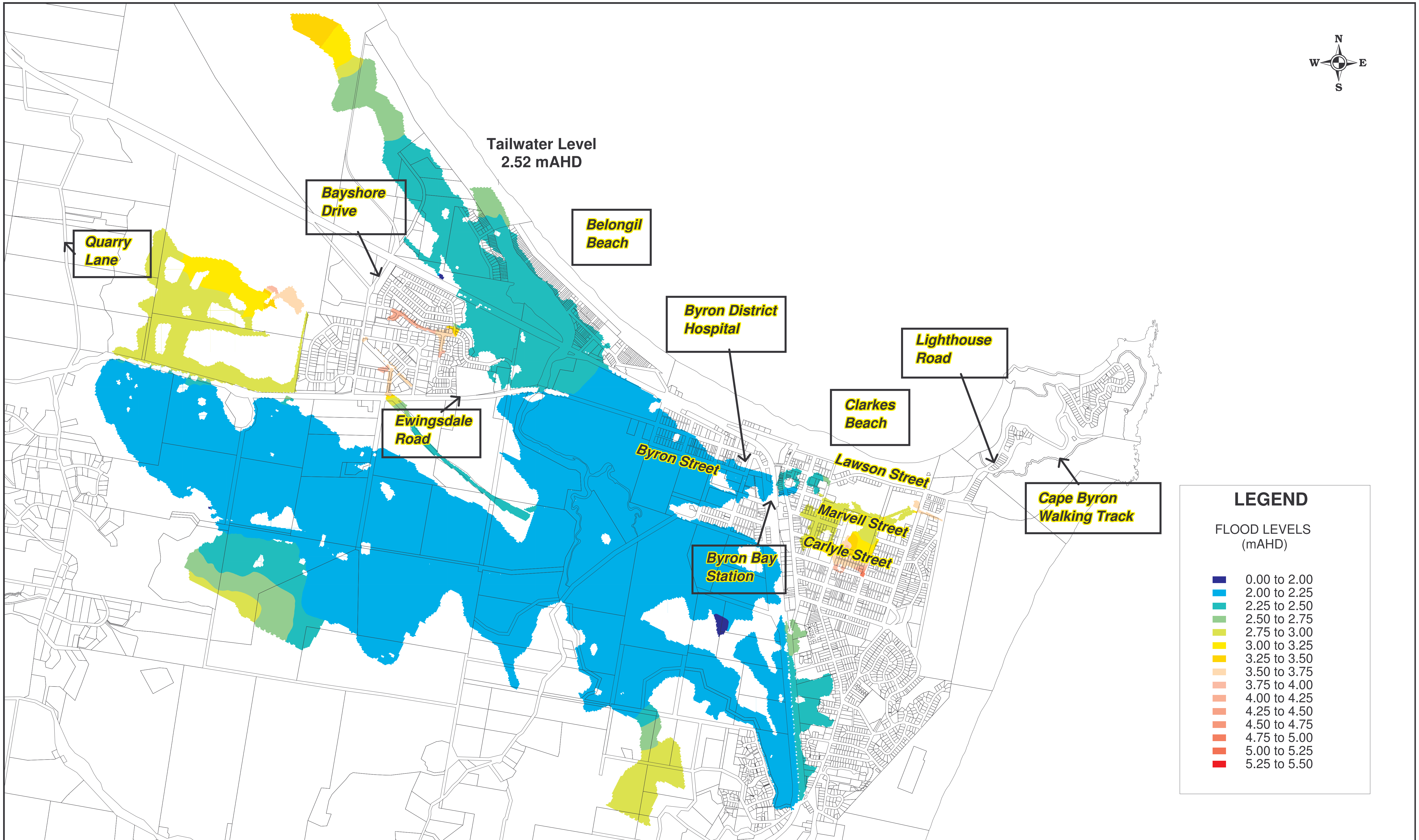
Project Title: **Belongil Creek Flood Study**

Figure 012: **5 year ARI Flood Levels, Existing Topography BSC Climate Change Scenario 2**

0.2 0 0.2 0.4 0.6
Kilometres
A3 Scale: 1:25,000

Project No. 3001041



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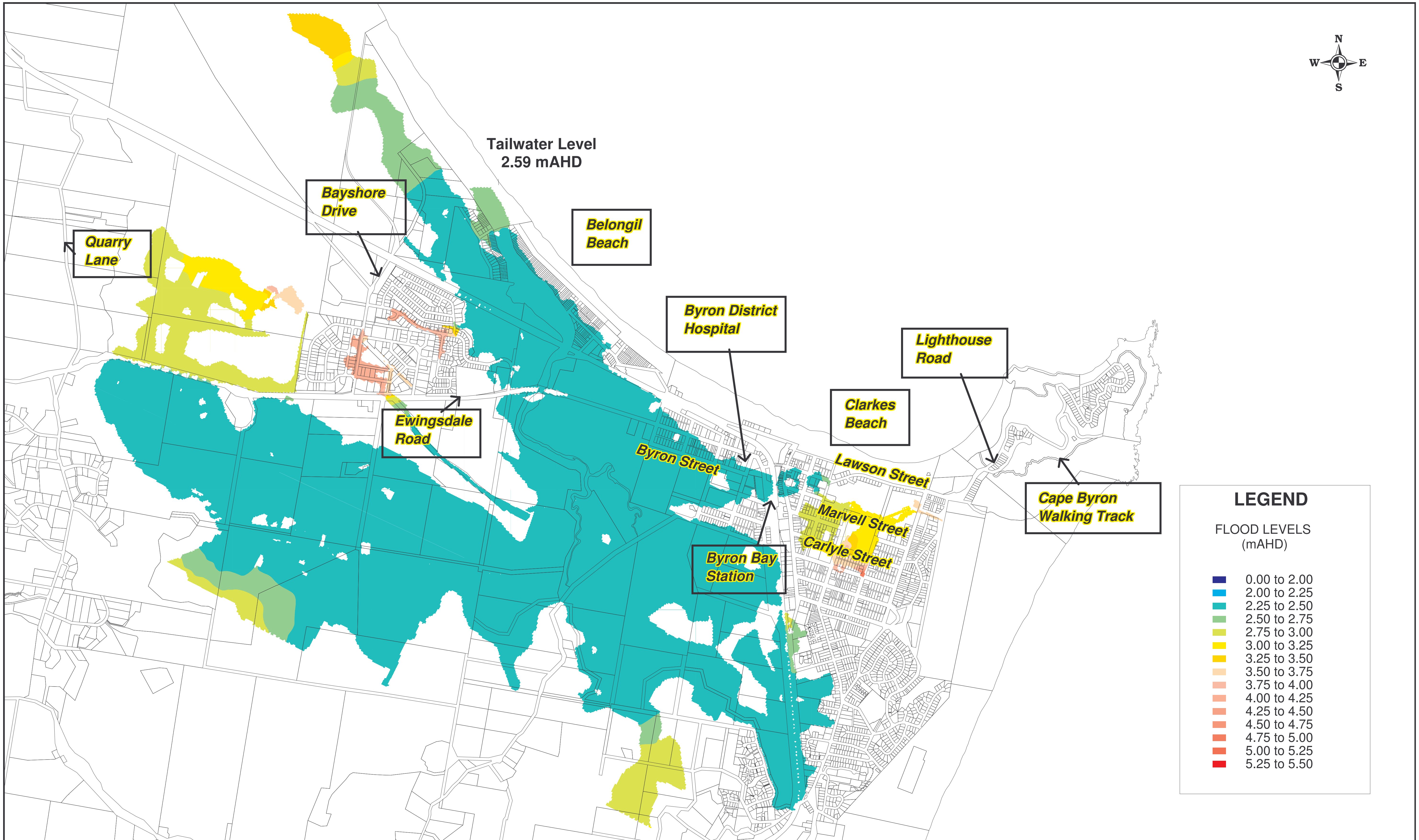
Project Title	**Belongil Creek Flood Study**
Figure 013	**10 year ARI Flood Levels, Existing Topography BSC Climate Change Scenario 2**
0.2 0 0.2 0.4 0.6 Kilometres A3 Scale: 1:25,000	Project No. 3001041



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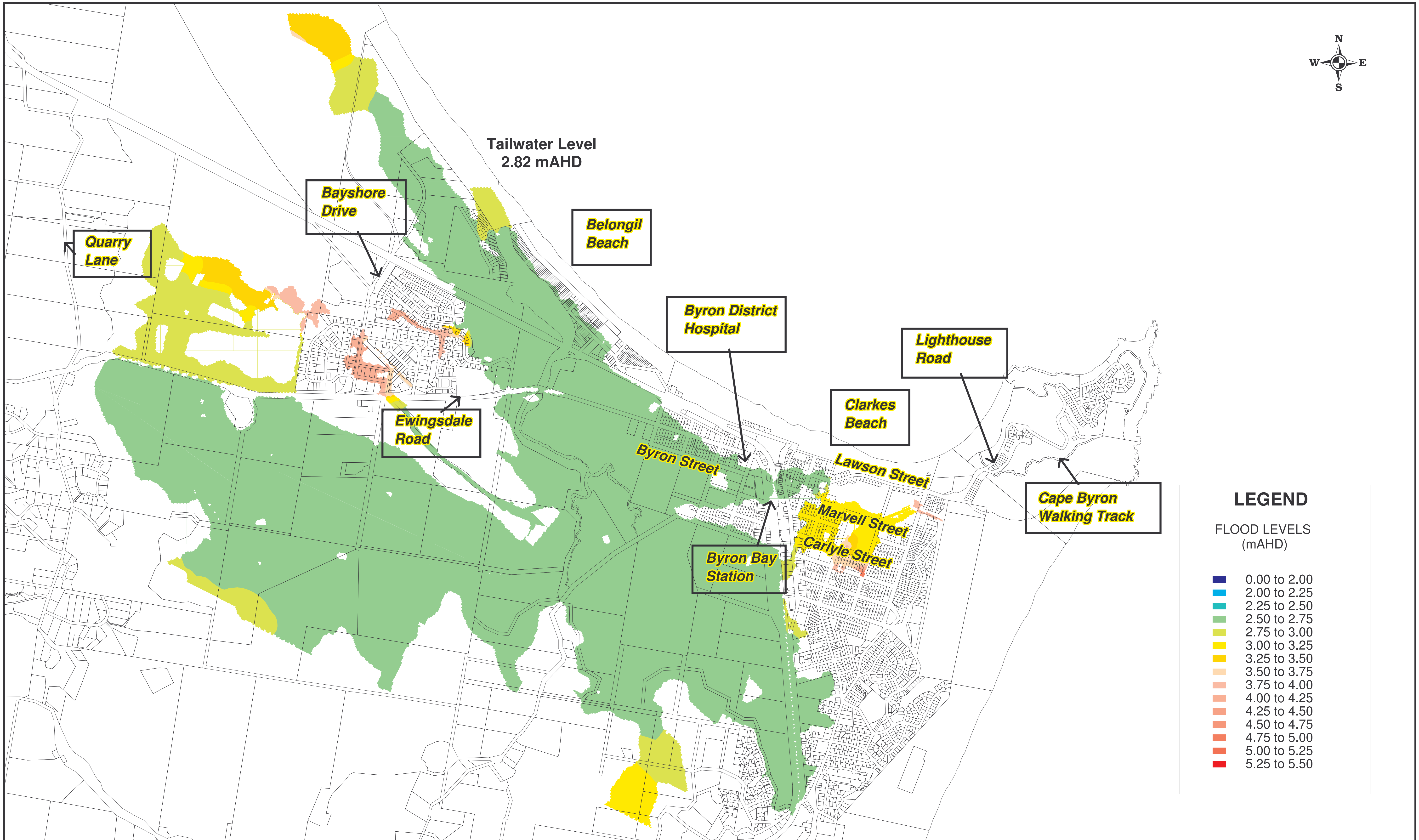
Project Title: **Belongil Creek Flood Study**

Figure 014 **20 year ARI Flood Levels, Existing Topography BSC Climate Change Scenario 2**

0.2 0 0.2 0.4 0.6
Kilometres
A3 Scale: 1:25,000

Project No. **3001041**



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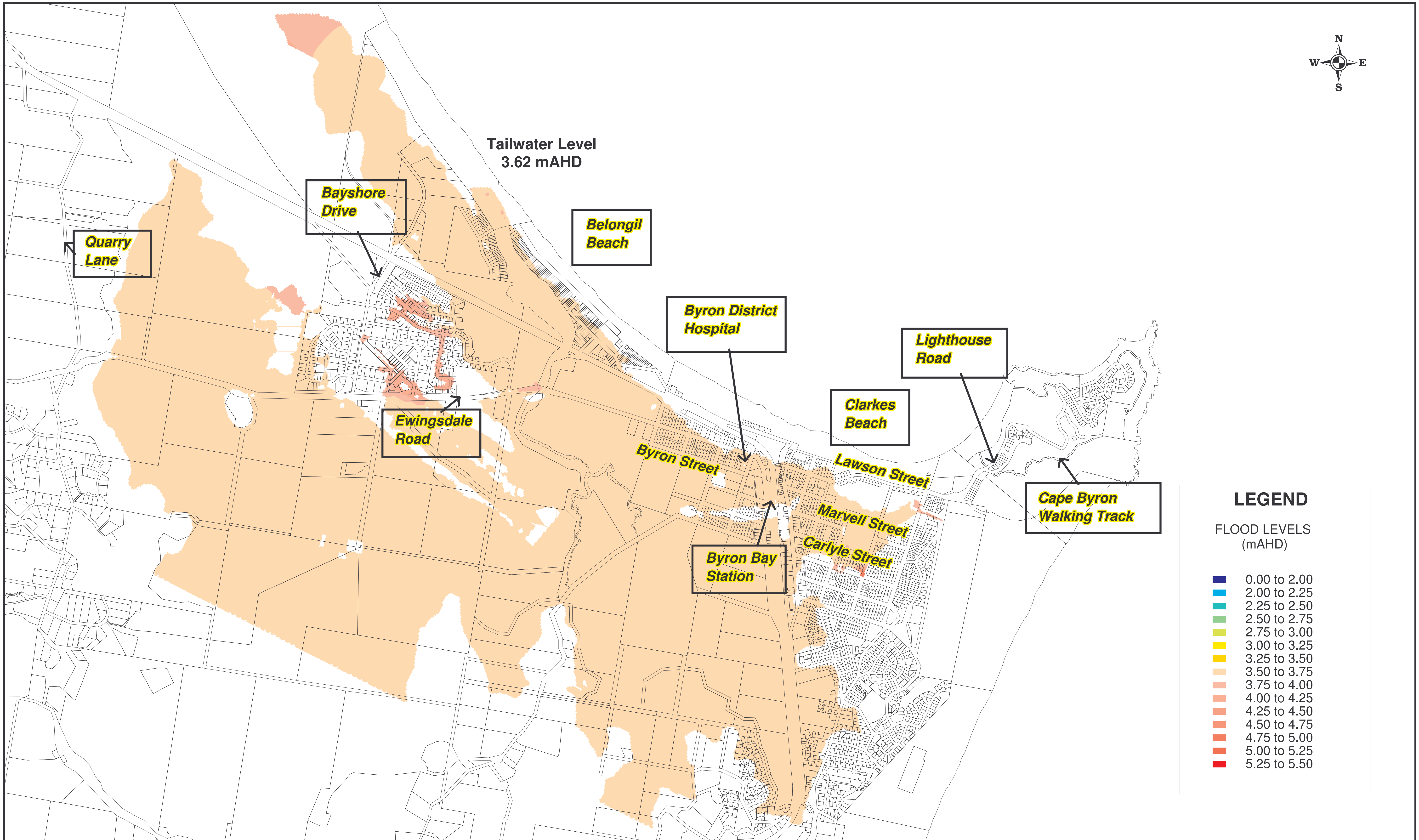
Project Title: **Belongil Creek Flood Study**

Figure 015 **100 year ARI Flood Levels, Existing Topography BSC Climate Change Scenario 2**

0.2 0 0.2 0.4 0.6
Kilometres
A3 Scale: 1:25,000

Project No. **3001041**



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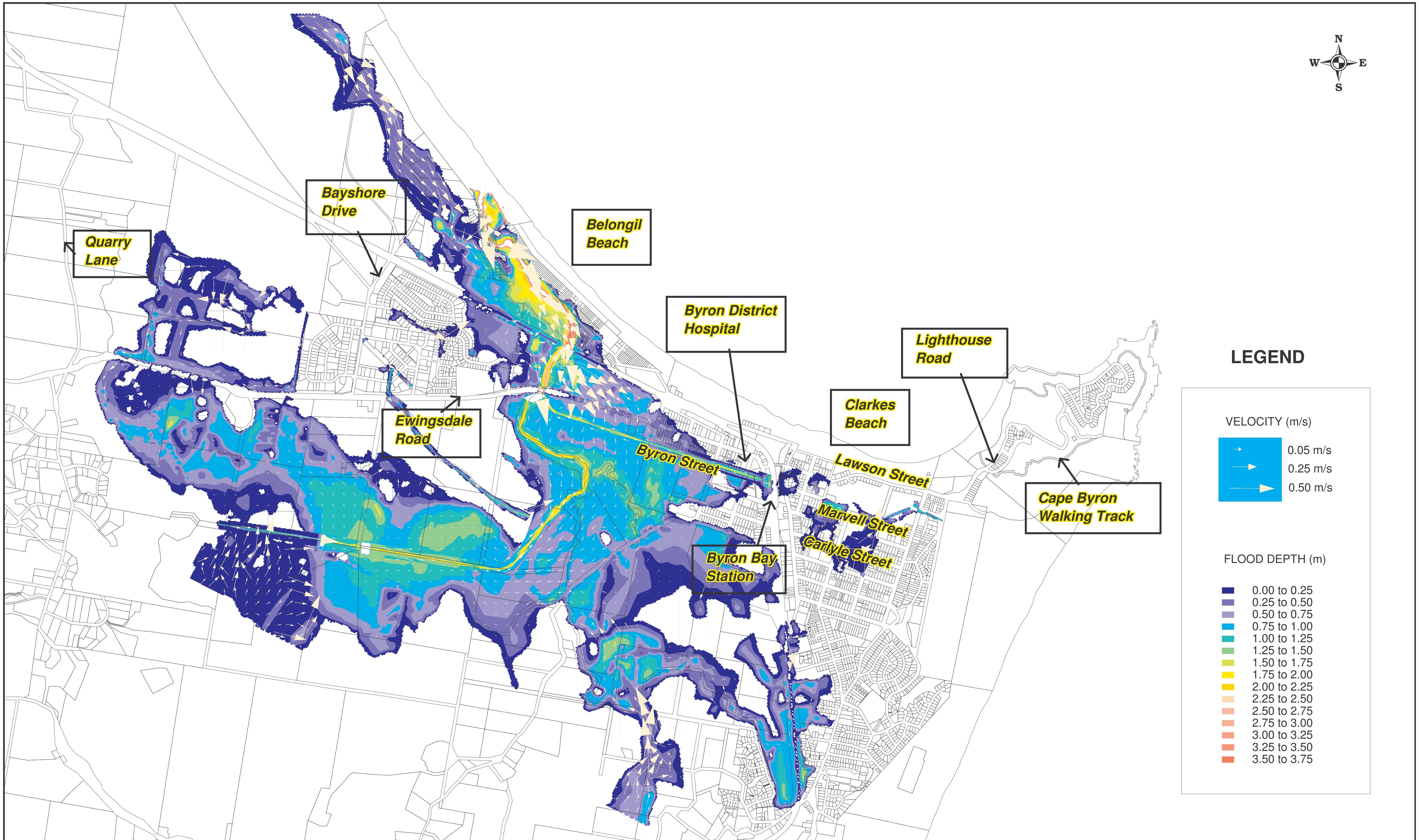
Project Title	**Belongil Creek Flood Study**
Figure 016	**PMF Flood Levels, Existing Topography BSC Climate Change Scenario 4**
0.2 0 0.2 0.4 0.6 Kilometres A3 Scale: 1:25,000	Project No. **3001041**



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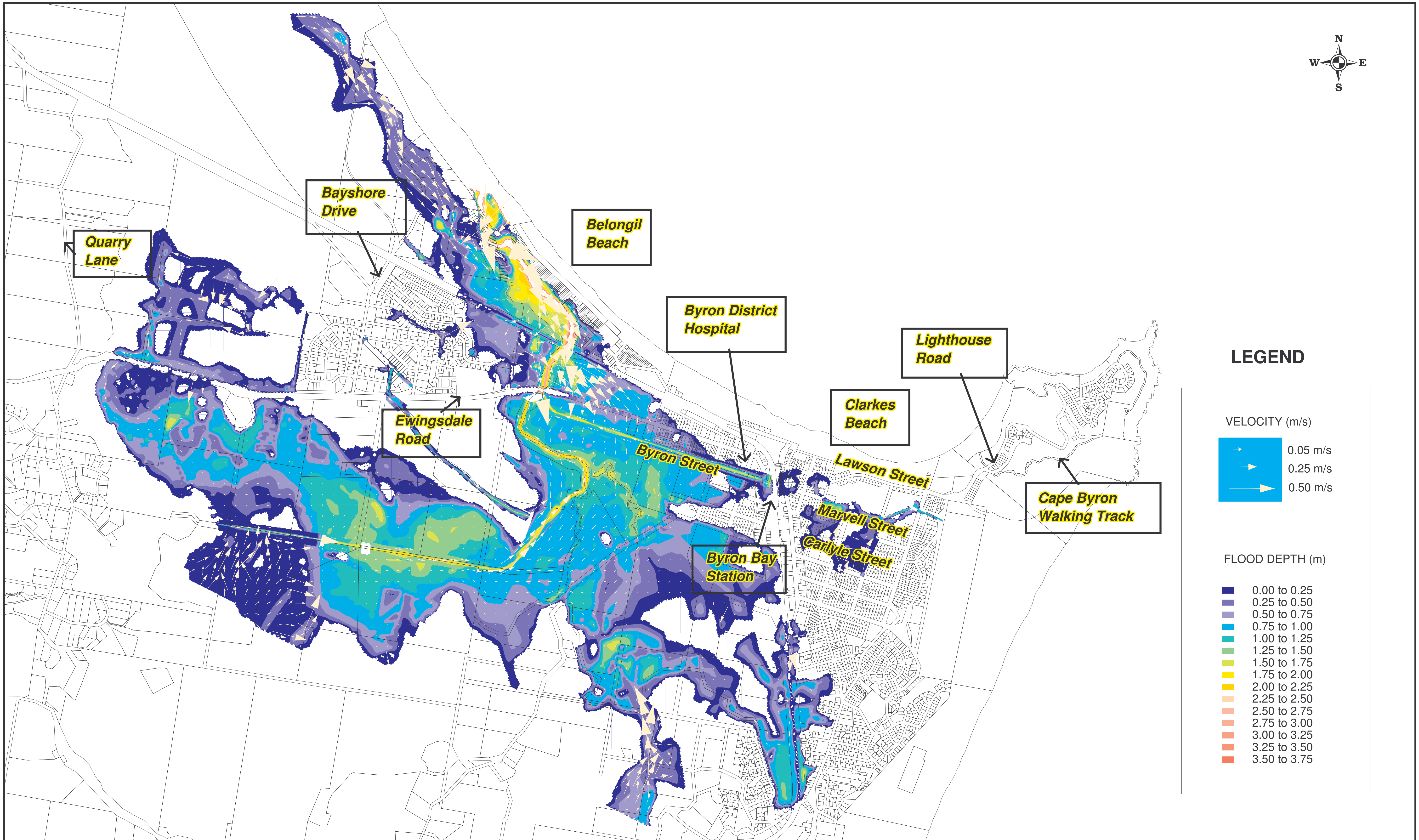
Project Title	**Belongil Creek Flood Study**
Figure 017	**5 year ARI Velocity-Depths, Existing Topography BSC Climate Change Scenario 2**
0.2 0 0.2 0.4 0.6 Kilometres A3 Scale: 1:25,000	Project No. **3001041**



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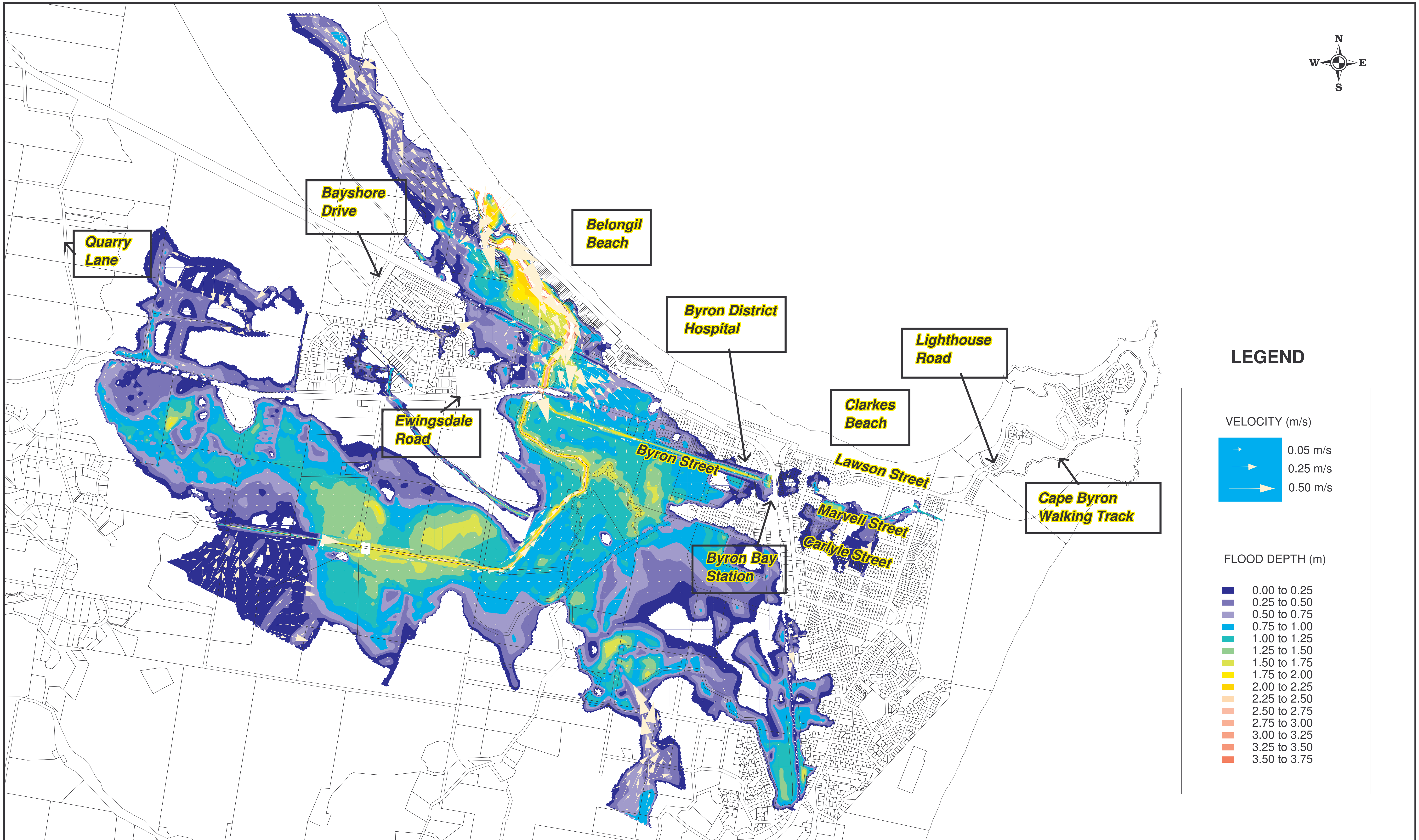
Project Title **Belongil Creek Flood Study**

Figure 018 **10 year ARI Velocity-Depths, Existing Topography BSC Climate Change Scenario 2**

0.2 0 0.2 0.4 0.6
Kilometres
A3 Scale: 1:25,000

Project No. **3001041**



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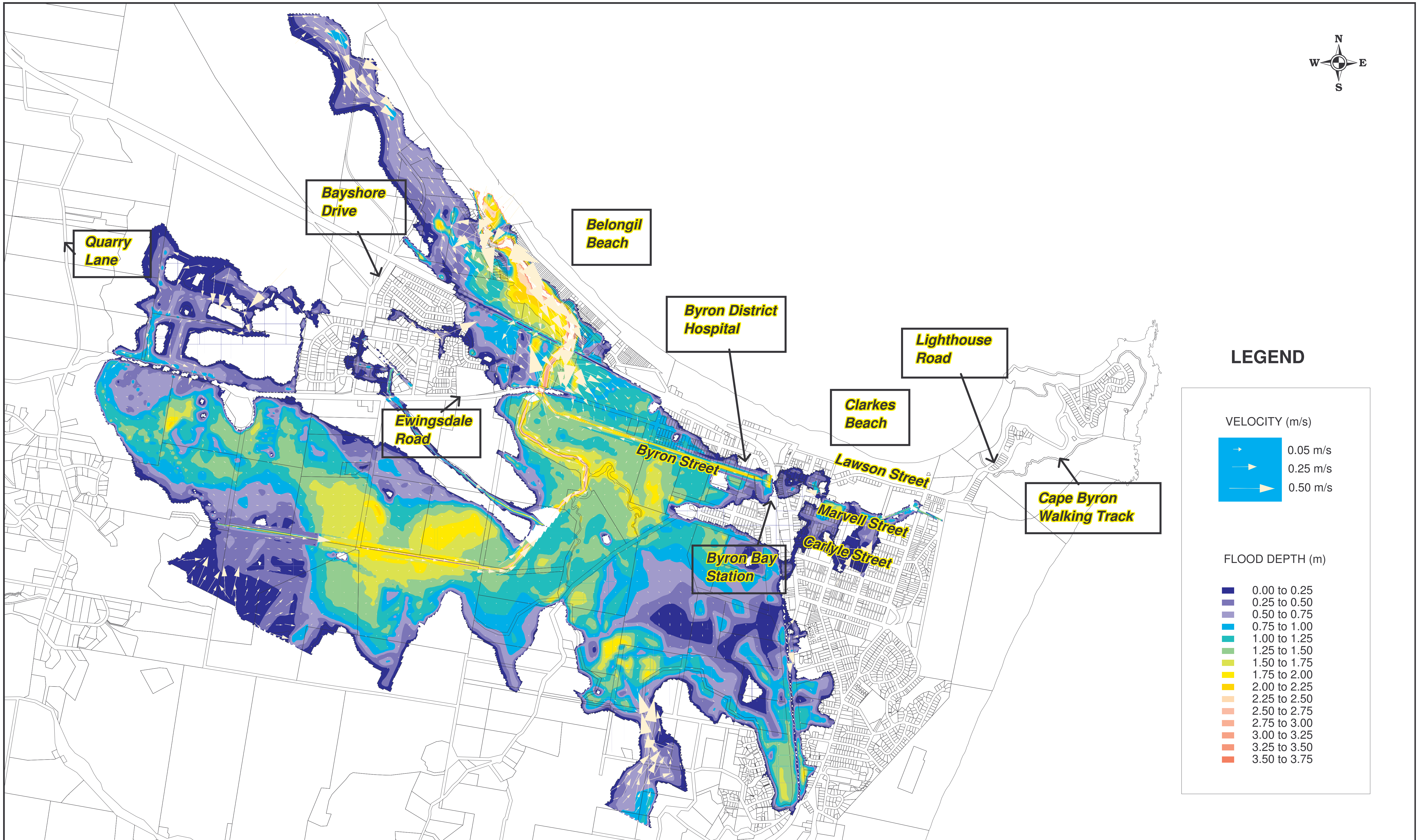
Project Title **Belongil Creek Flood Study**

Figure 019 **20 year ARI Velocity-Depths, Existing Topography BSC Climate Change Scenario 2**

0.2 0 0.2 0.4 0.6
Kilometres
A3 Scale: 1:25,000

Project No. **3001041**



For

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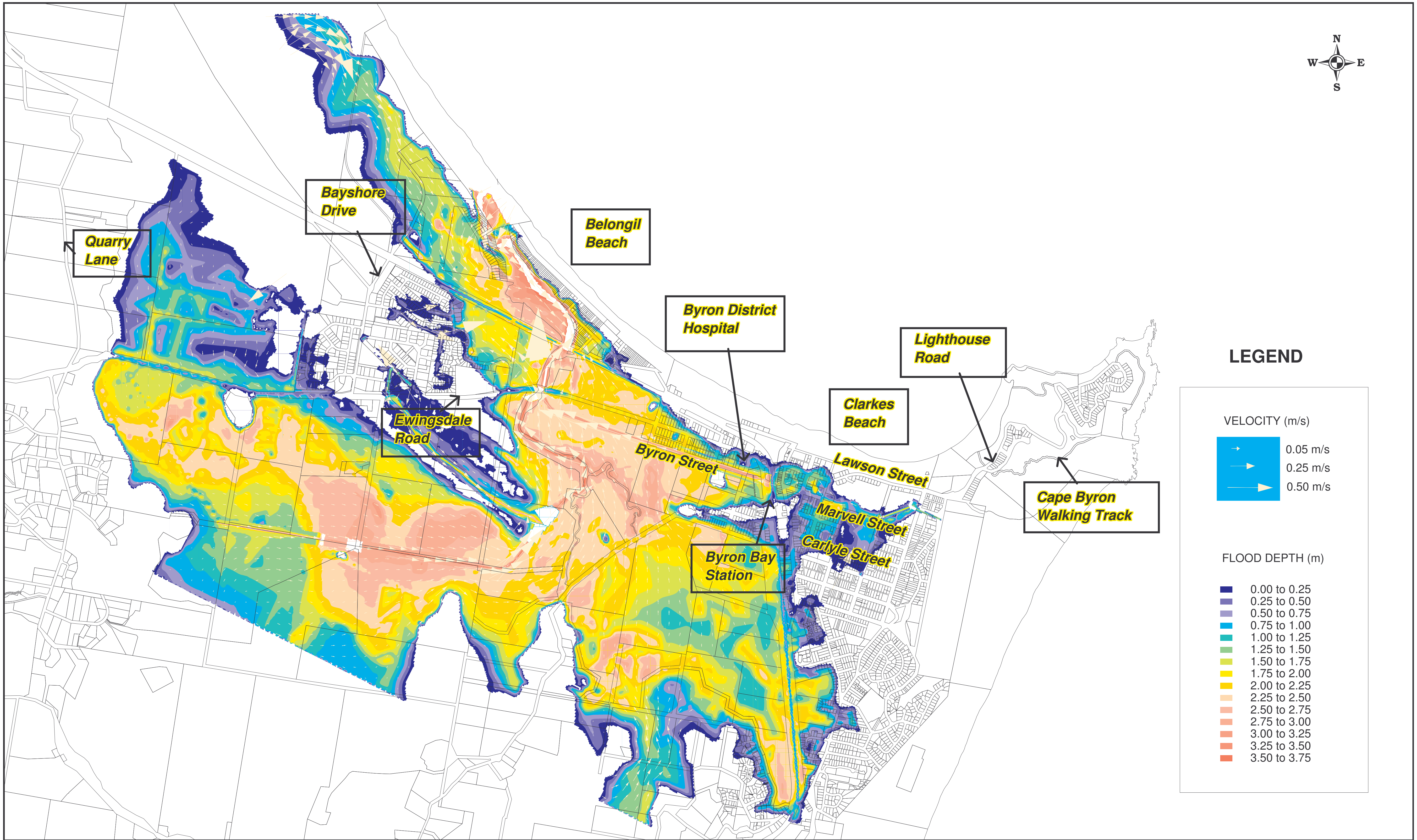
Project Title **Belongil Creek Flood Study**

Figure 020 **100 year ARI Velocity-Depths, Existing Topography BSC Climate Change Scenario 2**

0.2 0 0.2 0.4 0.6
Kilometres
A3 Scale: 1:25,000

Project No. **3001041**



For

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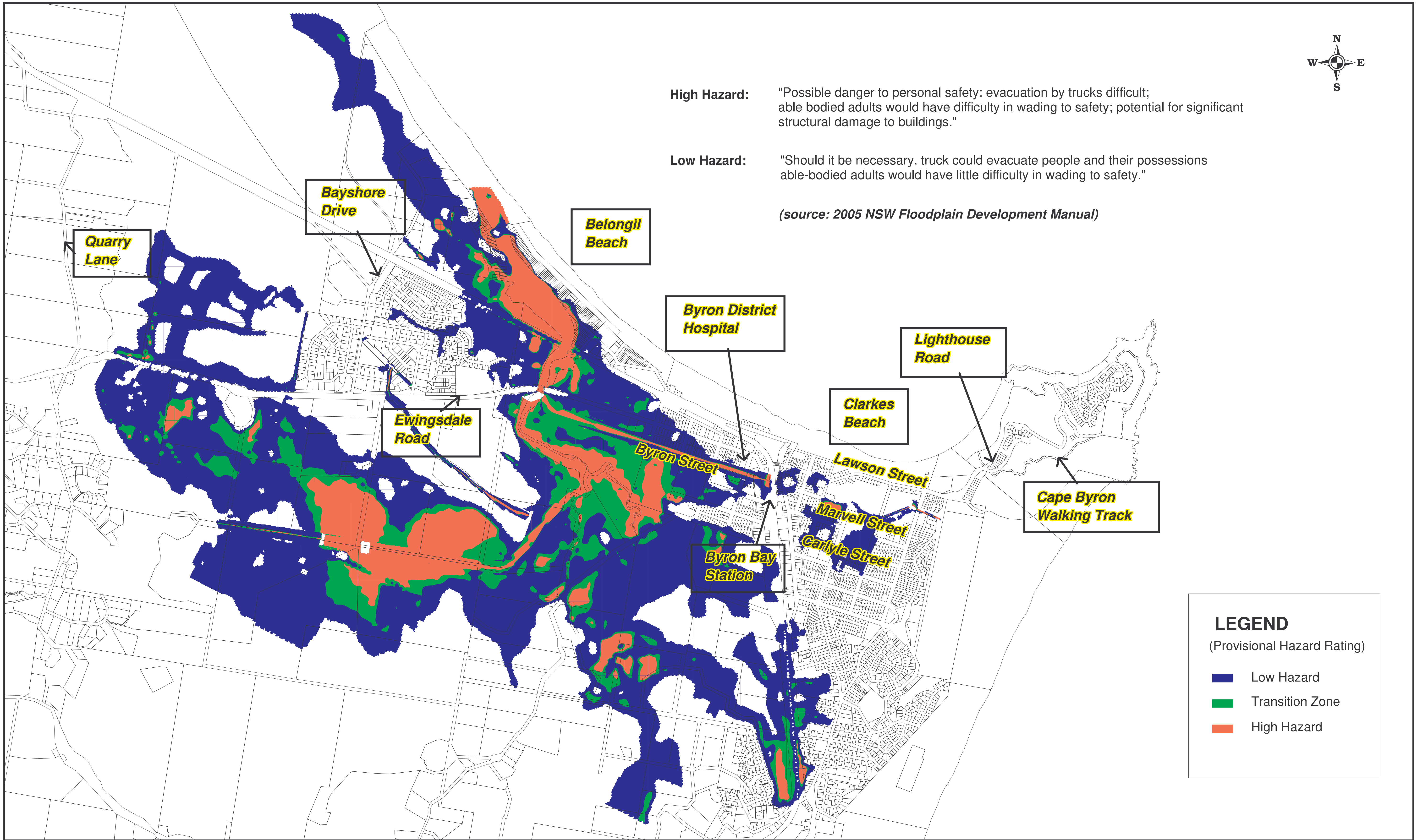
Project Title	Belongil Creek Flood Study
Figure 021	PMF Velocity-Depths, Existing Topography BSC Climate Change Scenario 4
0.2 0 0.2 0.4 0.6 Kilometres A3 Scale: 1:25,000	Project No. 3001041



For

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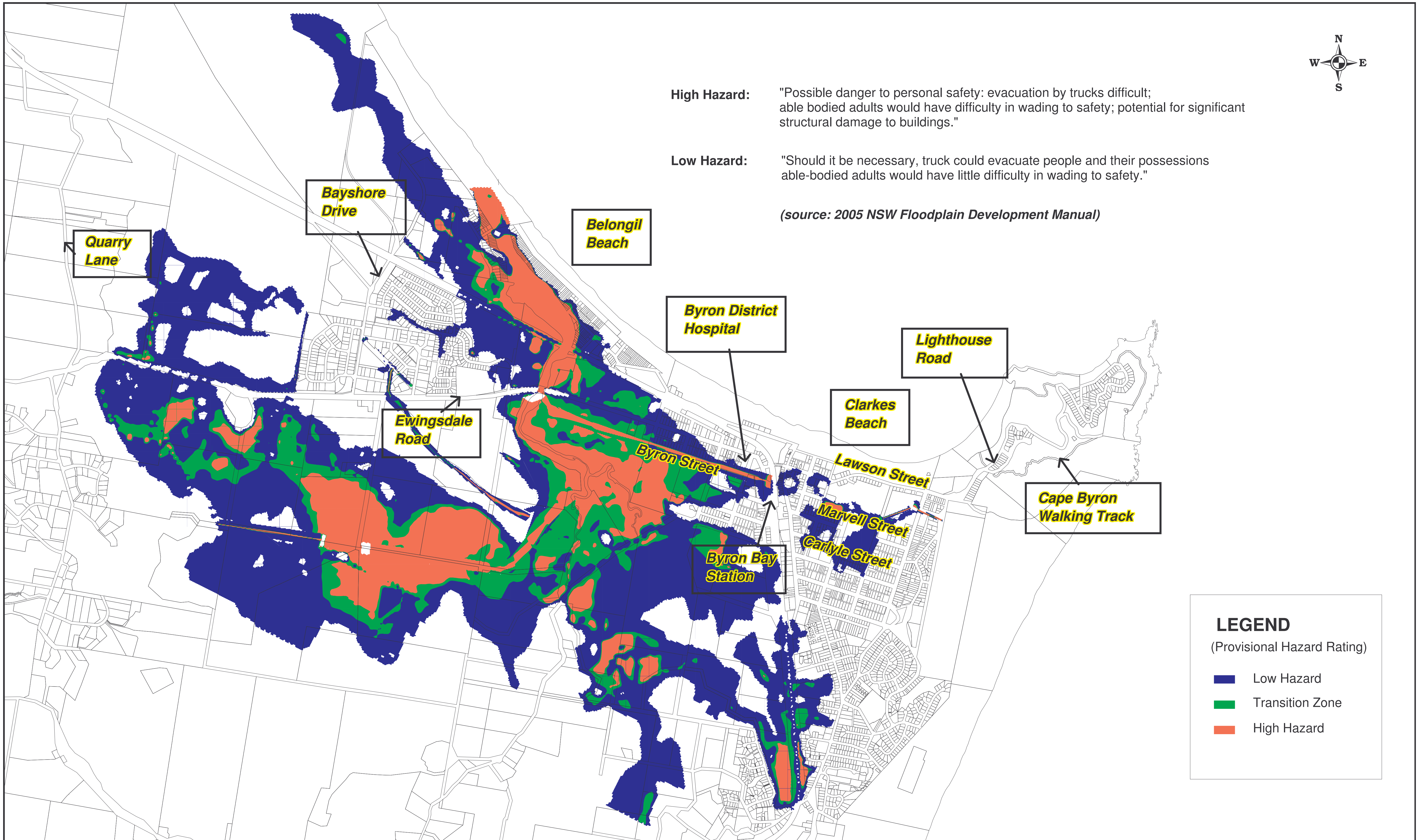
Project Title	**Belongil Creek Flood Study**
Figure 022	**5 year ARI Provisional Hazard Map** **Existing Topography** **BSC Climate Change Scenario 2**
Project No.	**3001041**



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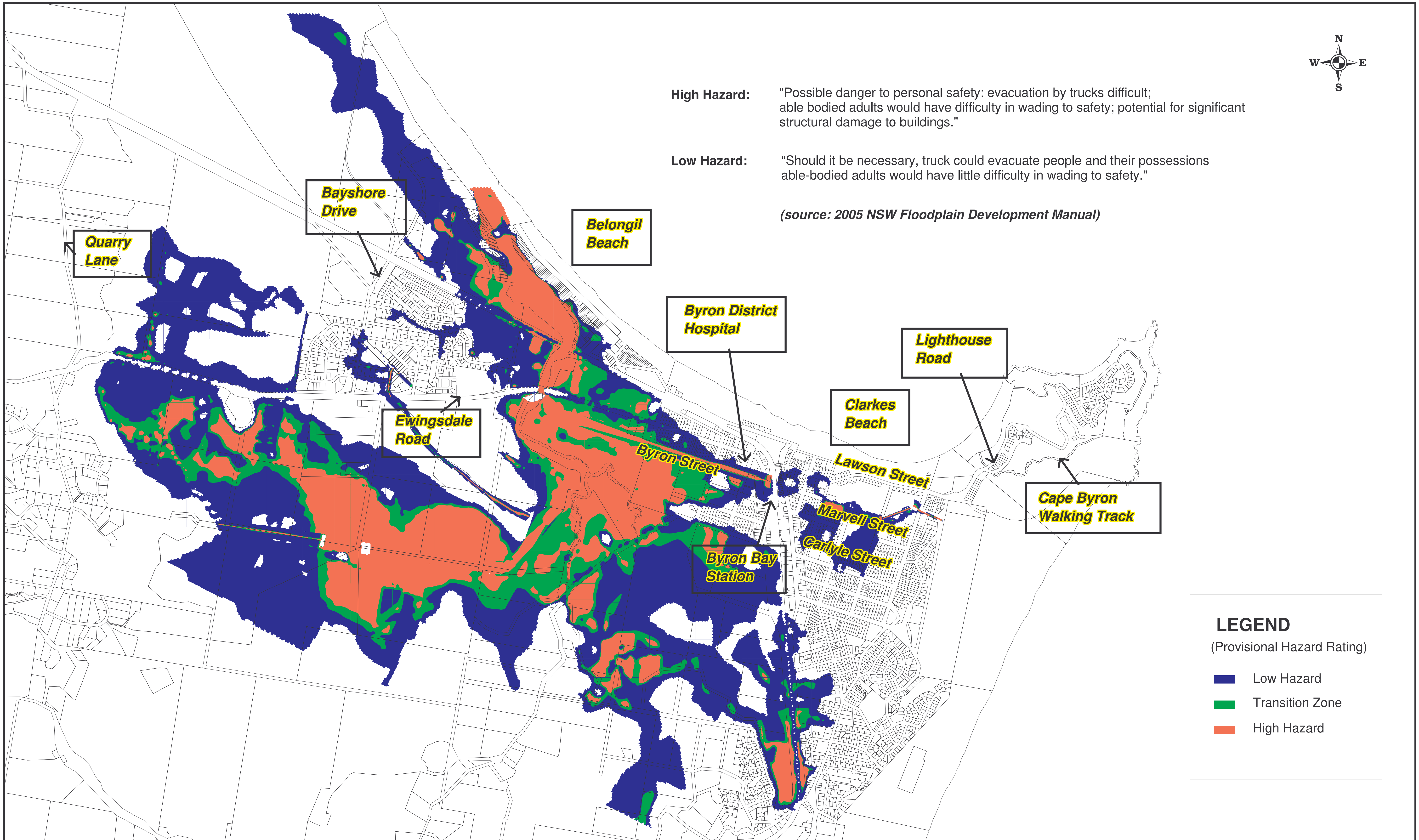
Project Title	**Belongil Creek Flood Study**
Figure 023	**10 year ARI Provisional Hazard Map** **Existing Topography** **BSC Climate Change Scenario 2**
0.2 0 0.2 0.4 0.6 Kilometres A3 Scale: 1:25,000	Project No. **3001041**



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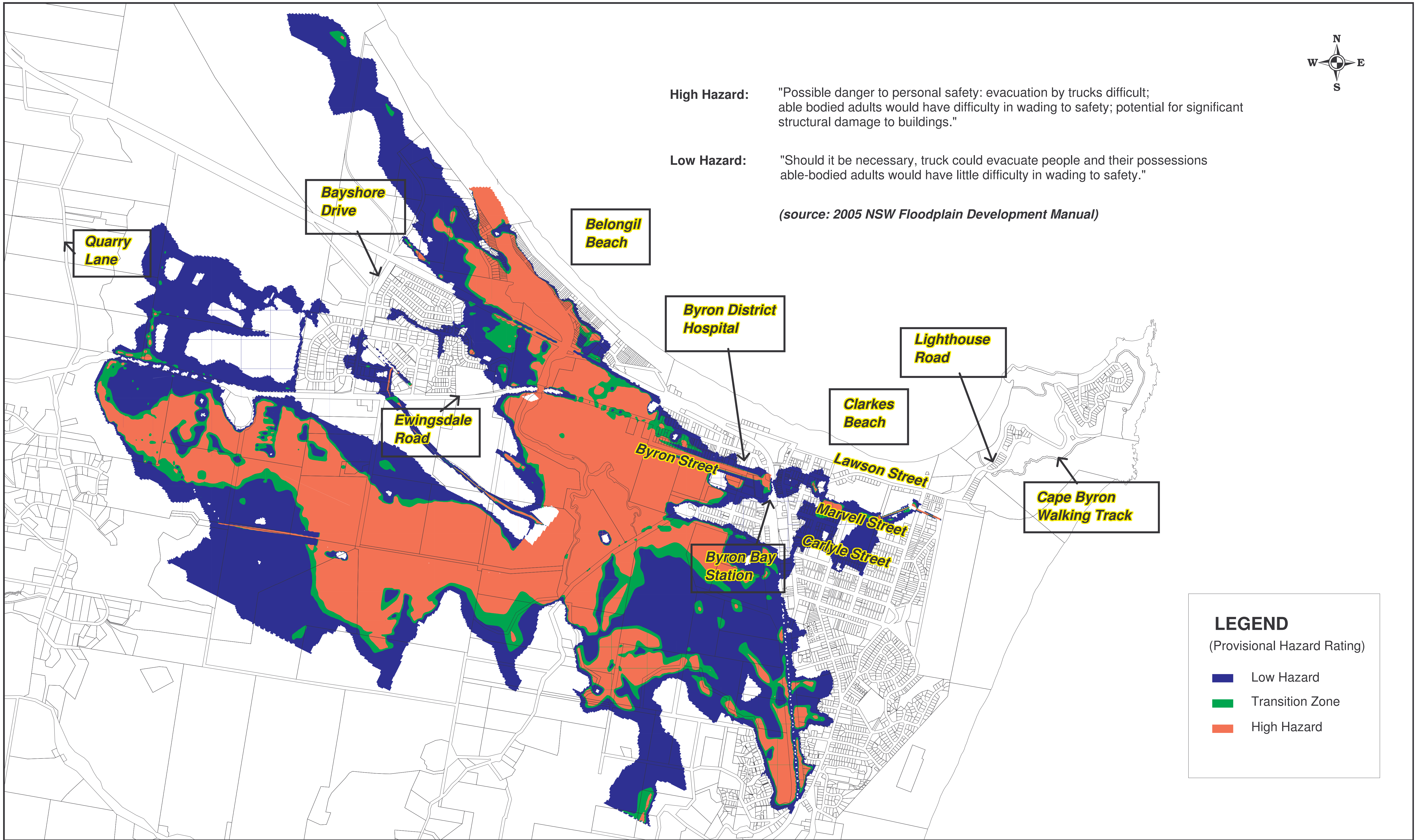
Project Title	**Belongil Creek Flood Study**
Figure 024	**20 year ARI Provisional Hazard Map** **Existing Topography** **BSC Climate Change Scenario 2**
0.2 0 0.2 0.4 0.6 Kilometres A3 Scale: 1:25,000	Project No. **3001041**



For

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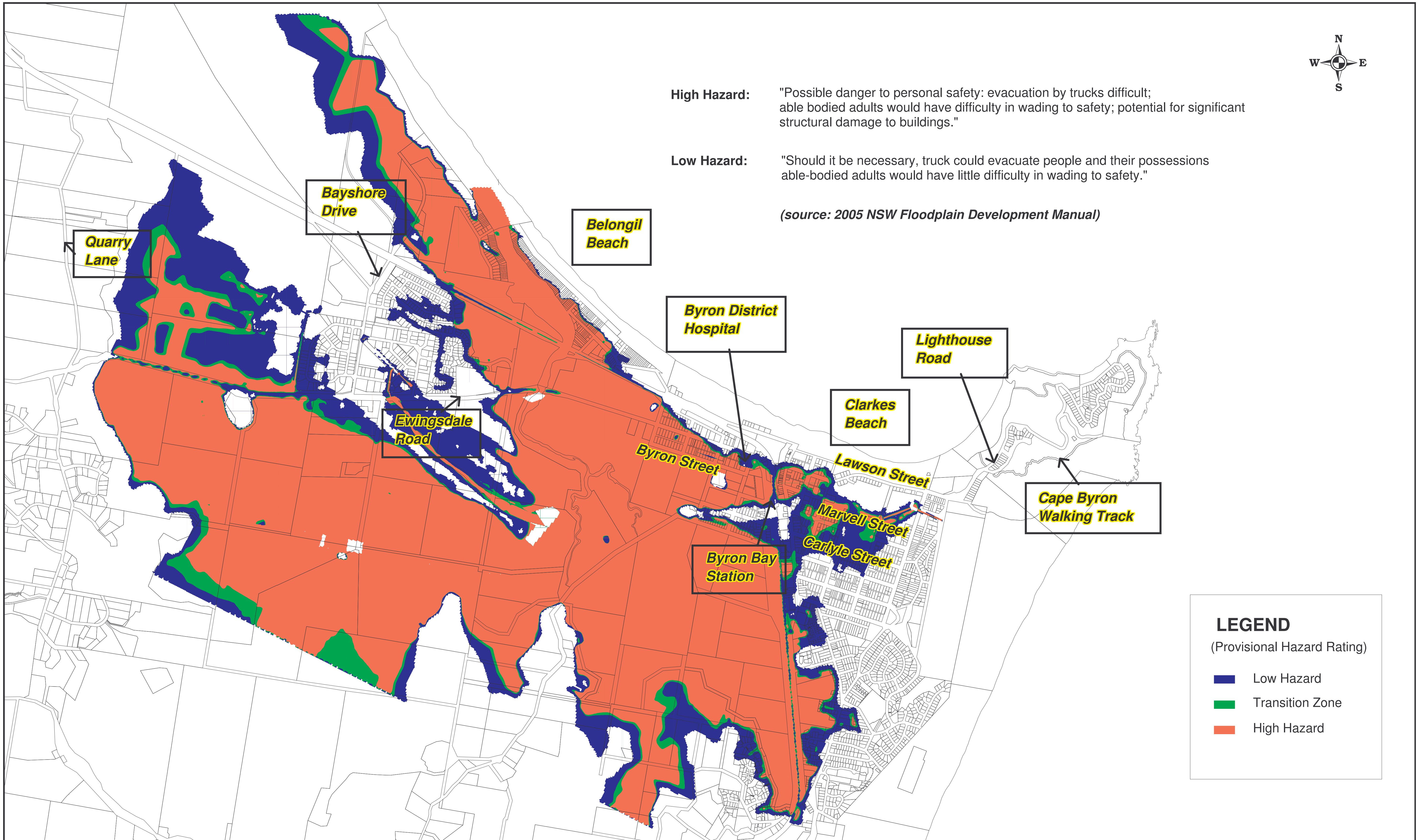
Project Title	**Belongil Creek Flood Study**
Figure 025	**100 year ARI Provisional Hazard Map Existing Topography BSC Climate Change Scenario 2**
0.2 0 0.2 0.4 0.6 Kilometres A3 Scale: 1:25,000	Project No. **3001041**



For

Byron Shire Council

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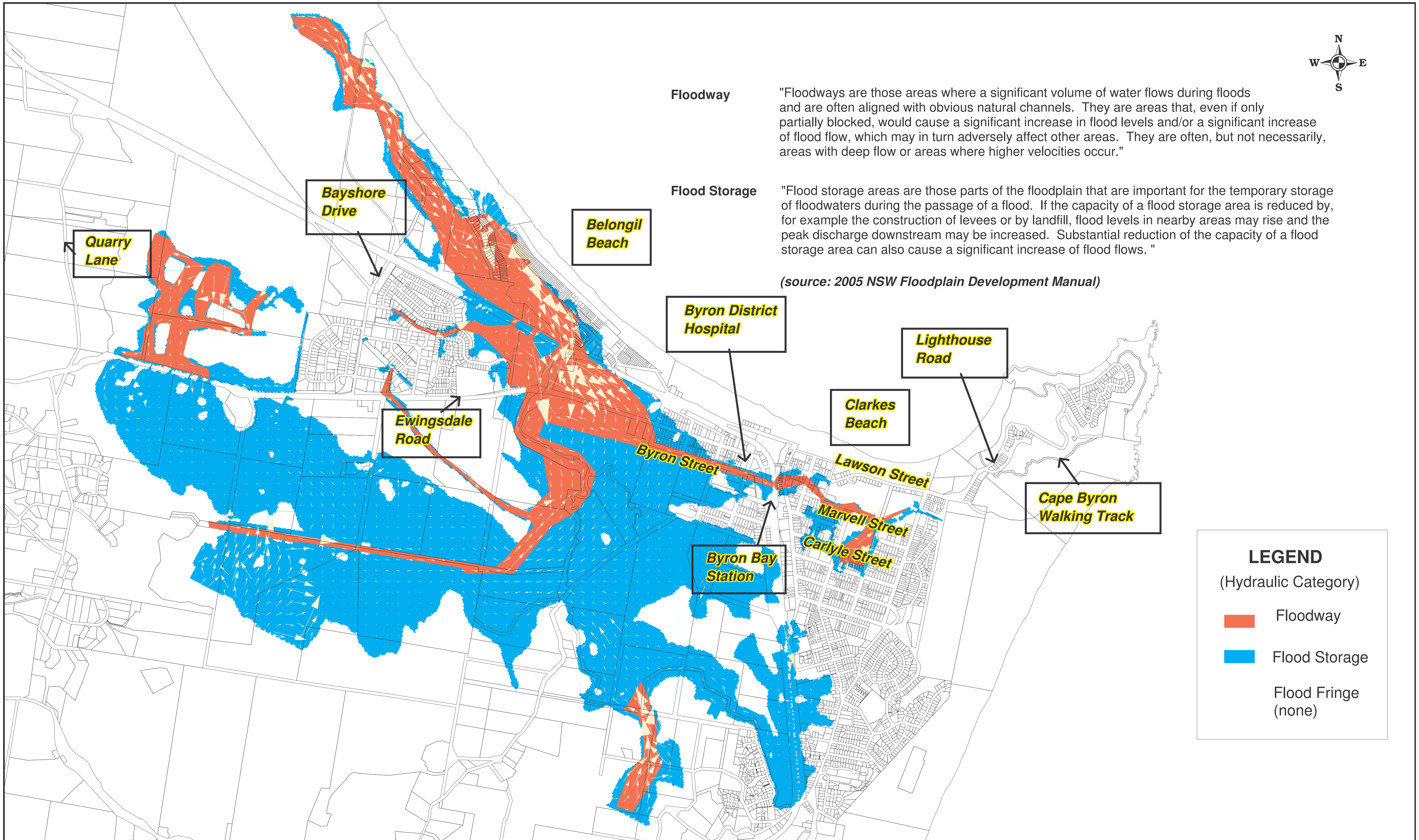
Project Title	**Belongil Creek Flood Study**
Figure 026	**PMF Provisional Hazard Map Existing Topography BSC Climate Change Scenario 4**

0.2 0 0.2 0.4 0.6
Kilometres
A3 Scale: 1:25,000

Project No.
3001041



Floodway "Floodways are those areas where a significant volume of water flows during floods and are often aligned with obvious natural channels. They are areas that, even if only partially blocked, would cause a significant increase in flood levels and/or a significant increase of flood flow, which may in turn adversely affect other areas. They are often, but not necessarily, areas with deep flow or areas where higher velocities occur."

Flood Storage "Flood storage areas are those parts of the floodplain that are important for the temporary storage of floodwaters during the passage of a flood. If the capacity of a flood storage area is reduced by, for example the construction of levees or by landfill, flood levels in nearby areas may rise and the peak discharge downstream may be increased. Substantial reduction of the capacity of a flood storage area can also cause a significant increase of flood flows. "

(source: 2005 NSW Floodplain Development Manual)

LEGEND

(Hydraulic Category)

- Floodway
- Flood Storage
- Flood Fringe (none)

For

Byron Shire Council

SMEC

SMEC Australia Pty Ltd
ACN 065 475 149

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North Sydney NSW 2060 Australia
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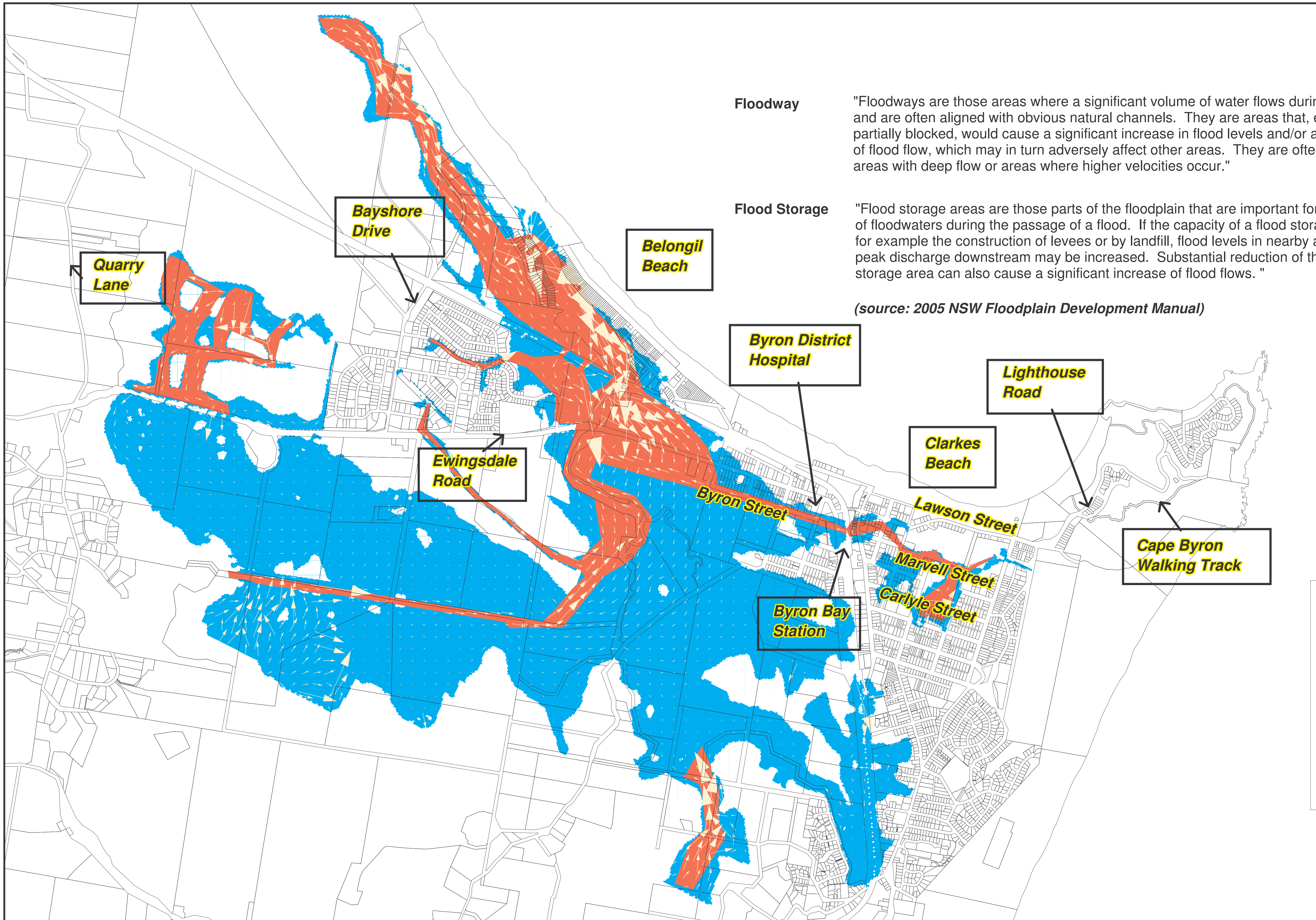
Project Title	**Belongil Creek Flood Study**
Figure 027	**5 year ARI Hydraulic Categorisation** **Existing Topography** **BSC Climate Change Scenario 2**
0.2 0 0.2 0.4 0.6 Kilometres A3 Scale: 1:25,000	Project No. **3001041**



Floodway "Floodways are those areas where a significant volume of water flows during floods and are often aligned with obvious natural channels. They are areas that, even if only partially blocked, would cause a significant increase in flood levels and/or a significant increase of flood flow, which may in turn adversely affect other areas. They are often, but not necessarily, areas with deep flow or areas where higher velocities occur."

Flood Storage "Flood storage areas are those parts of the floodplain that are important for the temporary storage of floodwaters during the passage of a flood. If the capacity of a flood storage area is reduced by, for example the construction of levees or by landfill, flood levels in nearby areas may rise and the peak discharge downstream may be increased. Substantial reduction of the capacity of a flood storage area can also cause a significant increase of flood flows. "

(source: 2005 NSW Floodplain Development Manual)

LEGEND

(Hydraulic Category)

- Floodway
- Flood Storage
- Flood Fringe (none)

For

Byron Shire Council

SMEC

SMEC Australia Pty Ltd
ACN 065 475 149

Level 6 76 Berry Street
North Sydney NSW 2060 Australia
PH (02) 9925 5555 FAX (02) 9955 5566

Project Title	**Belongil Creek Flood Study**
Figure 028	**10 year ARI Hydraulic Categorisation Existing Topography BSC Climate Change Scenario 2**
0.2 0 0.2 0.4 0.6 Kilometres A3 Scale: 1:25,000	Project No. **3001041**

Floodway "Floodways are those areas where a significant volume of water flows during floods and are often aligned with obvious natural channels. They are areas that, even if only partially blocked, would cause a significant increase in flood levels and/or a significant increase of flood flow, which may in turn adversely affect other areas. They are often, but not necessarily, areas with deep flow or areas where higher velocities occur."

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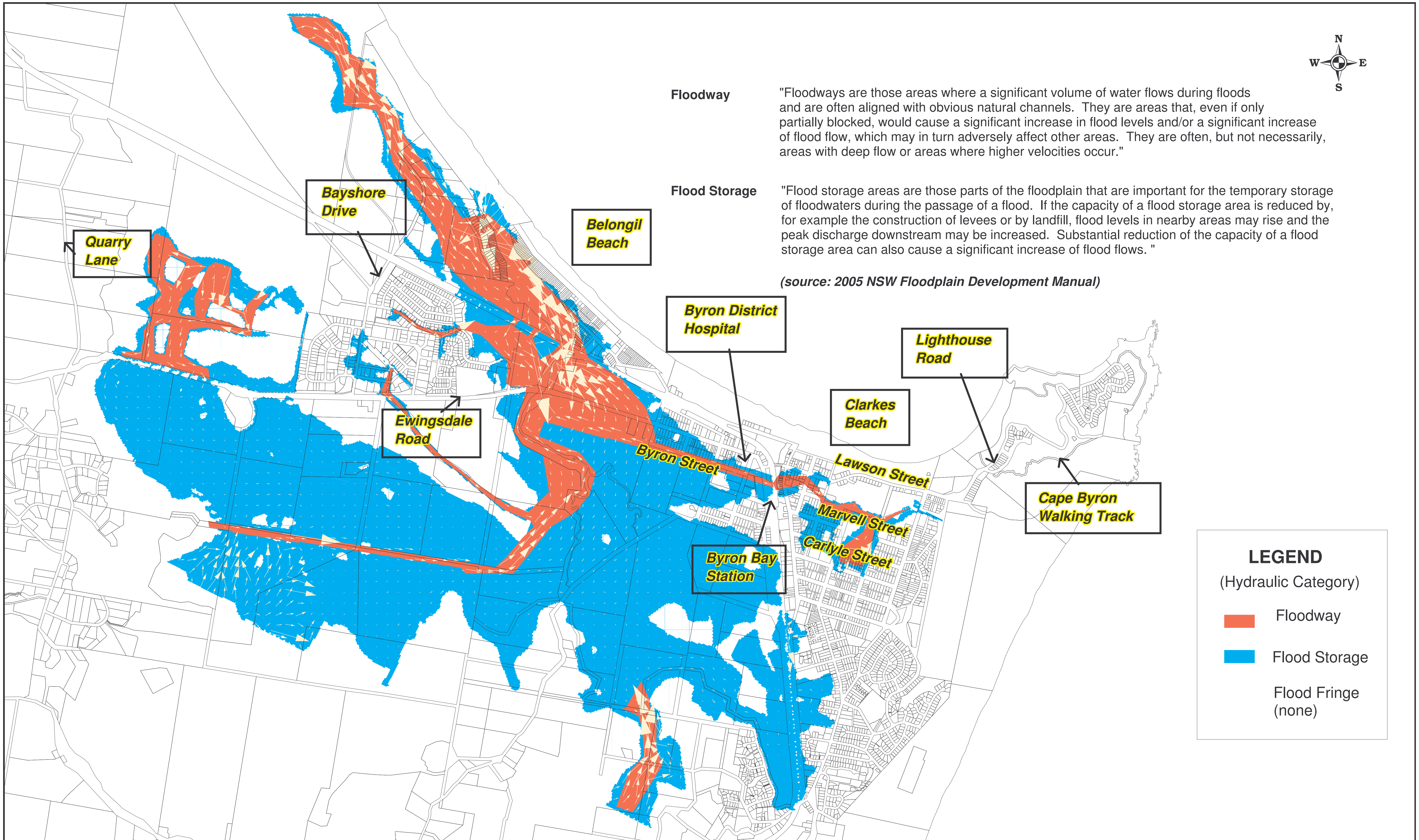
(source: 2005 NSW Floodplain Development Manual)



For

Byron Shire Council

SMEC

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PH (02) 9925 5555 FAX (02) 9955 5566

Project Title	**Belongil Creek Flood Study**
Figure 029	**20 year ARI Hydraulic Categorisation** **Existing Topography** **BSC Climate Change Scenario 2**
0.2 0 0.2 0.4 0.6 Kilometres A3 Scale: 1:25,000	Project No. **3001041**

Floodway "Floodways are those areas where a significant volume of water flows during floods and are often aligned with obvious natural channels. They are areas that, even if only partially blocked, would cause a significant increase in flood levels and/or a significant increase of flood flow, which may in turn adversely affect other areas. They are often, but not necessarily, areas with deep flow or areas where higher velocities occur."

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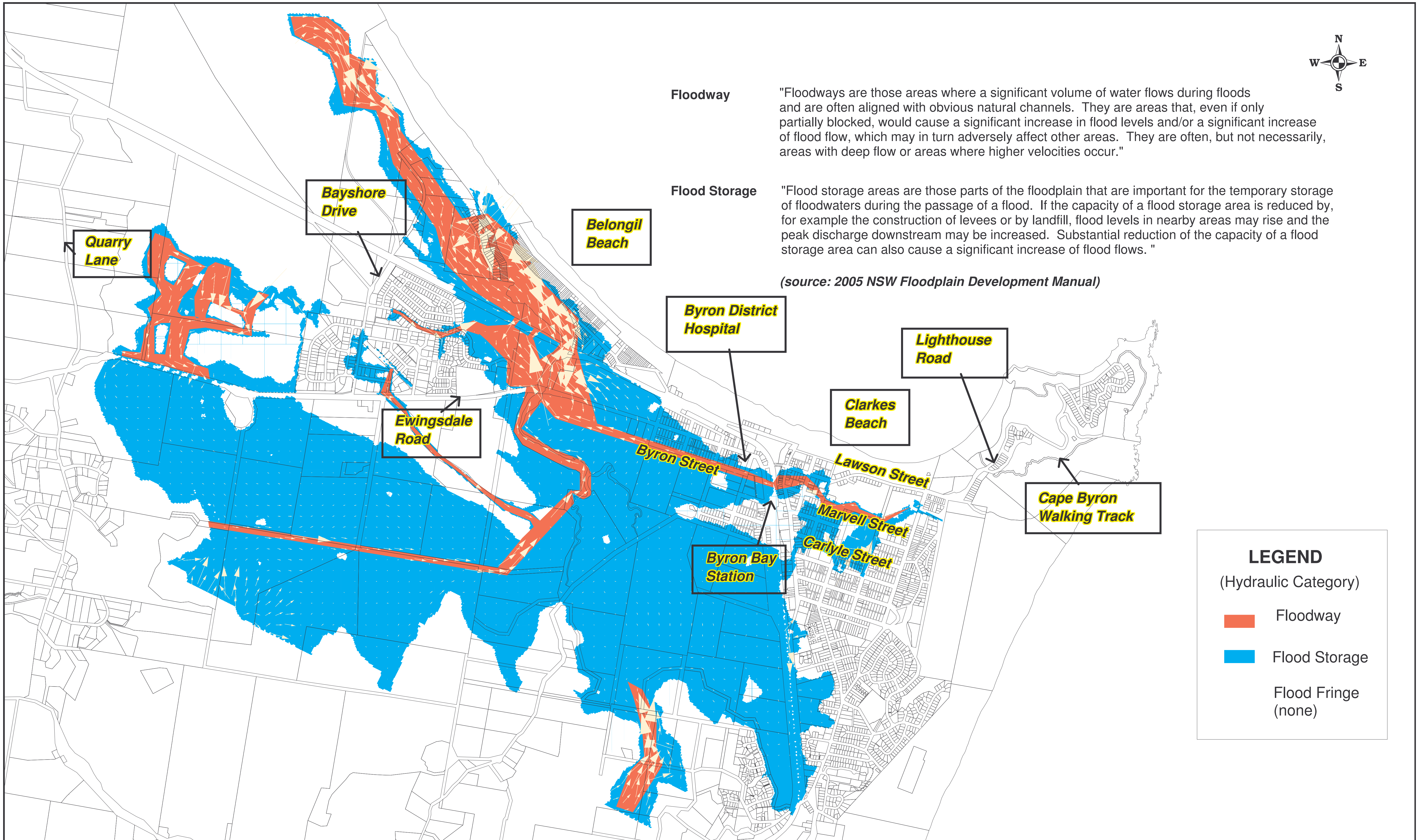
(source: 2005 NSW Floodplain Development Manual)



For

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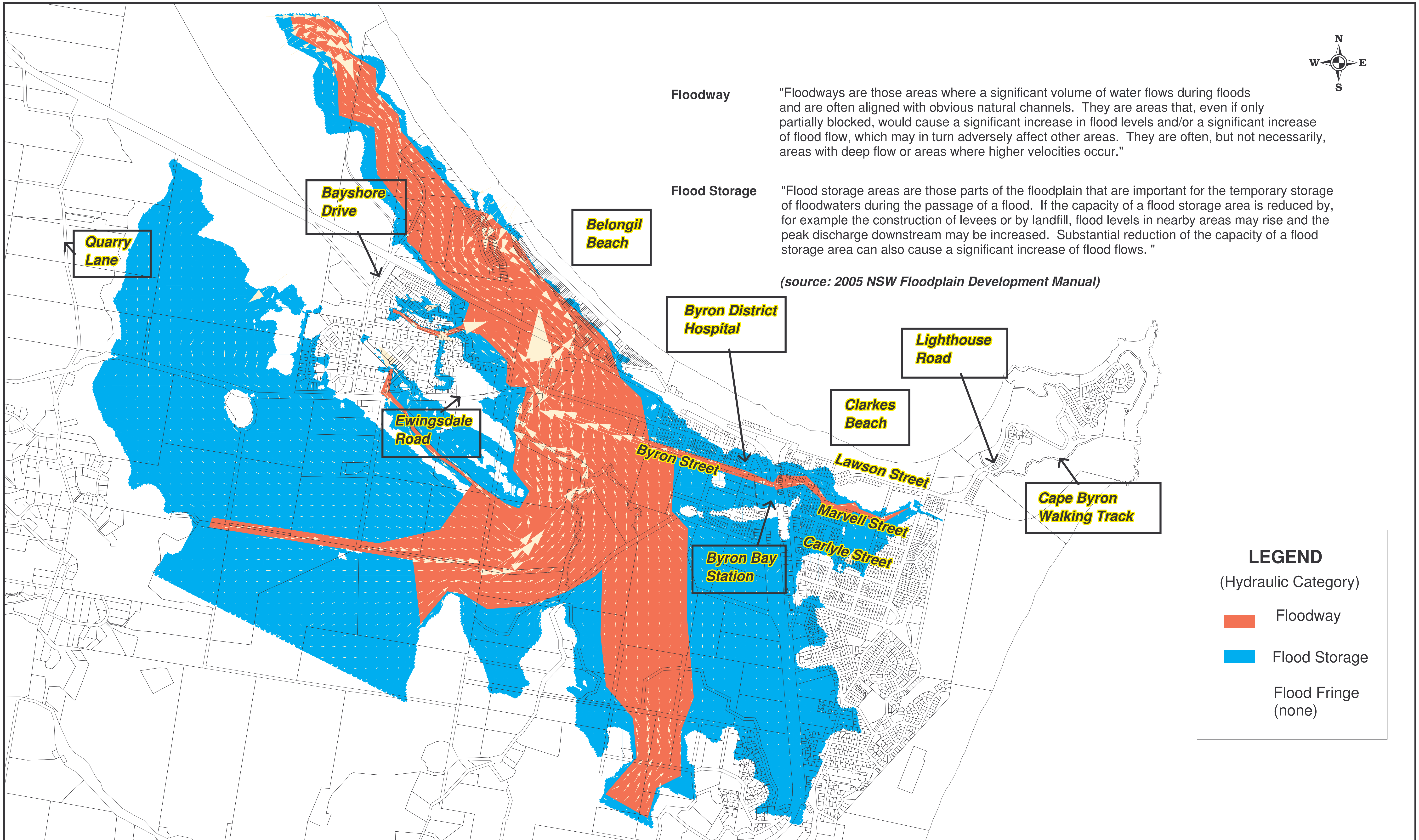
Level 6 76 Berry Street
North Sydney NSW 2060 Australia
PH (02) 9925 5555 FAX (02) 9955 5566

Project Title	**Belongil Creek Flood Study**
Figure 030	**100 year ARI Hydraulic Categorisation** **Existing Topography** **BSC Climate Change Scenario 2**
0.2 0 0.2 0.4 0.6 Kilometres A3 Scale: 1:25,000	Project No. **3001041**



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(source: 2005 NSW Floodplain Development Manual)

For

Byron Shire Council

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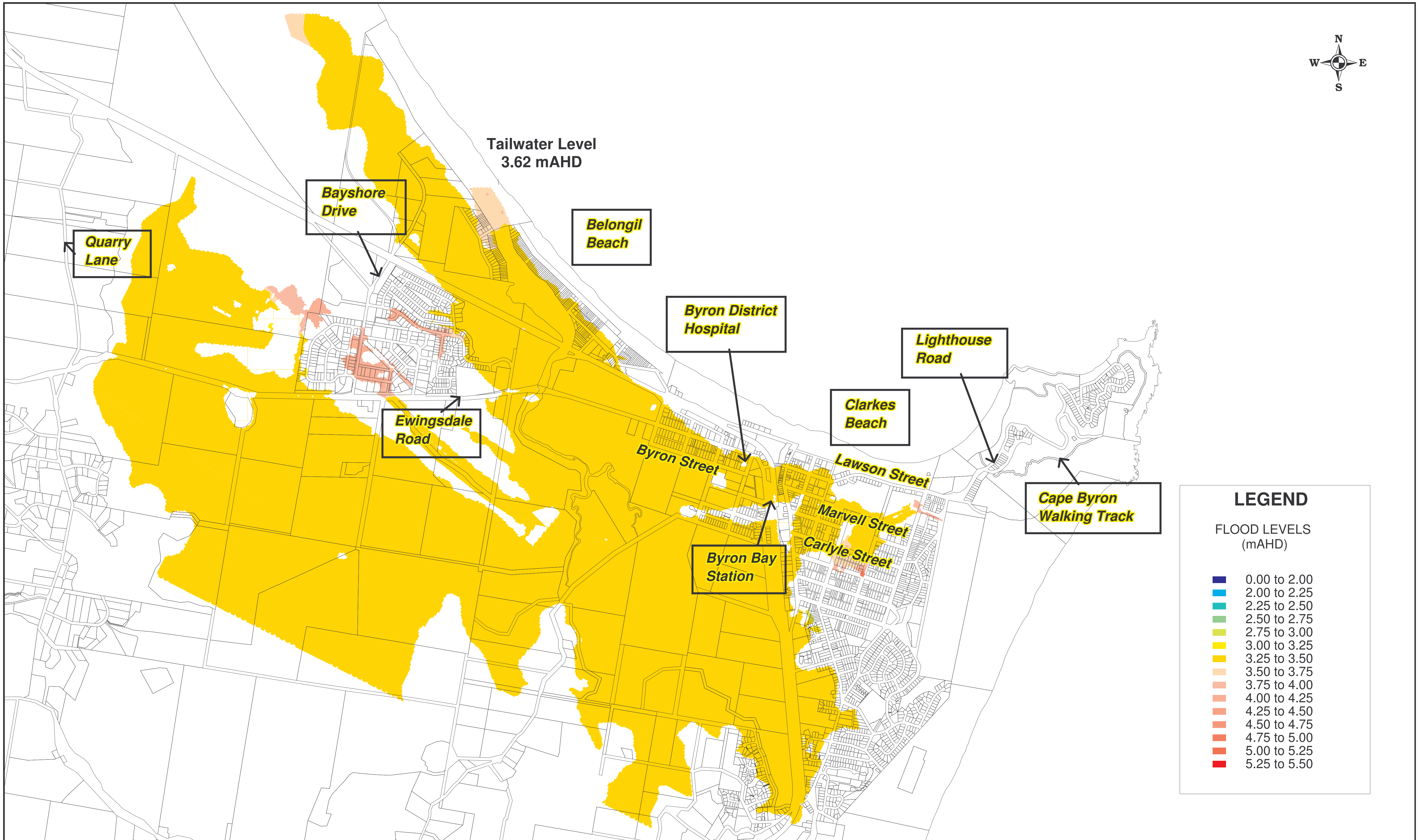
Level 6 76 Berry Street
North Sydney NSW 2060 Australia
PH (02) 9925 5555 FAX (02) 9955 5566

Project Title	**Belongil Creek Flood Study**
Figure 031	**PMF Hydraulic Categorisation** **Existing Topography** **BSC Climate Change Scenario 4**

0.2 0 0.2 0.4 0.6
Kilometres
A3 Scale: 1:25,000

Project No.
3001041



For

Byron Shire Council

SMEC

SMEC Australia Pty Ltd
ACN 065 475 149

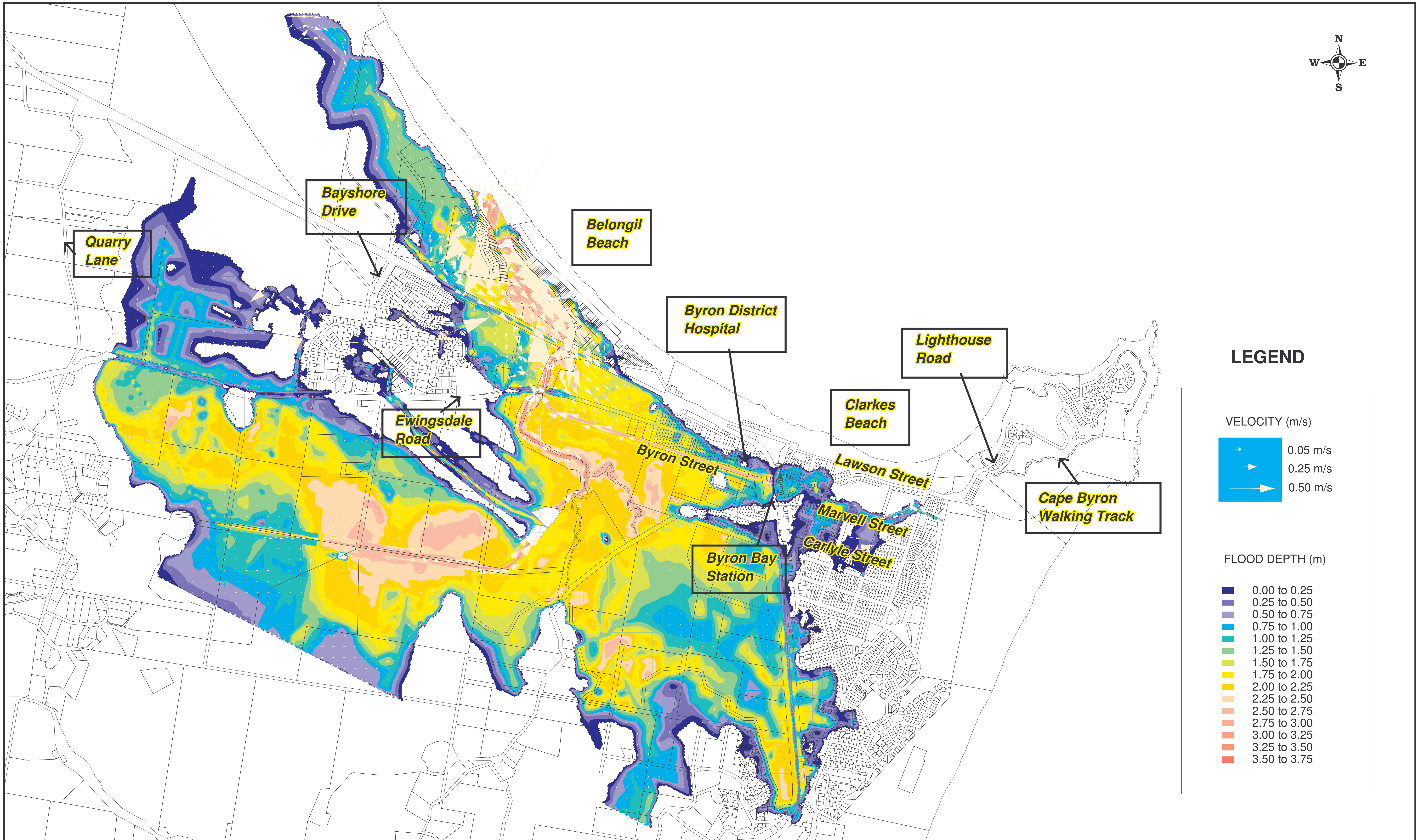
Level 6 76 Berry Street
North Sydney NSW 2060 Australia
PH (02) 9925 5555 FAX (02) 9955 5566

Project Title: **Belongil Creek Flood Study**

Figure 032 **100 year ARI Flood Levels, Existing Topography BSC Climate Change Scenario 4**

0.2 0 0.2 0.4 0.6
Kilometres
A3 Scale: 1:25,000

Project No. **3001041**



For

Byron Shire Council

SMEC

SMEC Australia Pty Ltd
ACN 065 475 149

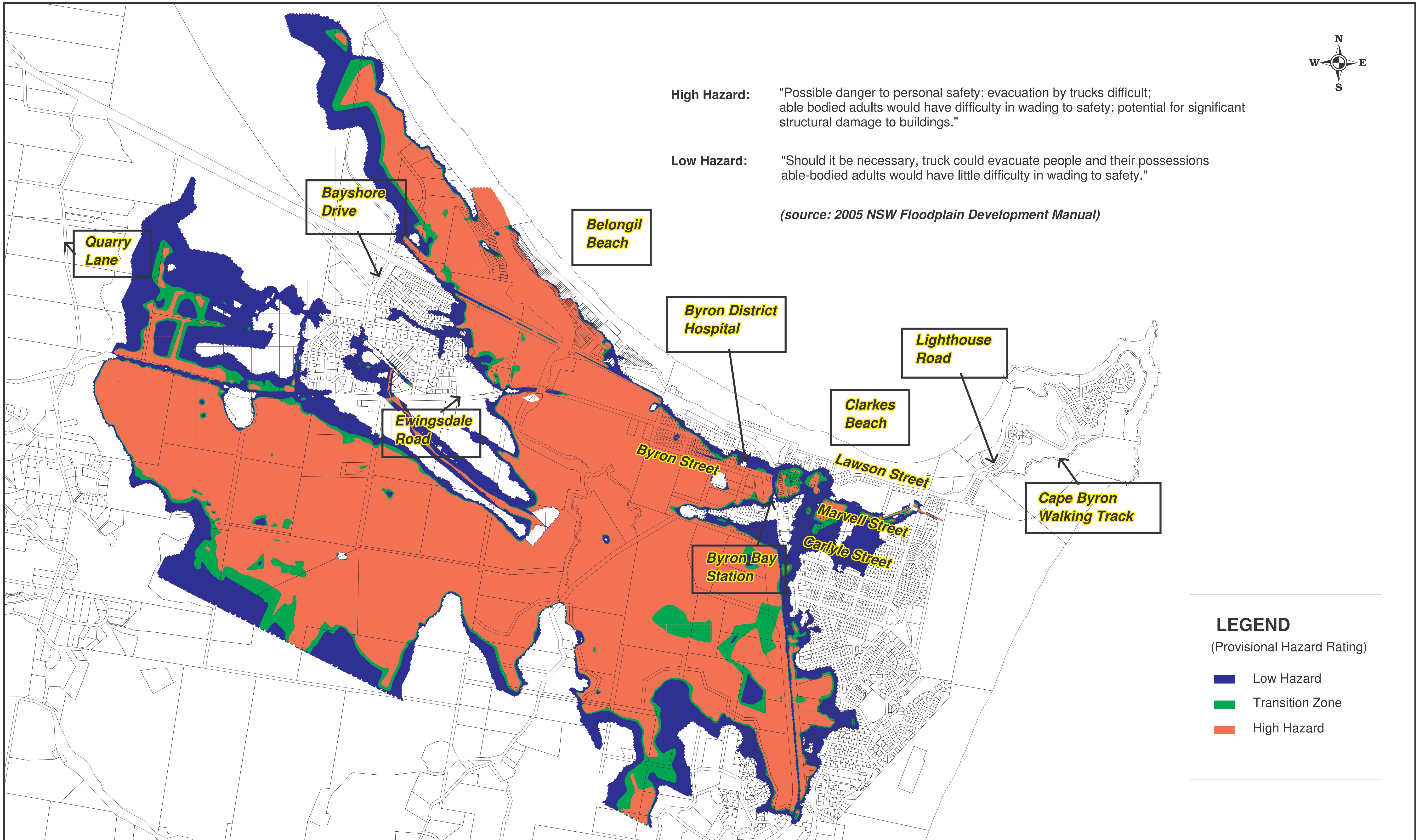
Level 6 76 Berry Street
North Sydney NSW 2060 Australia
PH (02) 9925 5555 FAX (02) 9955 5566

Project Title **Belongil Creek Flood Study**

Figure 033 **100 year ARI Velocity-Depths, Existing Topography BSC Climate Change Scenario 4**

0.2 0 0.2 0.4 0.6
Kilometres
A3 Scale: 1:25,000

Project No. **3001041**



For

Byron Shire Council

SMEC

SMEC Australia Pty Ltd
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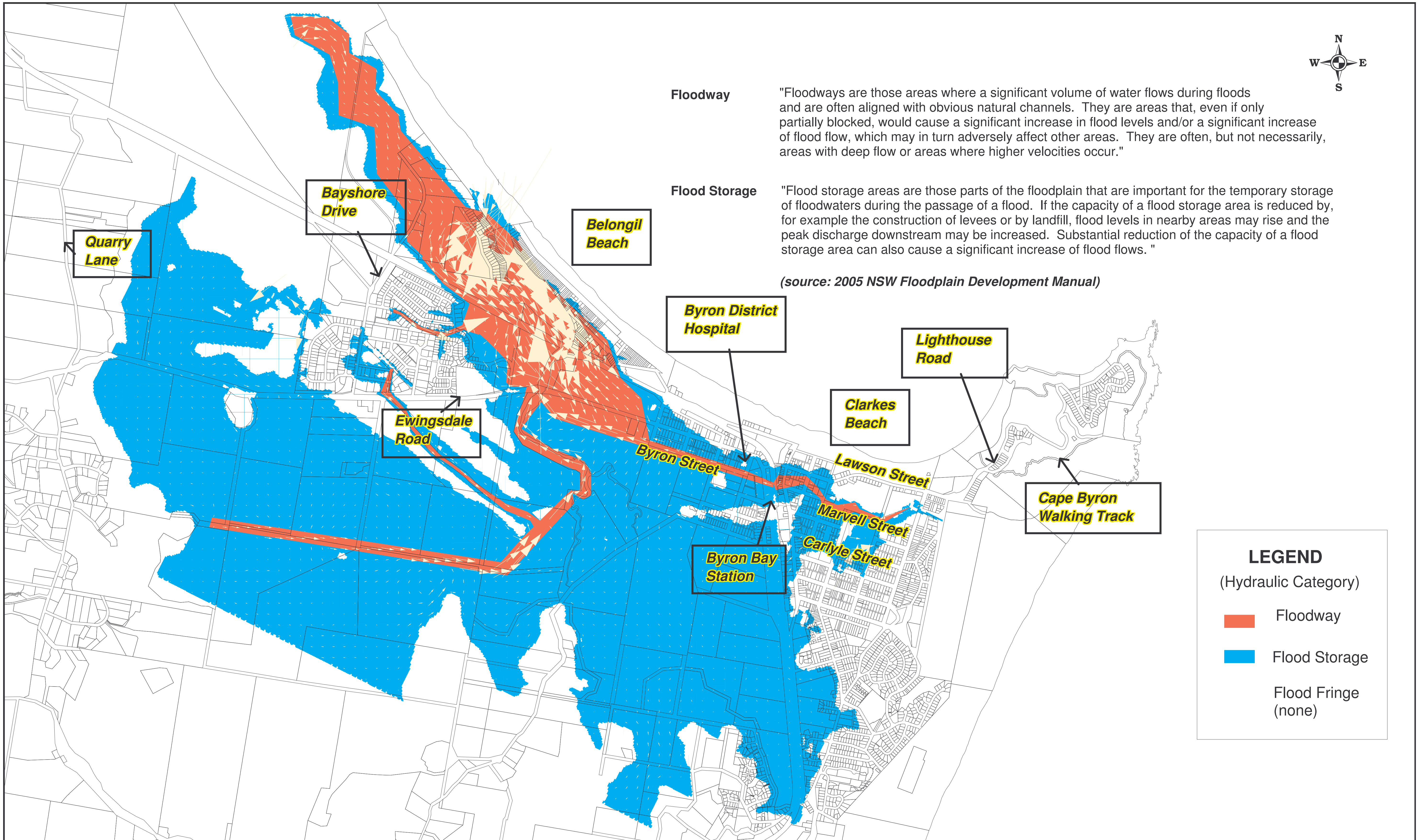
Level 6 76 Berry Street
North Sydney NSW 2060 Australia
PH (02) 9925 5555 FAX (02) 9955 5566

Project Title	**Belongil Creek Flood Study**
Figure 034	**100 year ARI Provisional Hazard Map** **Existing Topography** **BSC Climate Change Scenario 4**
0.2 0 0.2 0.4 0.6 Kilometres A3 Scale: 1:25,000	Project No. **3001041**



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(source: 2005 NSW Floodplain Development Manual)

For **Byron Shire Council**	SMEC SMEC Australia Pty Ltd ACN 065 475 149 Level 6 76 Berry Street North Sydney NSW 2060 Australia PH (02) 9925 5555 FAX (02) 9955 5566	Project Title	**Belongil Creek Flood Study**
		Figure 035	**100 year ARI Hydraulic Categorisation** **Existing Topography** **BSC Climate Change Scenario 4**
		0.2 0 0.2 0.4 0.6 Kilometres A3 Scale: 1:25,000	Project No. **3001041**

APPENDIX 2 : Resident Flood Marks

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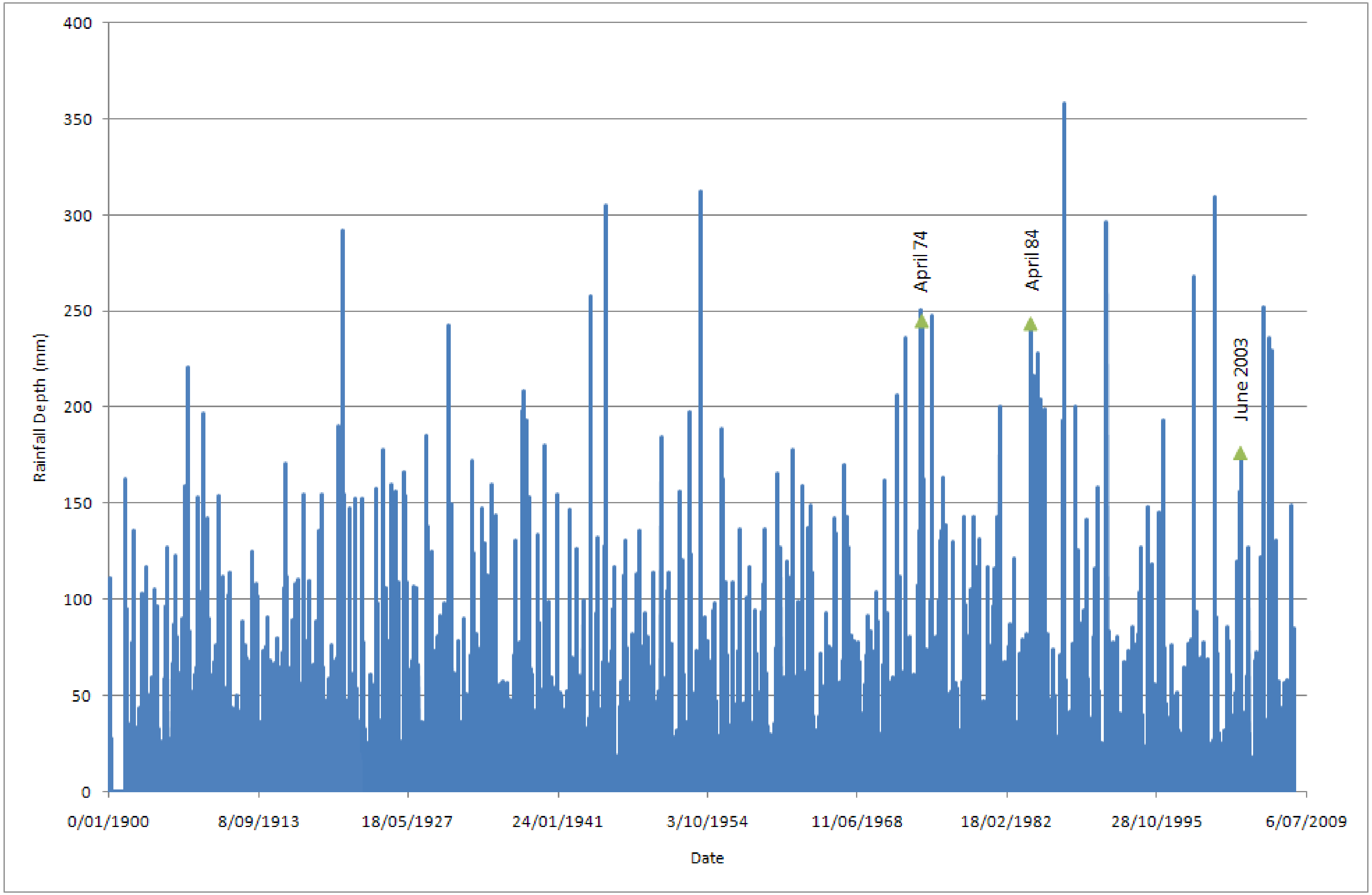
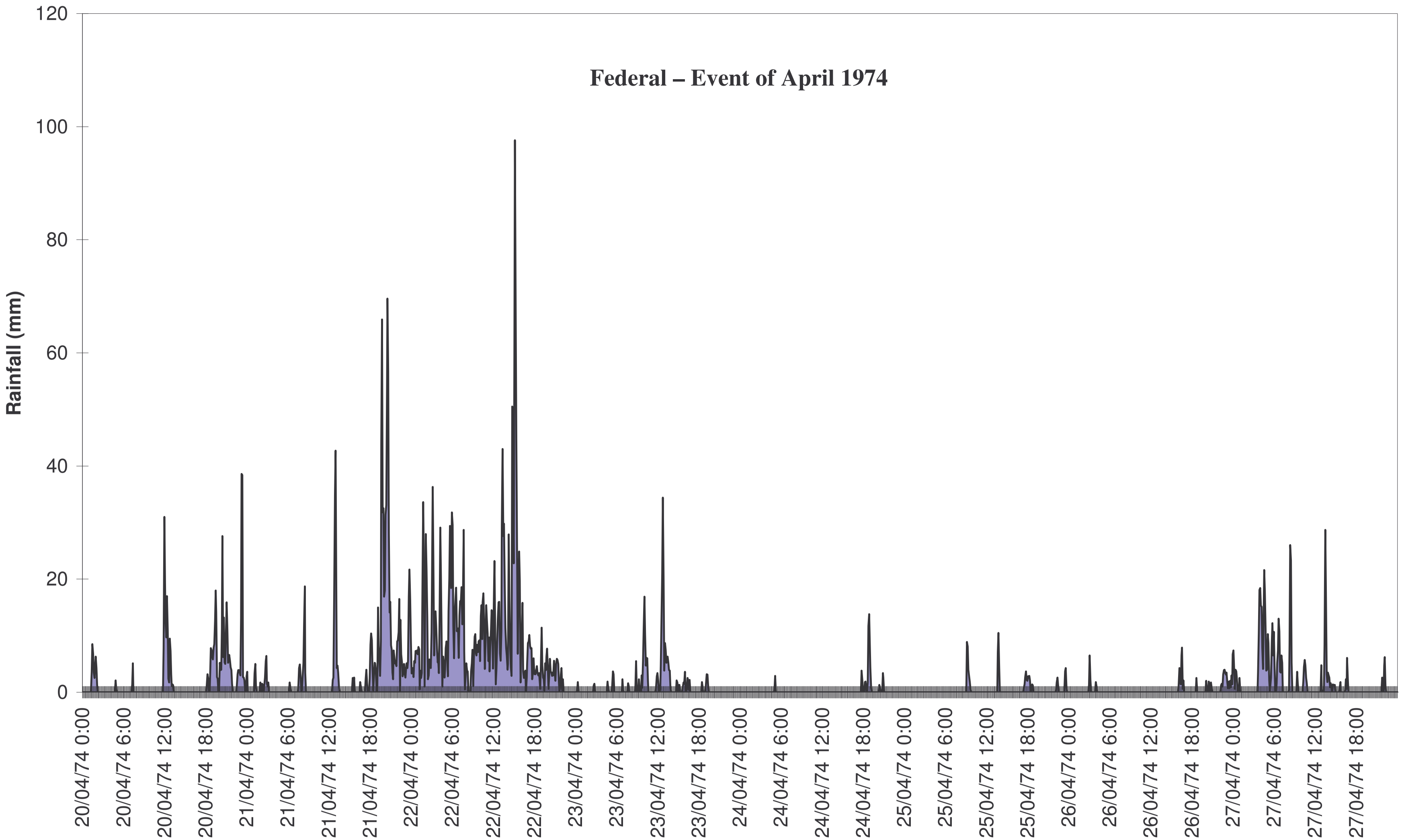
NAME	ADDRESS	PHONE	EVENT	RL	COMMENTS
Barbara Turner	6 Burns St	6685 7824	2003	3.47	Met with owner. Had a reference to bottom rail of fence. Seemed to be a reliable mark.
Steve Packer	Byron Surf Shop	0419 464 232	1998		Estimated to be approx. 200 mm above orig. cordial factory floor
	Cnr Fletcher and Lawson Sts				or 300 to 400 above top of kerb in Lawson St
J & J Pearse	38 Shirley Lane	6685 5317	1998 & 2000	1.92	Reliable marks from owner authenticated with photographs
Helen McKay	20Cavanbah St		Jun-05	4.01	Reliable mark but property seems to be sitting
					in a depression. Do not use as a flood level
Max Pendegast	36 Kingsley St	6685 6443	2003 & 1984	4.32	Local flooding. Very reliable mark from long time resident
					Max indicated that the problem was now not as bad after some of the drains were cleaned out.
Sheree Farnsworth	11 Bunjil Place				Spoke to residents at No. 9. Seems to be a local drainage problem
Katrina Evans	32 Gordon St	6685 5801			
	36 Gordon St			2.08	Esimated top flood level mark June 2005
	38 Gordon St			2.29	Esimated top flood level mark June 2005
BrentYoung	Unit 3/4 Cape Court	6685 6148			
Teresa Heal	21 Middleton St	6685 5293	2005 & 2006	2.62	Very reliable mark referred to step
Peter & Gloria Kelly	14 Marvel St	6685 7502	2003 & 1995	2.61	Very reliable mark. Debris on garage wall
			2006		
Byron Bay Self Storage	8-10 Tasman Way		Recent Jan 2006 ?	3.51	Estimated flood level on driveway

APPENDIX 3 : Observed Rainfall Patterns



Daily Rainfall Totals – Station 58007 (Byron Bay, Jacaranda Drive), 1900 to 2008


Federal – Event of April 1974
Rainfall (mm)
120
100
80
60
40
20
0
20/04/74 0:00
20/04/74 6:00
20/04/74 12:00
20/04/74 18:00
21/04/74 0:00
21/04/74 6:00
21/04/74 12:00
21/04/74 18:00
22/04/74 0:00
22/04/74 6:00
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26/04/74 0:00
26/04/74 6:00
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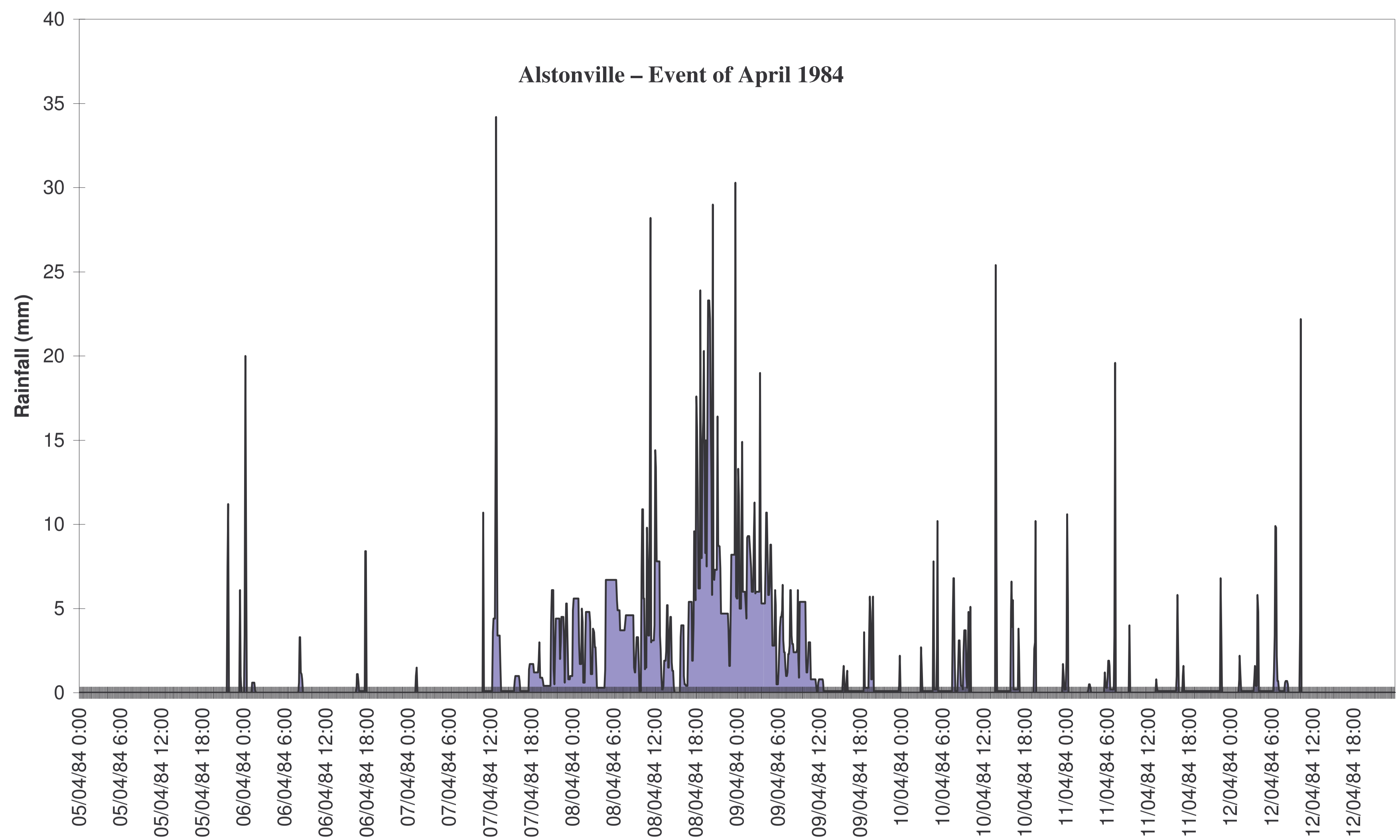
27/04/74 12:00
27/04/74 18:00


Alstonville – Event of April 1984
Rainfall (mm)
0
5
10
15
20
25
30
35
40
05/04/84 0:00
05/04/84 6:00
05/04/84 12:00
05/04/84 18:00
06/04/84 0:00
06/04/84 6:00
06/04/84 12:00
06/04/84 18:00
07/04/84 0:00
07/04/84 6:00
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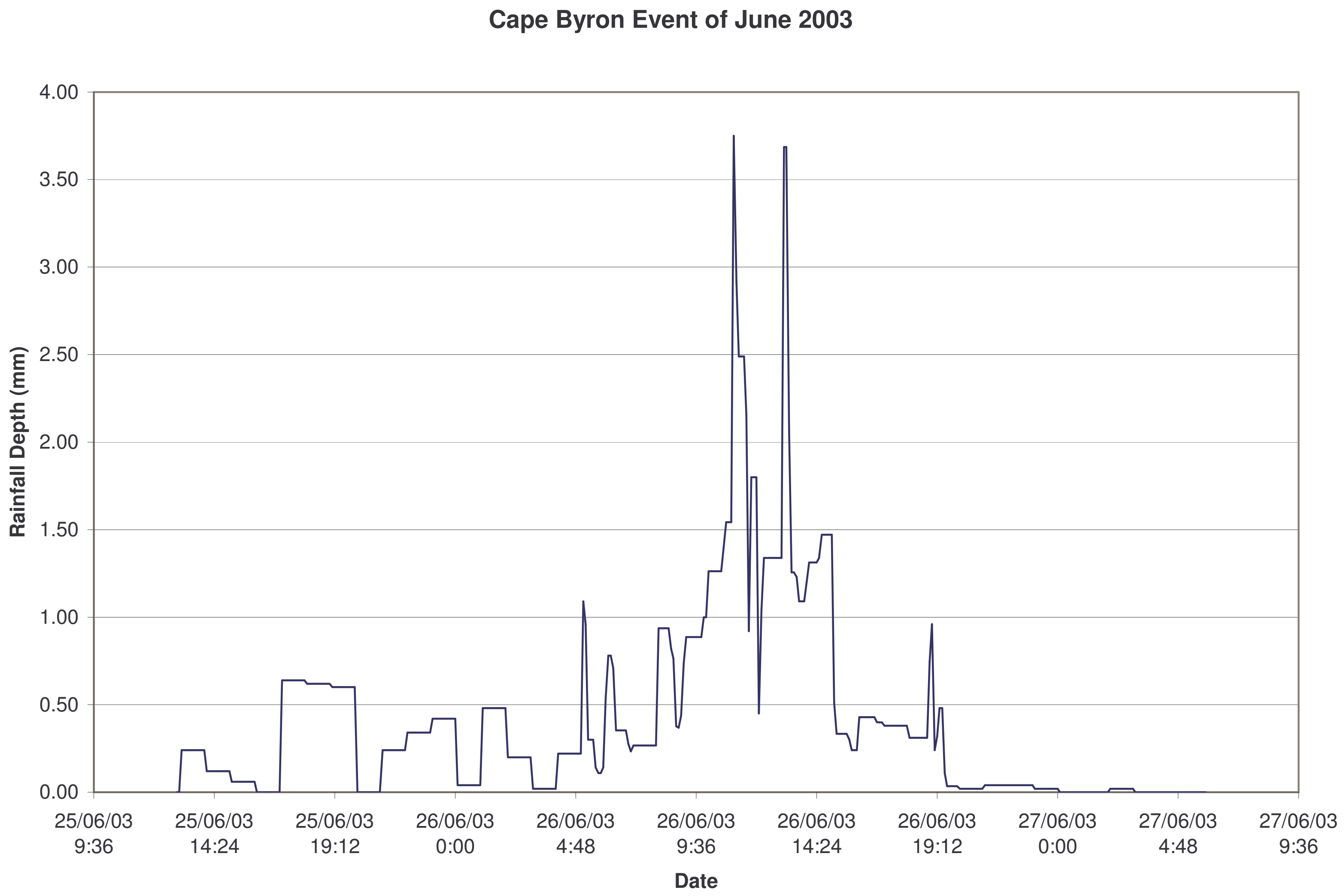
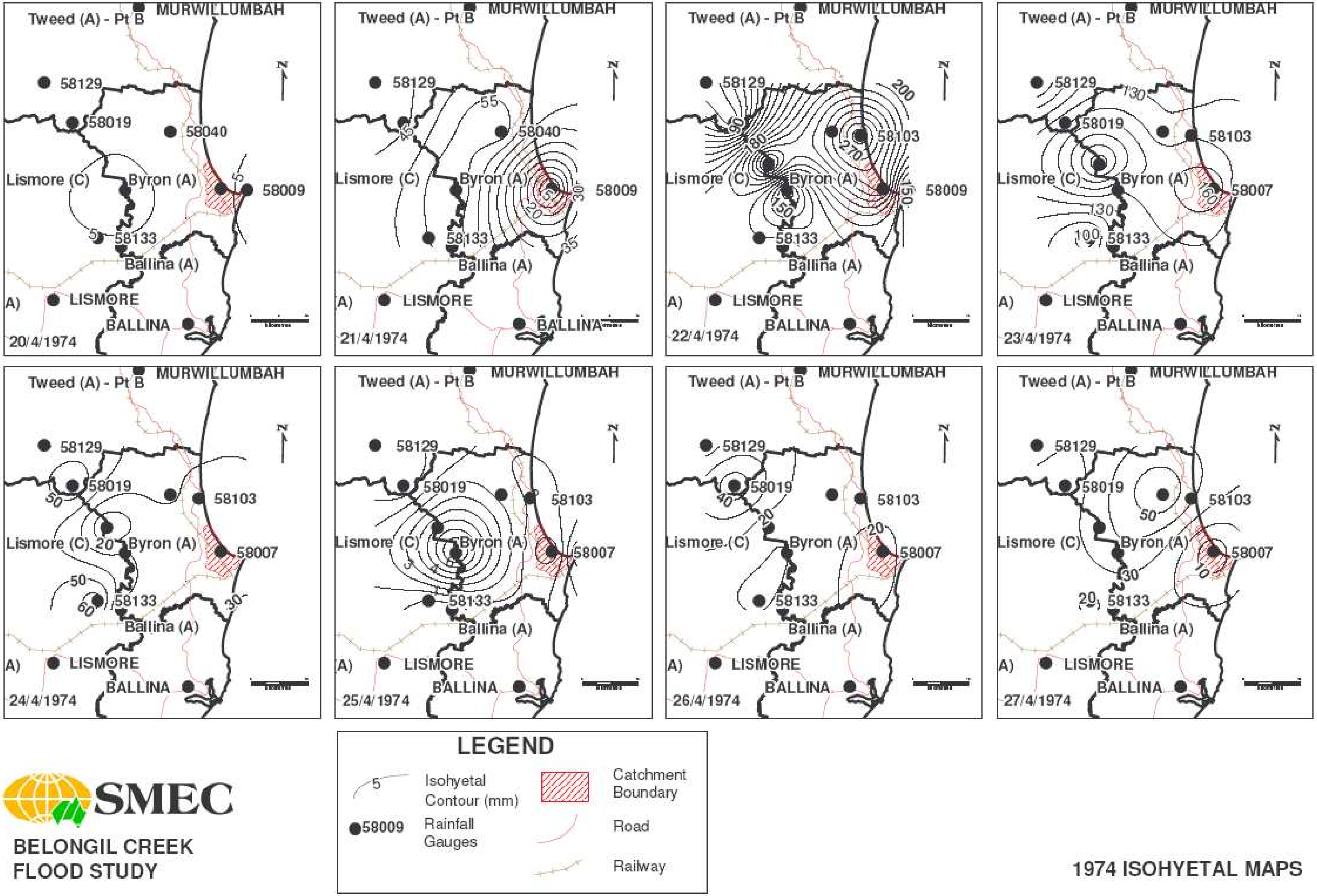
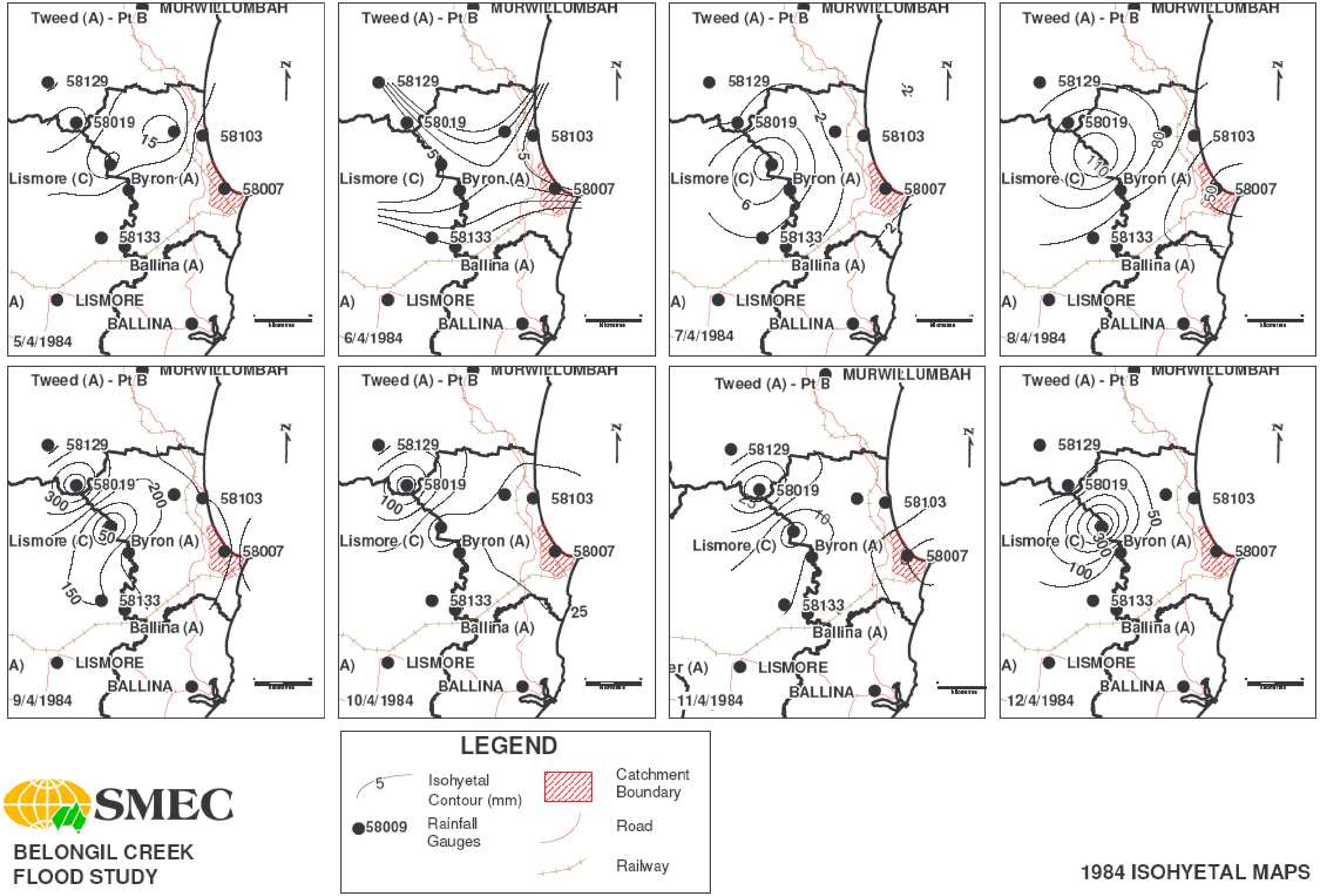
12/04/84 12:00
12/04/84 18:00


Cape Byron Event of June 2003
Rainfall Depth (mm)
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
25/06/03 9:36
25/06/03 14:24
25/06/03 19:12
26/06/03 0:00
26/06/03 4:48
26/06/03 9:36
26/06/03 14:24
26/06/03 19:12
27/06/03 0:00
27/06/03 4:48
27/06/03 9:36
Date



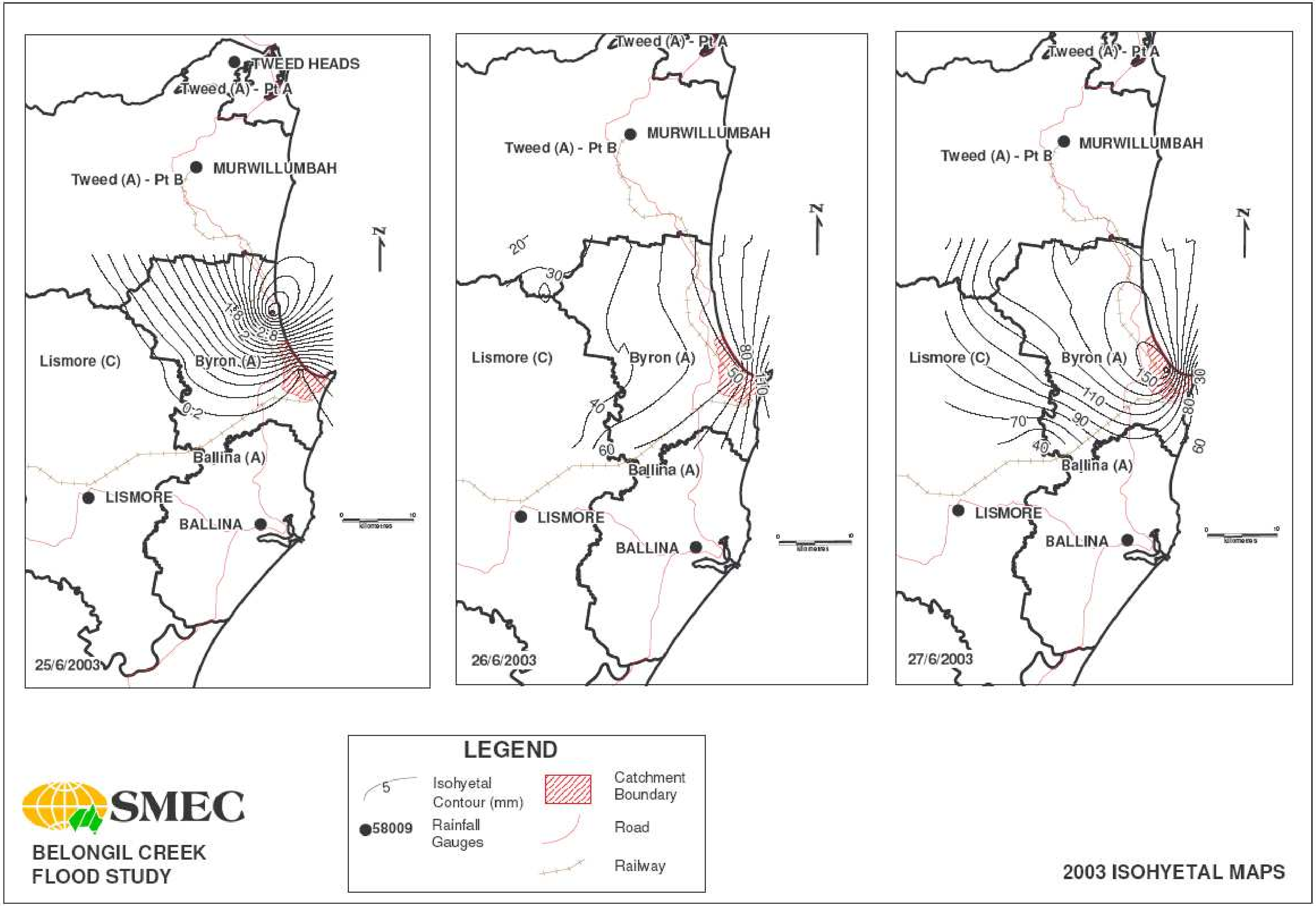
BELONGIL CREEK FLOOD STUDY

1974 ISOHYETAL MAPS



BELONGIL CREEK FLOOD STUDY

1984 ISOHYETAL MAPS


TWEED HEADS
Tweed (A) - Pt A
Tweed (A) - Pt B
MURWILLUMBAH
Lismore (C)
Byron (A)
Ballina (A)
LISMORE
BALLINA
25/6/2003
26/6/2003
27/6/2003
N
LEGEND
Isohyetal Contour (mm)
58009 Rainfall Gauges
Catchment Boundary
Road
Railway
SMEC
BELONGIL CREEK
FLOOD STUDY
2003 ISOHYETAL MAPS

APPENDIX 4 : Design Tailwater Derivation

In order to correctly model the hydraulics of the creek and predict flood levels within the Belongil Creek catchment accurately, the downstream water level at the entrance to the creek, or *tailwater level*, needs to be accurately predicted.

The tailwater level for floods in Belongil Creek is determined by the nearshore ocean water level. This level may depend on several factors including:

6. the astronomical tide, which is the greatest contributor by far and is in the order of metres;
7. storm surge, comprising barometric setup and coast-wide wind setup, which is in the order of tenths of a metre;
8. the passage of coastally trapped waves, which can be in the order of tenths of a metre,
9. fresh water inflow, and
10. wave setup.

These components of tailwater level are illustrated in Figure 1 below.

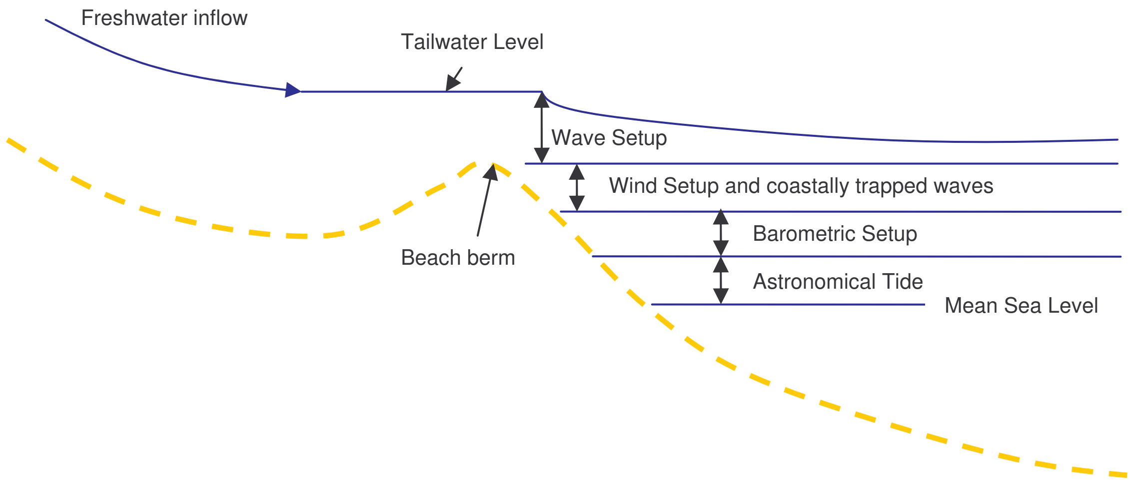


Figure 1 – Components of tailwater level at Belongil Creek

As the tidal stage (1) is entirely predictable, the combination of the contributions to water level in (2) to (5) above is referred to as the tidal anomaly (the difference between measured water levels and tidal predictions).

Extensive and precise field measurements of tidal anomalies have been made in various estuaries on the NSW coast (*eg.* in the Brunswick River entrance) over many years and these have included the occurrence of cyclonic events, such as that undertaken in March 1993 during the passage of *Cyclone Roger* (Nielsen and Hanslow, 1995).

It is noted that the Annual Exceedance Probability (AEP) for water level will not necessarily be equivalent to the AEP for precipitation, despite the fact that both positive tidal anomalies and heavy precipitation are often correlated because they are driven commonly by the same weather systems. For example, the largest tidal anomaly that has been recorded, which was during the severe storm on the 26 May 1974, which peaked at 0.59 m at Fort Denison (Higgs & Nittim, 1986) and which has been assigned an Annual Recurrence Interval of 77 years, was not associated with a 77 year ARI rainfall event but, rather, the annual return interval of the rainfall that was associated with that storm has been assessed variously at around 20 years. In addition, the tidal anomaly in a river entrance may peak at its maximum value for a few hours only, which may not necessarily occur with the peak of the wave setup nor with the peak of the passage of the flood wave.

The downstream control will also depend on the estuary entrance. The estuary mouth is intermittently open, with catchment flooding and sand transport being the main factors that influence the opening and closing of the mouth. The entrance condition will depend on the relative magnitudes of the littoral drift transporting sand to the inlet which acts to close the entrance and the channel discharge which acts to keep the channel open.

Should the inlet be open to the sea, as portrayed in **Figure** 2, then ocean levels will provide a tailwater control on the discharge of estuary floodwaters. In the nearshore zone these levels will be influenced not only by the tidal stage and storm surge but also by nearshore wave and wind setup. Should the inlet be closed (**Figure** 3), the crest of the beach berm will present as a weir controlling the downstream water level for floodwater discharge. However, berm levels are low and wave action on elevated water levels will cause overtopping.

During a large storm event, it is assumed that the estuary entrance would open soon after the onset of the storm, due to scour of the berm caused by the passage of floodwaters. Thus, it is assumed that the bed level at the estuary entrance would be approximately 1.0 m below Australian Height Datum (AHD).

While a higher sea level would increase the crest height of the beach berm at the wave entrance under natural conditions, it is assumed that Council's policy of opening the channel to relieve flooding would continue into the future and that the entrance would scour to a similar level in a major storm event as it does today.

Figure 2 – Typical view of Belongil Creek Outlet, entrance open

Figure 3 – Typical view of Belongil Creek Outlet, entrance closed

Astronomical Tide

The tides of the NSW coast are semidiurnal with a diurnal inequality. This means that there are two high tides and two low tides each day and there is a once-daily inequality in the tidal range. The mean tidal range is around one metre and the tidal period is around 12.5 hours. Tides vary according to the phases of the moon. The higher spring tides occur near and around the time of new or full moon and rise highest and fall lowest from the mean sea level. The average spring tidal range is 1.3 metres and the maximum range reaches two metres. Neap tides occur near the time of the first and third quarters of the moon and have an average range of around 0.8 metres.

For this study, a typical spring tidal cycle has been chosen for the astronomical tide component of the downstream water level. This has been assumed to not change as a result of climate change.

Storm Surge

Storm surge is the increase in water level above that of the normal tide that results from the low barometric pressures, which are associated with severe storms and cause sea level to rise, and strong onshore winds that pile water up against the coast.

Measured values of storm surge at Sydney include 0.59 m for the extreme storm event of 25–26 May 1974 and 0.54 m for the extreme storm event of 31 May – 2 June 1978 (Haradasa et al., 1991). Both of these extreme events were coincident with spring high tides with the water level in the 1974 event reaching the maximum recorded at Fort Denison of 1.5 m AHD.

Barometric setup is related directly to the measured barometric pressure. Ignoring all other effects, the water level rises 0.1 m above the predicted lunar tidal stage for each 10 hectopascals that the pressure falls below 1013 hPa (NSW Government, 1990). During the May/June 1974 storm event on the Central Coast of New South Wales, the measured barometric pressure was approximately 990 hPa, with approximately 0.25 m of barometric storm surge and 0.30 m due to wind setup.

The Bureau of Meteorology has records that indicate the paths of various tropical cyclones throughout Australia. Byron Bay lies close to the southern limit of the passage of tropical cyclones, and their occurrence offshore of Byron Bay is less frequent than what would be expected for the tropical coasts of Australia. Nevertheless, several cyclones have been recorded in the vicinity of Byron Bay since records began. Recorded cyclones in the region bounded by 26°S and 31°S and 151°E and 156°E are listed in Table 3 below. Note that the central pressures listed in the table correspond to the lowest barometric pressure of the cyclone while it was tracking within the region bounded by the above coordinates.

A time history of central barometric pressure was obtained from the Bureau of Meteorology records for cyclone Zoe in March 1974. From this time history, a time-series of storm-surge was derived for use in the model. The maximum barometric storm surge that would have resulted from cyclone Zoe would have been 0.45m, as the central barometric pressure at the peak of the storm was 968 hPa. An additional surge of 0.3 m due to wind setup has been added to these values, consistent with the estimated value of wind setup from the 1974 event at Sydney.

For the purpose of the modelling, it was assumed that the design storm surge would occur during a week of spring tides. This is a somewhat conservative assumption, as it leads to higher design water levels than would be expected if the cyclone was to occur during a neap tide regime and thus worse conditions for tailwater levels. However, there is a 50% chance that a cyclone would occur during a week of spring tides as opposed to neap tides.

A further conservative assumption is that the peak of the storm surge coincides with the peak of the spring tide.

An exceedence analysis was carried out on the central barometric pressures of all the cyclones recorded within the Byron Bay area (data for 31 cyclones were used in the analysis). Table 3 summarises the ten most intense of these cyclones. The exceedence analysis is illustrated in **Figure** 4. The corresponding maximum storm surge values for various recurrence interval storms were derived from this exceedence analysis – these values were subsequently used in the modelling and are provided in Table 4.

Ideally, a joint-probability analysis should be undertaken to ascertain the joint occurrence probability of high freshwater discharge and oceanic water levels for a particular storm. For example, a 100 year ARI discharge may be associated with a 20 year ARI tailwater level, or a 20 year ARI discharge may be associated with a 100 year ARI tailwater level.

TABLE 13. RECORDED TROPICAL CYCLONES IN THE BYRON BAY AREA (SOURCE – BUREAU OF METEOROLOGY DATA)

Date	Name (if applicable)	Rank	Central Pressure (hPa)	Estimated pressure storm surge (m)
29/01/1967	DINAH	1	950	0.63
11/03/1974	ZOE	2	968	0.45
31/12/1962		3	978	0.35
27/02/1980	SIMON	3	978	0.35
2/02/1990	NANCY	5	980	0.33
18/02/1992	DAMAN	5	980	0.33
7/03/1995	GERTIE	5	980	0.33
19/02/1954		8	982	0.31
14/01/1964	AUDREY	9	984	0.29
21/01/1994	REWA	10	985	0.28

TABLE 14. ADOPTED STORM SURGE VS ARI

ARI	Cyclone central pressure (hPa)	Adopted Pressure Storm Surge (m)	Adopted Wind setup Storm Surge (m)
5	980	0.35	0.30
10	975	0.40	0.30
20	970	0.45	0.30
50	960	0.50	0.30
100	955	0.60	0.30

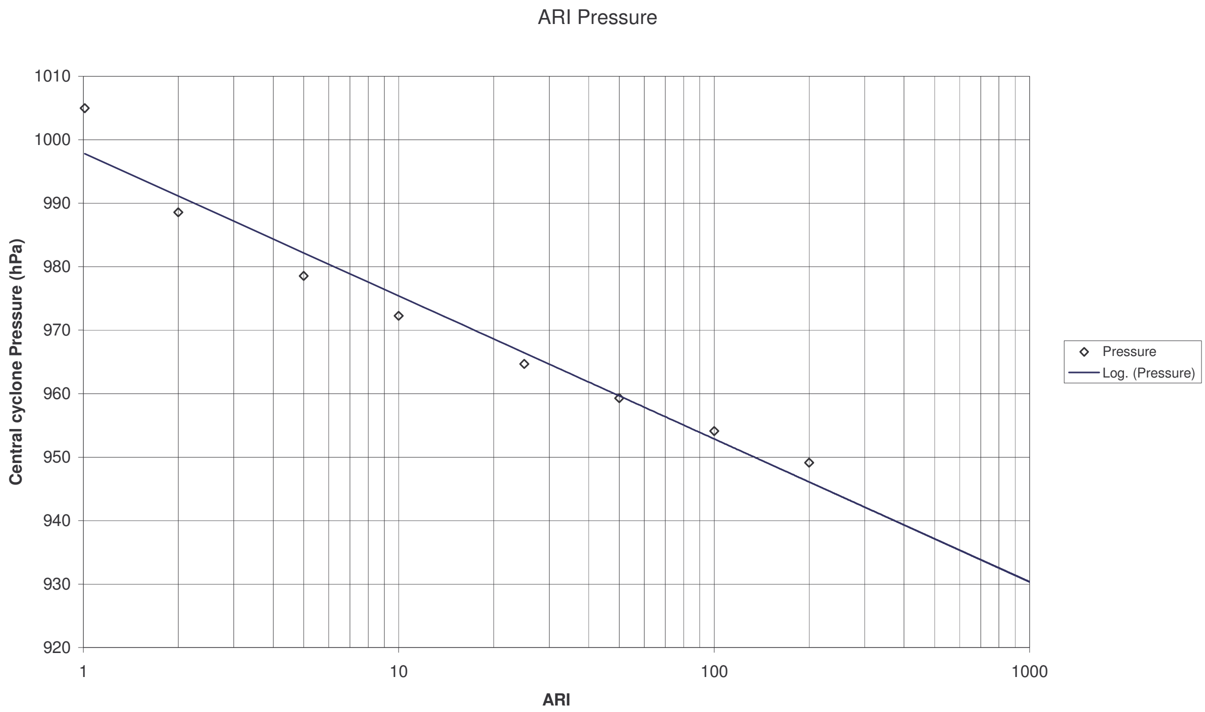


Figure 4 – ARI Plot of central cyclone pressure (derived from Bureau of Meteorology Data)

It would appear possible to combine the statistical properties of storm parameters with the results of surge modelling to determine the recurrence statistics of surge levels. However, there is some considerable difficulty in combining surge frequency statistics with tide height statistics. Methods based on the application of conditional probabilities have been applied but there are still difficulties in allowing for the variability of tidal amplitude, which is by far the greatest component of elevated water levels on the NSW coast, with wave setup, which introduces a further time-dependent variable. These complexities make the solution intractable (Nielsen and Adamantidis, 2002).

For the purposes of this study, pressure storm surge from Table 4 was applied for all AEP discharges. An additional storm surge due to wind setup of 0.3 m (consistent with estimated values at Sydney from the 1974 storm) was added to the pressure surge values from Table 4.

Wave Setup

Further elevation of the water level at the shoreline results from the breaking action of waves causing, what is termed, wave setup and wave runup. Wave setup may be perceived as the conversion of part of the wave's kinetic energy into potential energy as the wave shoals onto the beach. The amount of wave setup will depend on many factors including, among other things, the heights and periods of the waves, the nearshore bathymetry and the slope of the beach.

Nielsen and Adamantidis (2002) carried out an ocean tailwater control study for Crooked Creek, on the NSW south coast. Crooked Creek is geographically similar estuary to Belongil Creek, in that both estuaries have a broad sheltered lagoon in their lower reaches, and both are intermittently closed or open depending on the transport of littoral sand drift from the beaches at their entrances.

Waves resulting from tropical cyclones are likely to approach the Belongil Creek estuary from the north-east. Gordon et. al. (1978) undertook a wave refraction study of the Byron Bay coast and found that, for waves having a 10 second wave period approaching from the north-east, the wave refraction coefficient may reach 0.8. This would result in a similar return period of wave height at the entrance of Belongil Creek to that which would be obtained at the entrance of Crooked Creek, from the analysis by Nielsen and Adamantidis (2002).

Ideally, a local wave transformation study should be undertaken to ascertain the water level anomaly due to wave setup. Such a wave transformation study would rely on local bathymetry data and beach slope data. Kulmar et al (2005) presents an AEP plot of significant offshore wave height and wave height duration for Byron Bay based on 28 years of record (**Figure** 5). From the Crooked River Study, which used a combination of offshore SWAN wave transformation modelling and nearshore SBEACH wave transformation modelling, a relationship between offshore significant wave height and wave setup at the creek entrance was derived (**Figure** 6). Two relationships were derived – one for a closed creek entrance and another for an open creek entrance. It was assumed that this relationship would be similar for Belongil Creek, and a wave setup for various AEPs was derived (Table 5).

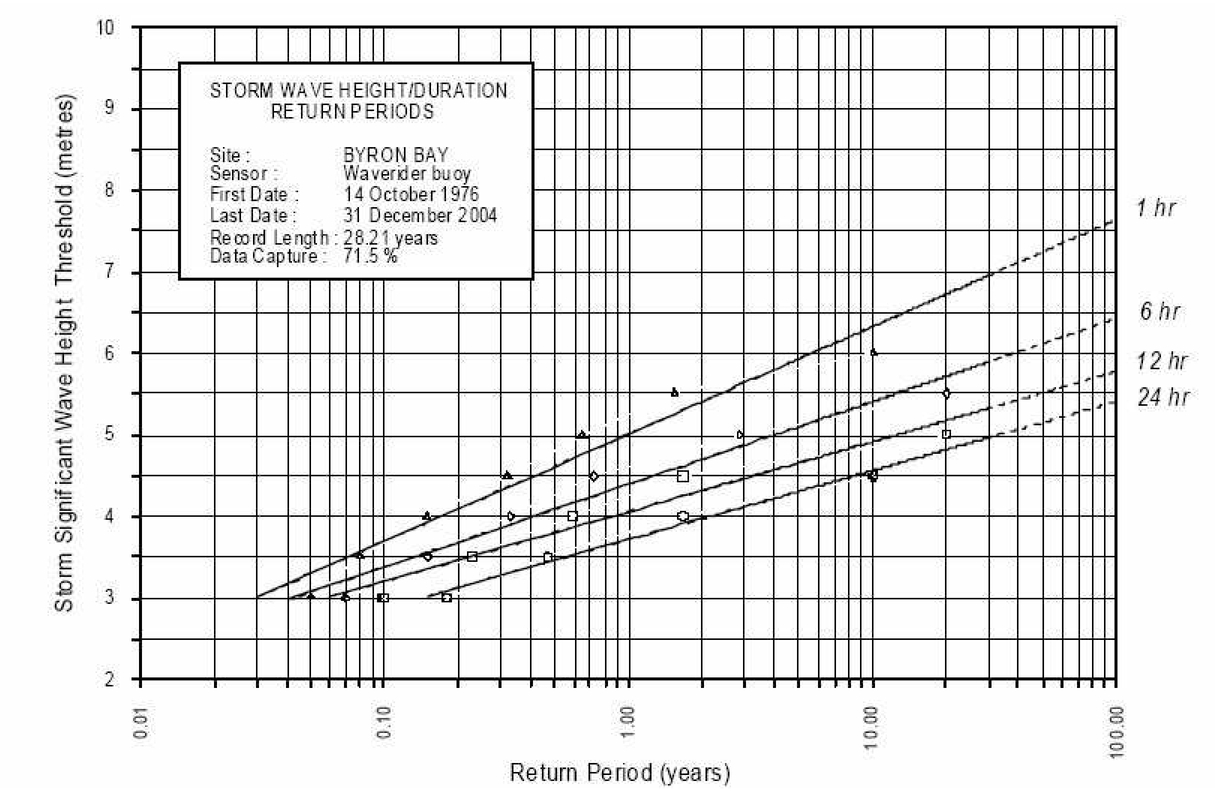


Figure 5 – AEP Plot, Significant wave height at Byron Bay (Kulmar et. al. 2005)

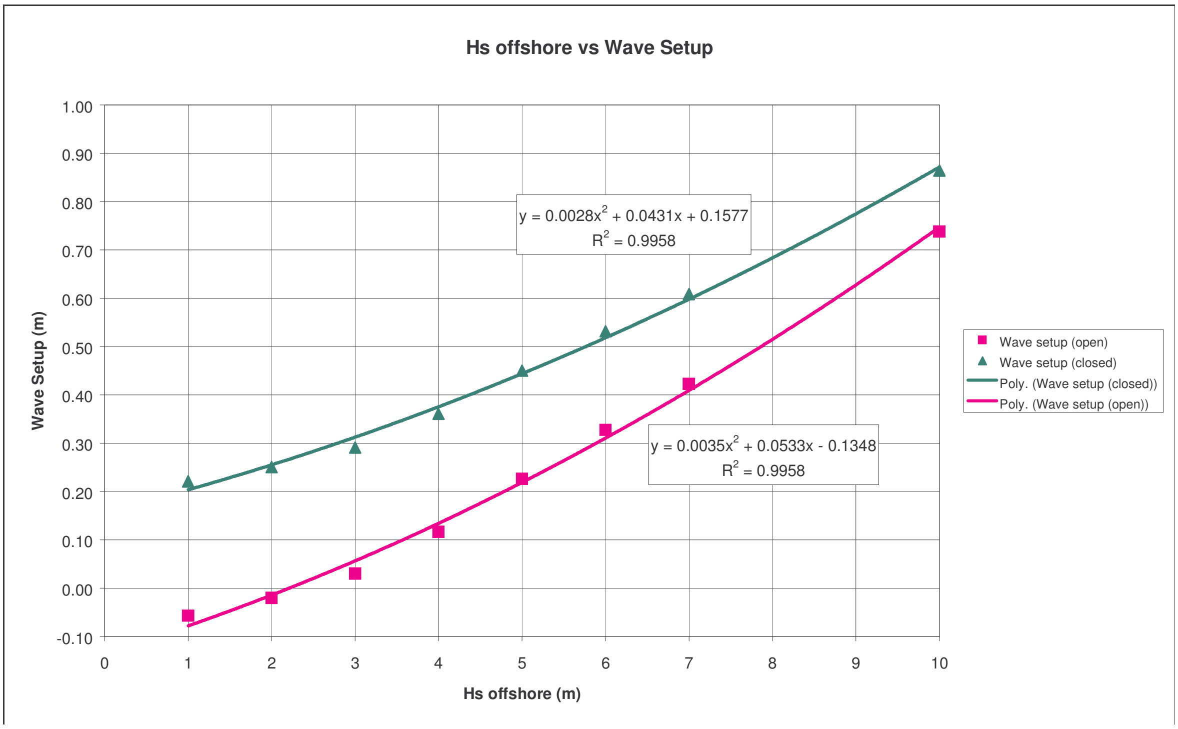


Figure 6 – H_s (offshore) vs Wave Setup at Crooked River Entrance (Nielsen & Adamantidis, 2002)

TABLE 15. ADOPTED WAVE SETUP VS ARI

ARI	Wave Setup Closed Entrance	Wave Setup Open Entrance
5	0.52	0.32
10	0.55	0.35
20	0.57	0.37
50	0.62	0.44
100	0.65	0.45

As for the other water level components, a conservative approach was adopted for the application of wave setup and it was assumed that the maximum wave setup would occur at the same time as the maximum storm surge and maximum spring tide level.

Wave setup for an open creek entrance has been adopted for this study.

Timing of Tailwater Conditions

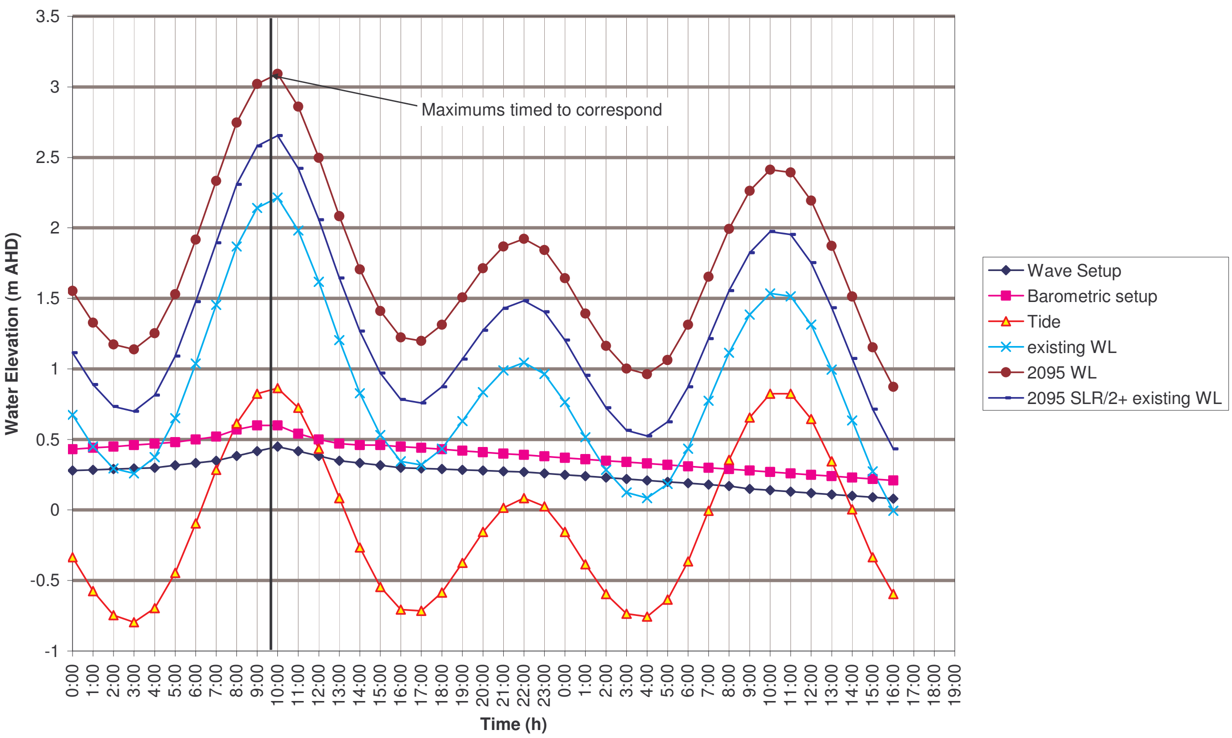


Figure 8 – Plot illustrating coincidence of spring tide, maximum storm surge and wave setup components

APPENDIX 5 : Tuflow Model Documentation

The following model documentation has been sourced from the document:

"TUFLOW User Manual", WBNM Oceanics, June 2006.

Tuflow

TUFLOW is a computer program for simulating depth-averaged, two and one-dimensional free-surface flows such as occurs from floods and tides. TUFLOW, originally developed for just two-dimensional (2D) flows, stands for Two-dimensional Unsteady FLOW. It now incorporates, the full functionality of the ESTRY 1D network or quasi-2D modelling system based on the full one-dimensional (1D) free-surface flow equations (see below). The fully 2D solution algorithm, based on Stelling 1984 and documented in Syme 1991, solves the full two-dimensional, depth averaged, momentum and continuity equations for free-surface flow. The initial development was carried out as a joint research and development project between WBM Oceanics Australia and The University of Queensland in 1990. The project successfully developed a 2D/1D dynamically linked modelling system (Syme 1991). Latter improvements from 1998 to today focus on hydraulic structures, flood modelling, advanced 2D/1D linking and using GIS for data management (Syme 2001a, Syme 2001b). TUFLOW has also been the subject of extensive testing and validation by WBM Pty Ltd and others (Barton 2001, Huxley, 2004).

TUFLOW is specifically orientated towards establishing flow patterns in coastal waters, estuaries, rivers, floodplains and urban areas where the flow patterns are essentially 2D in nature and cannot or would be awkward to represent using a 1D network model.

A powerful feature of TUFLOW is its ability to dynamically link to the 1D network (quasi-2D) hydrodynamic program ESTRY. The user sets up a model as a combination of 1D network domains linked to 2D domains, ie. the 2D and 1D domains are linked to form one model.

TUFLOW solves the depth averaged 2D shallow water equations (SWE). The SWE are the equations of fluid motion used for modelling long waves such as floods, ocean tides and storm surges. They are derived using the hypotheses of vertically uniform horizontal velocity and negligible vertical acceleration (ie. a hydrostatic pressure distribution). These assumptions are valid where the wave length is much greater than the depth of water. In the case of the ocean tide the SWE are applicable everywhere.

The 2-D SWE in the horizontal plane are described by the following partial differential equations of mass continuity and momentum conservation in the X and Y directions for an in-plan cartesian coordinate frame of reference.

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (Hu)}{\partial x} + \frac{\partial (Hv)}{\partial y} = 0$$ (2D Continuity)

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - c_f\, v + g\frac{\partial \zeta}{\partial x} + g\, u\frac{\sqrt{u^2+v^2}}{C^2 H} - \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \frac{1}{\rho}\frac{\partial p}{\partial x} = F_x$$

(X Momentum)

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + c_f\, u + g\frac{\partial \zeta}{\partial y} + g\, v\frac{\sqrt{u^2+v^2}}{C^2 H} - \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \frac{1}{\rho}\frac{\partial p}{\partial y} = F_y$$

(Y Momentum)

where

ζ = *Water surface elevation*

u and v = *Depth averaged velocity components in X and Y directions*

H = *Depth of water*

t = *Time*

x and y = *Distance in X and Y directions*

c_f = *Coriolis force coefficient*

C = *Chezy coefficient*

μ = *Horizontal diffusion of momentum coefficient*

p = *Atmospheric pressure*

ρ = *Density of water*

F_x and F_y = *Sum of components of external forces (eg. wind) in X and Y directions*

The terms of the SWE can be attributed to different physical phenomena. These are propagation of the wave due to gravitational forces, the transport of momentum by advection, the horizontal diffusion of momentum, and external forces such as bed friction, rotation of the earth, wind, wave radiation stresses, and barometric pressure.

The computational procedure used is an alternating direction implicit (ADI) finite difference method based on the work of Stelling, 1984. The method involves two stages each having two steps, giving four steps overall. Each step involves solving a tri-diagonal matrix.

Stage 1, step 1 solves the momentum equation in the Y-direction for the Y-velocities. The equation is solved using a predictor/corrector method, which involves two sweeps. For the first sweep, the calculation proceeds column by column in the Y-direction. If the signs of all velocities in the X-direction are the same the second sweep is not necessary, otherwise the calculation is repeated sweeping in the opposite direction.

The second step of Stage 1 solves for the water levels and X-direction velocities by solving the equations of mass continuity and of momentum in the X-direction. A tri-diagonal equation is obtained by substituting the momentum equation into the mass equation and eliminating the X-velocity. The water levels are calculated and back substituted into the momentum equation to calculate the X-velocities. This process is repeated for a recommended two iterations. Testing on a number of models showed there to be little benefit in using more than two iterations.

Stage 2 proceeds in a similar manner to Stage 1 with the first step using the X-direction momentum equation and the second step using the mass equation and the Y-direction momentum equation.

The solution as formulated by Stelling has been enhanced and improved to provide much more robust wetting and drying of elements, upstream controlled flow regimes (eg. supercritical flow and upstream controlled weir flow), modifications to cells to model structure obverts (eg. bridge decks) and additional energy losses due to fine-scale features such as bridge piers.

ESTRY is a powerful network dynamic flow program suitable for mathematically modelling floods and tides (and/or surges) in a virtually unlimited number of combinations.

The program was developed by WBM Oceanics Australia over a period of twenty-five years and has been successfully applied on hundreds of investigations ranging from simple single channel applications to complex quasi-2D flood models. The network schematisation technique used allows realistic simulation of a wide variety of 1D and quasi-2D situations including complex river geometries, associated floodplains and estuaries. By including non-linear geometry it is possible to provide an accurate representation of the way in which channel conveyance and available storage volumes vary with changing water depth, and of floodplains and tidal flats that become operable only above certain water levels.

There is a considerable amount of flexibility in the way the network elements can be interconnected, allowing the representation of a river by many parallel channels with different resistance characteristics and the simulation of braided streams and rivers with complex branching. This flexibility also allows a variable resolution within the network so that areas of particular interest can be modelled in fine detail with a coarser network representation being used elsewhere.

The model is based on a numerical solution of the unsteady fluid flow equations (momentum and continuity), and includes the inertia terms. This capability of modelling tidal flows has the added advantage of enabling the tidal portion of a flood model to be calibrated separately using readily obtainable measurements of the tide levels and flows. Extension of the calibrated tidal model into the floodplain then results in a more accurate flood model in which the flood channels can be calibrated separately against available flood records.

The 1D solution in TUFLOW uses an explicit finite difference, second-order, Runge-Kutta solution technique (Morrison and Smith, 1978) for the 1-D SWE of continuity and momentum as given by the equations below. An implicit scheme was also developed, however, testing and experience has shown the explicit scheme to be preferred. The equations contain the essential terms for modelling periodic long waves in estuaries and rivers, that is: wave propagation; advection of momentum (inertia terms) and bed friction (Manning's equation).

$$\frac{\partial (uA)}{\partial x} + B\frac{\partial \zeta}{\partial t} = 0 \qquad \text{(1D Continuity)}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial \zeta}{\partial x} + k|u|u = 0 \qquad \text{(2D Momentum)}$$

$where$

$u = depth\ and\ width\ averaged\ velocity$

$\zeta = water\ level$

$t = time$

$x = distance$

$A = cross\ sectional\ area$

$B = width\ of\ \ flow$

$k = energy\ loss\ coefficient = \frac{gn^2}{R^{4/3}}$

$n = M'annings\ n$

$R = Hydraulic\ Radius$

$g = acceleration\ due\ to\ gravity$

In addition to the normal open channel flow situations, a number of special types of channel are available including:

- uniform open channel, with or without specified bed gradient;
- subcritical and supercritical flow regimes;
- non-inertial channels;
- multiple circular or rectangular box culverts;
- bridges;
- weir channels for flow across roadways, levees etc;
- user defined structures; and
- uni-directional channels of any type capable of being specified, to allow flow in only one direction.

The type of information provided as output by the model for a flood or tide simulation includes the water levels, flows, and velocities throughout the area being modelled for the simulation period. Other information available includes maximum and minimum values of these variables as well as total integral flows (integrated with time) through each network channel.