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BUNDEENA CREEK FLOOD STUDY

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ACKNOWLEDGEMENTS

The Bundeena Creek Flood Study has been prepared by WorleyParsons Services Pty Ltd on behalf of Sutherland Shire Council. The project has been funded jointly by Council and the NSW Office of Environment & Heritage (*OEH*) (*formerly the Department of Environment, Climate Change and Water*), under the New South Wales Government's Floodplain Management Program.

The Study is the culmination of many months of investigation, analysis and modelling, which has been supported by valuable contributions from volunteer members of the Bundeena Creek Floodplain Management Committee. Particular thanks are extended to relevant officers at Council and OEH for their technical contribution and guidance over the duration of the study.

FOREWORD

The State Government's Flood Policy is directed towards providing solutions to existing flooding problems in developed areas and ensuring that new development is compatible with the flood hazard and does not create additional flooding problems in other areas. Policy and practice are defined in the Government's Floodplain Development Manual (*2005*).

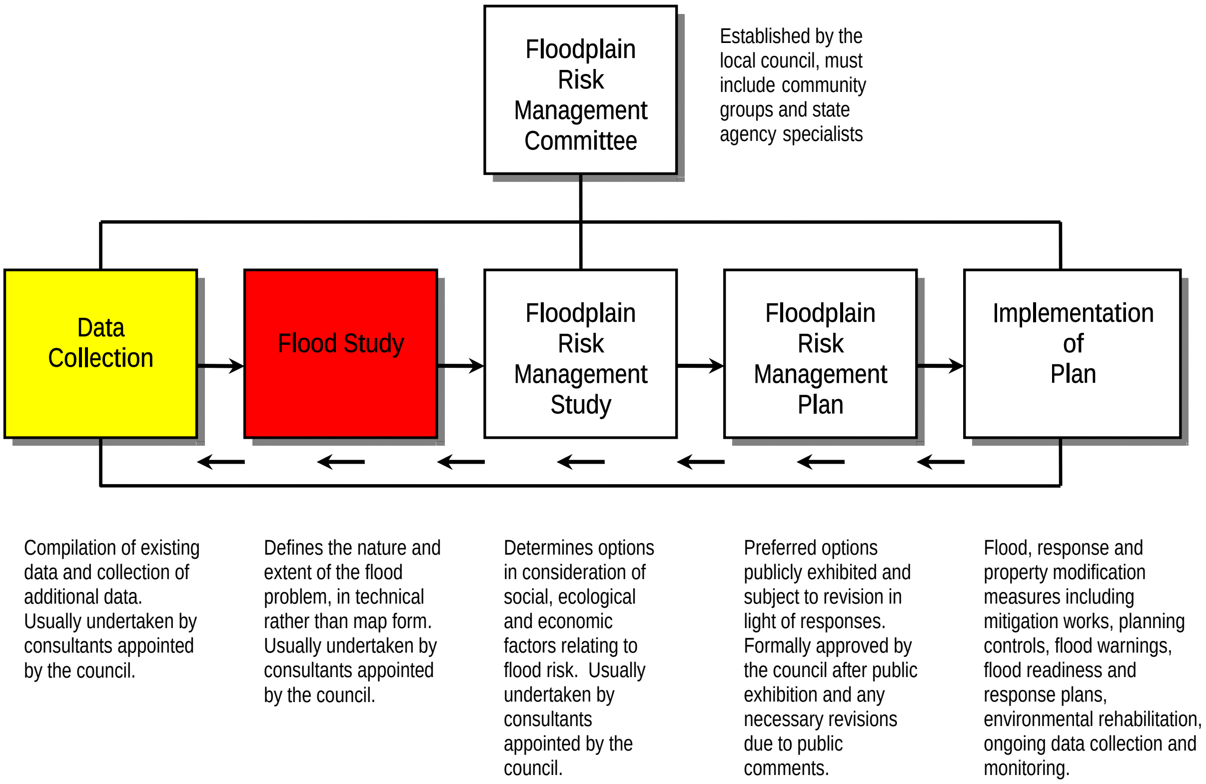
Under the Policy, the management of flood liable land remains the responsibility of Local Government. The State Government subsidises flood mitigation works to alleviate existing problems and provides specialist technical advice to assist Local Government in the discharge of their floodplain risk management responsibilities.

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

STAGES OF FLOODPLAIN RISK MANAGEMENT

STAGE	DESCRIPTION
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 developments.
3. Floodplain Risk Management Plan	Involves formal adoption by Council of a plan of management for the floodplain.
4. Implementation of Plan	Results in construction of flood mitigation works to protect existing development and the application of environmental and planning controls to ensure that new development is compatible with the hazard.

A detailed description of the inter-relationship between these stages is provided overleaf. The link between the various outcomes of the studies involved in the floodplain risk management process and the implementation of measures (*both planning and structural*) to reduce flood damages is also shown.



Source: *'Floodplain Development Manual'* (*2005*)

1. INTRODUCTION

Bundeena Creek drains a 2.8 km^2 catchment that extends south of the township of Bundeena, located at the southern extent of the Sydney basin (*refer* **Figure 1.1**). The catchment is characterised by its basin-like topography with high ground rising within the Royal National Park to the south, west and east. The catchment extends south approximately 1.8 kilometres from Bundeena Bay, to a ridgeline that runs parallel to the Big Marley Trail. The catchment drains north towards its outlet at Horderns Beach in Bundeena Bay.

A significant portion of the township of Bundeena lies in the lower part of the catchment. It should be noted that around 20% of the catchment is located at elevations of 2 m AHD or lower. A coastal sand dune along Horderns Beach forms a ridgeline to the north with an elevation of approximately 4.5 m AHD.

During rainfall events, stormwater runoff is discharged into Bundeena Creek via two main inflows; the western branch and the eastern branch. The western branch drains forested land and is characterised by a relatively sizeable flood storage area (*approximately 3 Ha*) located 350 metres south-west of the Bundeena Bowling and Sports Club (*refer* **Figure 1.1**). The eastern branch drains a combination of forested land to the south and urban area to the north-east. Both branches join in the swamp area located immediately south of Scarborough Street. After passing beneath Scarborough Street the Bundeena Creek channel becomes more defined, meandering towards Bundeena Drive before reaching its outlet at Horderns Beach.

Given the low-lying nature of the basin area located within the northern extent of the catchment, tidal influence on flood levels extends across a majority of the lower catchment.

The Bundeena Creek catchment has a history of local drainage and flooding issues particularly in the low lying areas of the town. The *'Bundeena Flood Management Study'* (*1993*) identified that over 200 properties in Bundeena have been previously affected by flooding. In 2004 Sutherland Shire Council completed an *'Initial Assessment of Major Flooding'* and identified the Bundeena Creek catchment as having the third largest exposure to inundation within the Sutherland LGA. This highlights the need to define flood risk in the Bundeena area.

Major flooding of the catchment has been documented as having occurred in November 1969, February/March 1977 and November 1984. Numerous other less severe floods have also occurred in the catchment in more recent times, with many residents indicating that roads and properties have been inundated as recently as July 2011 and March/April 2012 after relatively minor rainfalls within the catchment.

As such, the modelling to be undertaken during this Flood Study aimed to provide a more robust and detailed definition of flooding behaviour within the study area and a series of maps and datasets that summarise the outputs of the model. This information will then be used directly as part of investigations for the subsequent Floodplain Risk Management Study and Plan.

2. STUDY METHODOLOGY

2.1 STUDY AREA

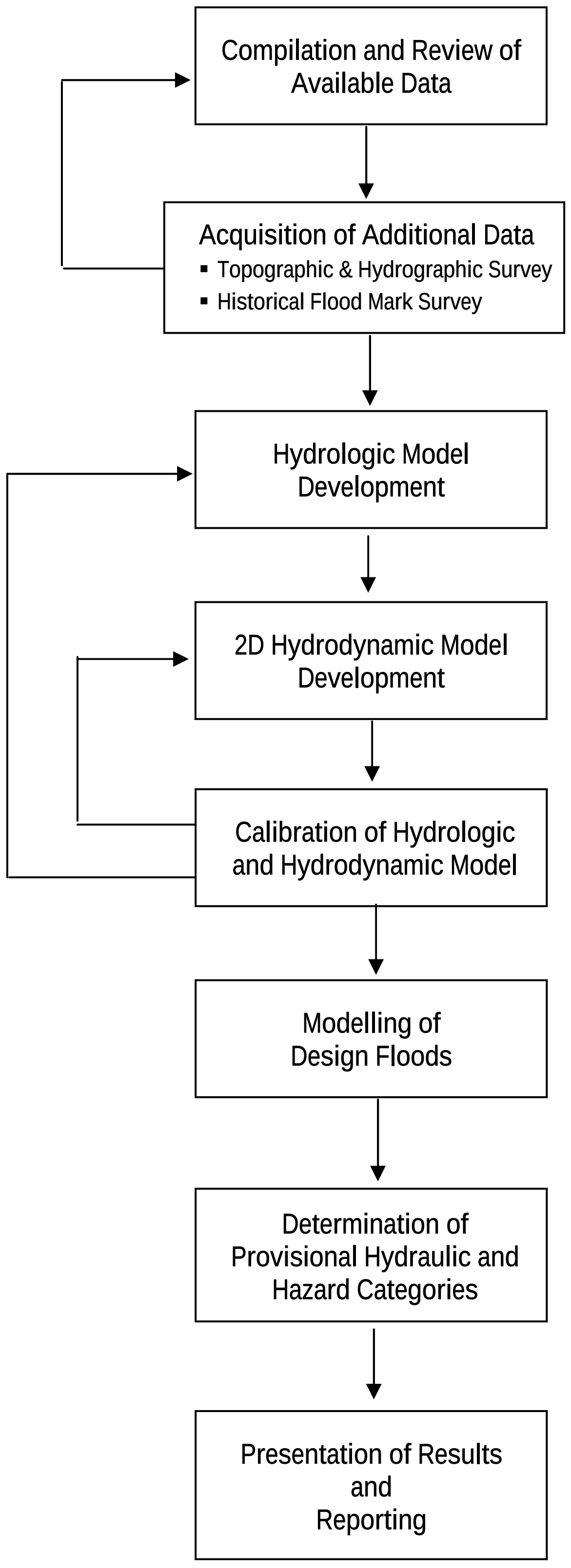
The study area defined by Council for the Flood Study is the Bundeena Creek catchment from the Royal National Park, 1.8 kilometres upstream from the coast down to its confluence with Bundeena Bay at Horderns Beach (*refer* **Figure 1.1**).

2.2 ADOPTED APPROACH

The general approach and methodology employed to achieve the study objectives involved:

- compilation and review of available information, including previously completed flood studies, water level gauge records, rainfall records, topographic mapping of the floodplain and details of bridge crossings and other structures;
- site inspections and interrogation of aerial photography and other GIS data in order to establish catchment roughness, slope and land-use attributes;
- the collection of historical flood information, including records of peak flood levels for previous floods;
- the development of a computer based hydrologic model to simulate the transfer of rainfall into runoff and its concentration in watercourse during flood events;
- the development of a computer based hydrodynamic model to simulate the movement of floodwaters through the Bundeena Creek floodplain;
- calibration and verification of the models;
- the determination of peak flood levels and flow velocities at selected locations along Bundeena Creek for the predicted 200, 100, 50, 20, 10, 5 and 2 year Average Recurrence Interval (ARI) floods (otherwise termed the 0.5%, 1%, 2% 5%, 10%, 20% and 50% Annual Exceedance Probability or AEP floods, respectively) and the Probable Maximum Flood (*PMF*); and
- sensitivity testing of climate change impacts and tailwater conditions (*1% AEP event only*).

The flow chart shown overleaf outlines the key steps and the sequence of work that has been undertaken in preparing this Flood Study.


Compilation and Review of Available Data
Acquisition of Additional Data
▪ Topographic & Hydrographic Survey
▪ Historical Flood Mark Survey
Hydrologic Model Development
2D Hydrodynamic Model Development
Calibration of Hydrologic and Hydrodynamic Model
Modelling of Design Floods
Determination of Provisional Hydraulic and Hazard Categories
Presentation of Results and Reporting

2.3 COMPUTER MODELS

Computer models are the most reliable and cost-effective tools available to simulate flood behaviour in rivers and streams. Two types of computer models were developed as part of the Flood Study for use in assessing and quantifying flooding characteristics within the Bundeena Creek catchment.

These are:

- a hydrologic model, covering the Bundeena Creek and its tributaries within the study area
- a hydrodynamic model, extending along the lower reaches of the Bundeena Creek catchment between upstream areas of elevation of 5 m AHD and its outlet at Horderns Beach.

The **hydrologic model** simulates catchment runoff following a particular rainfall event. The main outputs from the hydrologic model are discharge hydrographs which define the quantity of runoff as well as the rate of rise, timing and magnitude of peak discharges resulting from the rainfall event. The discharge hydrographs are utilised as inputs into the hydrodynamic model.

The **hydrodynamic model** simulates the passage of floodwater along waterway reaches and across floodplain areas. The hydrodynamic model calculates key flooding characteristics such as flood levels, flow velocities, floodwater depths and flood hazard at selected points of interest throughout the study area.

3. REVIEW OF AVAILABLE DATA

3.1 HISTORY OF FLOODING

European settlement commenced in the study area around 1832. It is generally agreed that the largest flood in memory experienced in Bundeena since this time occurred in November 1969. The flood occurred as a result of heavy rainfall across the catchment over a 24 hour period. There are no water level gauges along Bundeena Creek and thus historical peak flood heights have been obtained through anecdotal evidence provided by residents.

Table 3.1 provides a list of documented flood events and the estimated peak levels during these events in Bundeena. A majority of the observations have been sourced from the *'Bundeena Flood Management Study'* (*1985*), unless specified otherwise.

Table 3.1 OBSERVED PEAK FLOOD LEVELS

FLOOD EVENT	PEAK FLOOD LEVEL (*mAHD*)			
	Downstream of Bundeena Drive	Upstream of Bundeena Drive	Downstream of Scarborough Street	Upstream of Scarborough Street
14 November 1969	2.0[1]	1.94, 2.06[1]	2.01 – 2.20	-
11 March 1975	1.32	-	-	-
23 February 1977	-	-	-	1.91-2.01
4 March 1977	-	-	1.83	1.77
8 November 1984	1.11, 1.23	1.20	1.55, <1.90	1.71 – 1.78
July 2011	-	-	-	1.75[2]
8 March 2012	-	-	2.0[2,3]	-

[1] *At Bundeena Drive*

[2] *Approximate level derived from 2013 Community Questionnaire*

[3] *At Scarborough Street*

3.2 PREVIOUS INVESTIGATIONS

A number of previous studies have been undertaken that relate to flooding within the study area. A synopsis of those investigations considered relevant to this study is provided in the following.

3.2.1 Bundeena Creek Flood Investigation (1976)

This study, completed by Cooper, assessed the 1% Annual Exceedence Probability (*AEP*) flood extent for Bundeena using the Rational Method and the Unit Hydrograph Procedure for peak flows and the Manning's Equation to determine levels in Bundeena Creek. The finalised report proposed the construction of a levee bank to a level of 2.8 m AHD to the south of the township, in order to utilise swamp area south of Scarborough Street as a flow retarding basin.

3.2.2 Bundeena Flood Management Study (1985)

A detailed flood study for Bundeena was undertaken by Cameron McNamara. A RORB hydrologic model was produced as part of the study to determine peak flows for the 100 year ARI event. A HEC-2 steady state analysis then determined 100 year ARI water surface profiles. Model calibration used data collected from the November 1969, March 1975, February 1977, March 1977 and November 1984 flood events. As there are no streamflow gauges in the catchment, the study relied heavily on resident interviews and discussions with Council officers. A floodplain risk management component was also included as part of the study, with potential mitigation options modelled using HEC-2 in order to assess their impact and efficiency in alleviating flooding in Bundeena. Five mitigation measures were investigated with a modified retarding basin (*based on the 1976 proposal*) recommended as the most effective mitigation option. It is understood that this option was not implemented due to issues with funding resources and environmental concerns.

3.2.3 Bundeena Flood Management Study (1993)

An updated floodplain risk management study was prepared by Kinhill Engineers. This study involved incorporating new information into the existing flood management study completed by McNamara. The study applied new design rainfall intensities to modelling as per the latest version of '*Australian Rainfall and Runoff – A guide to flood estimation'* (*Institution of Engineers, Australia 1987*). The study recognised new developments within the floodplain and also incorporated Sutherland Shire Council's 1992 topographical survey of the floodplain area. The digital terrain model relied on 2 metre surface contours derived from orthophotos.

A RAFTS hydrologic model was developed in order to determine peak flows entering Bundeena Creek downstream of Scarborough Street for the 20 year and 100 year ARI events as well as the Probable Maximum Flood (*PMF*). A single inflow was extracted and applied to a MIKE-11 hydraulic model that utilised approximately 20 cross-sections taken along the Bundeena Creek floodplain.

The flood study component of the project identified flood levels of 1.88 m AHD and 1.96 m AHD for the 20 year ARI and 100 year ARI events respectively for the area upstream of Scarborough Street.

Flood mitigation options were recommended as part of the floodplain risk management plan component of the project. The study also included recommendations for improving stormwater quality in the Bundeena Creek catchment.

3.2.4 Sea Level Rise Risk Assessment (2011)

GHD completed a Sea Level Rise Risk Assessment for all coastal areas within the Sutherland Shire LGA. The primary aim was to determine the climate change impacts on sea level rise in the vicinity of coastal catchments for the 2050 and 2100 horizons. The study indicated that the current 100 year ARI tide and storm surge ocean level in the vicinity of

Bundeena is 1.51 m AHD. This study assisted in providing contemporary and relevant tailwater levels that have been adopted as part of this study.

3.3 AVAILABLE DATA

A range of data is required to develop a flood model and for that model to be applied to simulate flood behaviour. Typically, contours of the land surface and cross-sections of the river and creek system are required to represent the floodplain topography and channel bathymetry. Details of critical hydraulic controls such as bridges and roadway embankments also need to be defined as they can influence flooding patterns. In addition, surface roughness parameters are required to reflect the influence that land features and vegetation may have on the way floodwaters travel overland. These are usually based on consideration of vegetation density and floodplain geomorphology.

Streamflow data and for historical flood level information is needed for calibration and verification of a flood model. Streamflow data is typically available from gauges where flows or water levels have been recorded over time. In this instance there are no historical or active stream flow gauges located within the Bundeena Creek catchment. Historical flood marks are usually established by field survey after a flood or from anecdotal information provided by those who witnessed or experienced the flood. This data is extremely valuable and can be used to calibrate and verify the flood model.

The data for this study has been obtained from a number of sources including Sutherland Shire Council, the State Water Corporation, the Bureau of Meteorology and the Office of Environment & Heritage (*formerly the Department of Environment, Climate Change & Water* (*DECCW*)).

Historical flood information was gathered from previously published flood level records, most of which was obtained from government agency archives. This was supplemented by data contained in previous investigations and anecdotal recollections and photographs gathered from community members as part of the study.

3.3.1 Topographic Data

An aerial laser survey was undertaken across Bundeena by AAM in 2005. This survey generated *Light Detection and Ranging* (*LiDAR*) data for the study area and nearby areas (*refer* **Figure 3.1**). This information has been made available by Sutherland Shire Council. It comprises spot elevations at an average spacing of 1.2 metres across all terrestrial areas in the study area. Available metadata indicates that spot elevations have a vertical accuracy of 0.2 metres and a horizontal accuracy of 0.4 metres.

The LiDAR data is considered to provide a reliable data-set defining the topography of the Bundeena Creek floodplain and has, therefore, been utilised as the primary source of topographic data for the study.

However, it should be noted that aerial laser survey techniques are unable to penetrate through water. Therefore, the LIDAR data does not include hydrographic features that are often important for flood modelling, such as the bathymetry of streams that carry water under normal flow conditions. That is, the LIDAR data does not always include data defining the bed and banks of the river and creek channels. Analysis of the LiDAR along Bundeena Creek indicates that the channel bed geometry is not clearly picked-up in the data for areas downstream of Scarborough Street.

Given the size and elevation of the Bundeena Creek channel, it is likely the aerial survey would have been conducted during a time when a significant volume of water would have been present in the lower sections of the creek. Trapezoidal extrapolations of the channel from the LiDAR data revealed that the volumes of water present in the LiDAR data are considered to represent a small percentage of the creek channel volume in many locations and a significantly smaller percentage of the wider floodplain volume. However, given the relatively small size of the Bundeena Creek catchment and the localised nature of the flood study it was concluded that additional channel volume may have an impact on flood levels. As such, it would be considered inappropriate to assume that the LiDAR data adequately represents the channel geometry and conveyance capacity of the Bundeena Creek channel. Thus an additional source of topographic data was required in order to adequately capture the bathymetry of Bundeena Creek appropriately for use in a two-dimensional hydrodynamic flood model.

WorleyParsons was able to acquire additional data in the form of a hydrographic survey undertaken by Sutherland Shire Council.

3.3.2 Hydrographic Data

Hydrographic survey of Bundeena Creek was undertaken by Sutherland Shire Council in 1984 and was updated in 1992. This survey encompassed a portion of the study area including cross-sections along Bundeena Creek between the southern extent of Liverpool Street and the outlet at Horderns Beach (*refer* **Figure 3.1**).

Using these cross-sections, a hydrographic surface of the Bundeena Creek channel was able to be created through the use of data point interpolation. This surface was used to complement the LiDAR within the hydrodynamic model's topographic database.

It should be noted that the cross-section data was provided in scanned PDF format. Therefore WorleyParsons was required to digitise these sections at their respective locations. In addition, WorleyParsons recognise that the geometry of the channel may have undergone some geomorphic change since the time of the survey. Accordingly, the LiDAR data was utilised to derive the present-day location and width of the channel while the Bundeena Creek hydrographic survey provided an indication of channel depth/shape below the standing water level. This approach ensured that the contemporary alignment of the creek was captured, but it also ensured that additional channel conveyance capacity was incorporated into the flood model.

3.3.3 Sub-Surface Drainage Data

In addition to floodwaters escaping the Bundeena Creek channel, high water levels in Bundeena Creek may also "back-up" the local sub-surface drainage network, inundating low lying areas of the catchment further from the creek. As such, it was deemed appropriate to incorporate the sub-surface drainage infrastructure of Bundeena into the hydraulic analysis for the Flood Study.

Accordingly, a detailed survey of key sub-surface drainage infrastructure was undertaken by Watson Buchan in April 2013. This survey encompassed sub-surface infrastructure that was located in the low-lying portion of the catchment; i.e., less than 2 metres AHD. The survey incorporated the stormwater pit and pipe network located along sections of Bundeena Drive, Liverpool Street, Horderns Lane, Thompson Street and Laurence Avenue (*refer* **Figure 3.1**).

3.3.4 Hydrologic Data

Extensive searches were also undertaken to obtain as much hydrologic data as possible for the Bundeena Creek catchment, for the purpose of setting model boundary conditions and model calibration. Typically, hydrologic data for coastal catchments usually exists in three forms, namely:

- pluviometer and daily read rain gauge rainfall records;
- stream discharge records (*however, no stream gauges exist along Bundeena Creek*); and
- tidal gauge records.

A summary of the data that was obtained is outlined in the following.

Historical Rainfall Data

Continuous rainfall data for specific storms is typically required for the calibration and verification of hydrologic computer models. This data is usually obtained from pluviometers located within or in the immediate vicinity of the catchment being modelled. Pluviometers generate plots of the instantaneous variation in rainfall over time.

An investigation was carried out to determine the location and details of rainfall gauges within the catchment and in the vicinity of the study area. The investigation included a search of the Bureau of Meteorology's (*BOM*) Water Resources Station Catalogue and New South Wales' Government's Water Information Database.

The investigation determined that no pluviometer stations are located within the study area. However, a combination of daily read and pluviometer rainfall stations were identified within and immediately north of the study area.

A summary of the gauges and the recorded rainfall data available for each of these gauges is listed in **Table 3.2**.

Table 3.2 SUMMARY OF INVESTIGATED RAINFALL GAUGES

RAINFALL GAUGE NAME	TYPE	LOCATION *[lat, long]*	DURATION OF RECORD AVAILABLE
Bundeena Composite	Daily Read	-34.08º, 151.15º	1964 to 1978
Bundeena Bowling Club	Daily Read	-34.08º, 151.15º	Unknown
Cronulla South Bowling Club	Daily Read	-34.07º, 151.15º	1934 to present
Sydney Airport AMO	Pluviometer	-33.95º, 151.17º	1994 to present

Tidal Data

Water level conditions in Bundeena Bay form the downstream boundary condition for the Flood Study. During a typical storm this water level can comprise tidal influence, storm surge and wave set-up.

The Manly Hydraulics Laboratory (*MHL*) has captured a time series record of tidal levels at Port Hacking since 1987. The Port Hacking tidal gauge is located within 1 kilometre of the foreshore of Horderns Beach and therefore is considered to provide the most appropriate approximation of tidal levels experienced at the mouth of Bundeena Creek. For dates prior to 1987 Sydney Ports Corporation recommend the use of tidal data recorded at Fort Denison to provide indicative tidal levels experienced at the outlet of Bundeena Creek. Fort Denison is located approximately 25 kilometres north-east of Bundeena in Sydney Harbour. A summary of the gauge information and the extent of the records are provided in **Table 3.3**.

Table 3.3 SUMMARY OF INVESTIGATED TIDAL STATIONS

GAUGING STATION NAME	LOCATION *[lat, long]*	DURATION OF RECORD AVAILABLE
Port Hacking	-34.19º, 151.25º	1987 to present
Fort Denison	-33.51º, 151.14º	1914 to present

3.3.5 Historical Flood Levels

Useful information from historical flood events was provided in previous studies, primarily the flood marks surveyed by as part of the Cameron McNamara study (*1985*). This included a list of recorded flood marks (*and their associated levels in metres above Australian Height Datum*) at a number of locations for various flood events, mainly relating to the November 1969 and November 1984 floods.

A number of photographs and indicative flood depths relating to other historic floods between 1969 and 2012 were also provided by Council and the Bundeena community.

3.3.6 Other Geographic Data

Various other sets of geographic data relating to the study area were also obtained from Sutherland Shire Council and other public domain / government sources. This includes aerial photography and GIS layers for cadastre, roadway, and sub-surface drainage information.

4. HYDROLOGIC MODELLING

4.1 HYDROLOGIC MODEL DEVELOPMENT

A hydrologic model of the Bundeena Creek Catchment was developed to simulate rainfall and runoff processes in the catchment and produce the creek flows (*discharges*) that are required to determine flood levels in the subsequent hydrodynamic models. The Runoff Analysis and Flow Training Simulation (*XP-RAFTS*) software package was used with the objective of quantifying design flood discharges from the upper sections of the catchment.

XP-RAFTS can be used to develop a deterministic runoff routing model for the simulation of catchment runoff processes. It incorporates a range of common catchment parameters into its calculation procedures and is recognised in *'Australian Rainfall and Runoff – A guide to Flood Estimation'* (*1987*) as a suitable tool for use in flood routing within Australian catchments.

XP-RAFTS was chosen for this investigation because it has the following attributes:

- it can account for spatial and temporal variations in storm rainfalls across a catchment;
- it can accommodate variations in catchment characteristics;
- it can be used to estimate discharge hydrographs at any location within a catchment; and,
- it has been widely used across eastern NSW and therefore, where suitable calibration data is not available, the results from modelling of other similar catchments can be used as a guide in the determination of model parameters.

The XP-RAFTS model was developed using a range of physical characteristics of the catchment. These include subcatchment area, average slope, percentage of impervious area and roughness. The model accounts for rainfall losses and routes the excess rainfall through the catchment of interest.

The model was used to estimate subcatchment runoff peaks and to generate discharge hydrographs for calibration simulations and to generate design inflow hydrographs for the subsequent hydrodynamic model simulations.

4.1.1 Subcatchment Details and Model Layout

In addition to the LiDAR topographic data across the catchment, Council's sub-surface drainage data was also used to define the subcatchment boundaries throughout the urbanised areas of Bundeena. These boundaries were checked during a detailed walkover of the catchment. LIDAR data and aerial photography were also used to confirm the subcatchment delineation within the study area.

The catchment definition process resulted in the creation of 19 subcatchments within the study area (*refer* **Figure 4.1**). Given the relatively small size of the catchment, a high resolution of subcatchments was adopted in order to define inflows at a level of detail suitable for a localised flood study.

Subcatchments were also differentiated on the basis of the alignment of major tributary flow paths and watershed boundaries, as well as the homogeneity of land use, vegetation and ground slope. Parameters such as catchment area, slope, and roughness and percentage impervious area were established from the available data and assigned to each subcatchment accordingly. Subcatchment boundaries were inserted at the locations where input hydrographs were to be extracted for hydrodynamic modelling.

The XP-RAFTS model development involved the creation of a node link arrangement over the subcatchment break-up shown in **Figure 4.1**. This provides the pathways for excess rainfall to be "routed" through each of the subcatchments. Details of the catchment parameters adopted for each model node, including lag times for floodwater passing between nodes, is contained in **Appendix A**.

4.1.2 Adopted Hydrologic Model Parameters

Rainfall Loss Model

In a typical rainfall event, not all of the rainfall that falls onto the catchment is converted to runoff. Depending on the prevailing 'wetness conditions' of the catchment at the commencement of the storm (*i.e., the antecedent wetness conditions*), some of the rainfall may be lost to the groundwater system through infiltration into the soil, or may be intercepted by vegetation and stored. This component of the overall rainfall is considered to be 'lost' from the system and does not contribute to the catchment runoff.

To account for rainfall losses of this nature, a rainfall loss model can be incorporated within the XP-RAFTS hydrologic model. For this study, the ***Initial-Continuing Loss Model*** was employed to simulate rainfall losses across the catchment. This model assumes that a specified amount of rainfall (*e.g., 10 mm*) is lost from the system to simulate initial catchment wetting when no runoff is produced, and that further losses occur at a specified rate per hour (*e.g., 1.5 mm/hour*). These further losses are referred to as continuing losses which aim to account for infiltration once the catchment is saturated. Both the initial and continuing losses are effectively deducted from the total rainfall over the catchment, thereby leaving the remaining rainfall to be distributed through the watershed as runoff.

As no definitive loss rate data is available for the Bundeena Creek catchment, initial estimates of rainfall loss rates were based on data contained in previous studies and on recommendations outlined in the XP-RAFTS User Manual and documented in *'Australian Rainfall and Runoff'* (*1987 and 1998*). As with previous flood studies, the percentage impervious areas for each sub-catchment were considered when assigning loss rates. The adopted loss rates are listed in **Appendix A**.

Adopted Roughness

Roughness values were assigned to each sub-catchment in the XP-RAFTS hydrologic model based on aerial photography of the Bundeena Creek catchment. The adopted Mannings 'n' values for each sub-catchment are listed in **Appendix A**.

4.1.3 Critical Duration and Design Storm Information

Rainfall Intensity-Frequency-Distribution (IFD) data for the catchment was obtained using the Bureau of Meteorology's online IFD tool (http://www.bom.gov.au/hydro/has/cdirswebx/), which is based on *'Australian Rainfall and Runoff – A Guide to Flood Estimation'* (1987). A copy of this data is provided in **Appendix A**.

In order to determine the critical storm duration for the Bundeena Creek catchment, a number of durations were tested for the 20%, 5% and 1% AEP events and PMF using the XP-RAFTS hydrologic model. **Table 4.1** provides a summary of the total peak discharges at the outlet at Horderns Beach for a range of durations for the 1% AEP storm. The highest discharge was derived for the 90 minute event, which was also reflected in the results for all individual sub-catchments, and also applied to the other frequency events. As such, the critical storm duration for the Bundeena Creek catchment is considered to be 90 minutes.

Table 4.1 SUMMARY OF CRITICAL STORM DURATION ANALYSIS

STORM DURATION *[minutes]*	TOTAL PEAK OUTLET DISCHARGE IN 1% AEP STORM *[m³/s]*
30	39.8
60	52.7
90	56.5
120	55.5

4.2 HYDROLOGIC MODEL CALBRIATION & VERIFICATION

Flood routing models such as XP-RAFTS should be calibrated or verified to confirm the accuracy of peak discharges and the total volume of runoff derived during a simulation. Conventionally, calibration involves the comparison of streamflow data from specific historic events against modelled discharges. In this instance, calibration of the XP-RAFTS in its own right is not possible as there are no streamflow gauges located on Bundeena Creek. However, the model was used to simulate the historic rainfall during storms in 1969, 1984 and 2012 to prepare discharge hydrographs for calibration of the TUFLOW hydraulic model (*refer* **Section 5.3**).

In cases where direct calibration is not possible verification against Rational Method calculations is considered practical. **Table 4.2** provides a comparison of calculated versus modelled 1% AEP peak discharges for key subcatchments in the Bundeena Creek catchment.

Table 4.2 XP-RAFTS MODEL RESULTS FOR 1% AEP EVENT

INDICATIVE LOCATION	XP-RAFTS NODE / SUBCATCHMENT (*refer* Figure 4.1)	PEAK DISCHARGE (XP-RAFTS) [m^3/s]	PEAK DISCHARGE (RATIONAL METHOD) [m^3/s]	DIFFERENCE [%]
Eastern Branch	Junction of 1E & 2E	16.8	6.3	63
Western Branch (Downstream of Flood Storage Area)	4W	20.4	22.4	9.7
Upstream of Scarborough Street	3M	55.2	54.4	1.5
Upstream of Bundeena Drive	4M	55.0	55.6	1.2
Horderns Beach Outlet	7M	56.5	59.5	5.3

The differences between the XP-RAFTS model results and the Rational Method calculation are generally less than 10%. Flows were noted to be considerably higher in the XP-RAFTS model at the Eastern Branch of Bundeena Creek. The Rational Method does not take into account catchment slope and thus tends to understate the peak discharges of steeper catchments. Upstream catchments draining to the point examined on the Eastern Branch are notably steep (*in the order of 10-15%, refer* **Figure 4.1**). As such, peak discharges would be expected to be larger than those determined by the Rational Method calculations.

It is considered that the XP-RAFTS model produces suitably reliable results for the purposes of this study, which was further confirmed as part of calibration of the TUFLOW model (*refer* **Section 5.3**).

5. HYDRODYNAMIC MODELLING

5.1 GENERAL

One of the most important outcomes from the study is the determination of peak flood levels, depths and flow velocities for a range of design floods. This information can be used to determine hydraulic categories (*floodway, flood storage and flood fringe*) and the variability in flood hazard across the floodplain. It will assist Sutherland Shire Council in future land use planning and in the assessment of development proposals.

As outlined in **Section 2.3**, computer models can be used to simulate flood behaviour and quantify key flood characteristics such as flood levels, flow velocities, floodwater depths and flood hazard at selected points of interest. The TUFLOW hydraulic modelling software package was chosen as the tool for this purpose and was applied to develop a computer model for the Bundeena Creek floodplain.

TUFLOW employs a finite difference, two-dimensional (*2D*) approach based around a regular grid. This grid serves as the basis on which the continuity and conservation of momentum equations (*Saint Venant equations*) are solved. Constraints to the equations, such as the catchment topography, catchment roughness, inflow and outflow boundaries or links to one-dimensional (*1D*) elements are all included in the model as exports from a GIS database. This database approach makes TUFLOW a powerful tool for developing complex one-dimensional (*1D*), two-dimensional (*2D*) and linked 1D / 2D flood models.

The upstream extents of the model are generally defined at less than 4 m AHD. The size and shape of the study area is such that it is practical to create a single two-dimensional model network that incorporates the entire area at a suitable level of resolution.

Development of the computer flood model was carried out over several stages and involved the following:

- Collation of all available topographic data to develop a Digital Terrain Model (*DTM*) of the area covered by the flood model. This data is converted to a grid with specified dimensions within the 2D network of the TUFLOW model. The data is also used to generate a bathymetric surface representative of the Bundeena Creek channel as it passes through the study area.
- Augmentation of the DTM to include important topographical features that may not have been included in the aerial survey data or that may be too fine to be easily “picked up” by the size of the grids within the TUFLOW network. For example, levees or retaining walls with widths of less than 1 metre are typically not adequately recognised within model networks with grid sizes of between 1 and 5 metres. Therefore, the topographic information needs to be manually adjusted to override the default elevations at critical locations.
- Use of aerial photography and other GIS data to define land-use areas for definition of hydraulic roughness throughout the model area.
- Calibration and verification of the flood model to historic flood events such as the November 1969, November 1984 and March 2012 flood events.

5.2 HYDRODYNAMIC MODEL DEVELOPMENT

5.2.1 2D Model Network Development

The overbank/floodplain topography within the study area is well represented by the terrain model constructed using the available LiDAR data. As discussed in **Section 3**, a hydrographic surface of the Bundeena Creek channel bathymetry was able to be created through the use of data point interpolation of surveyed points. This surface was used to complement the LiDAR within the model's topographic database.

The topography was used to define a grid within the 2D network of the model which consisted of square grids with a width of 1 metre. TUFLOW further divides each grid into four smaller squares in order to perform its hydraulic calculations. Therefore, the topography is eventually sampled at 0.5 metre intervals. Trial simulations of a preliminary model network setup indicated that the definition of flowpaths and terrain objects was adequate at this resolution.

The extent of the two-dimensional TUFLOW model network is shown in **Figure 5.1**.

Augmentation of the topographic data was also required in order to ensure adequate definition of any important topographical features that may not have been captured in the LiDAR data-set or that may have been too fine to be "picked up" within the 1 metre grid size. It is also important that the crest levels are used as the elevation value for the representative grid cell for such features; i.e. roads and levee embankments. Locations that received particular attention within the study area included the Bundeena Creek channel, the retaining wall structures near the outlet at Horderns Beach, the retaining wall structure downstream of Scarborough Street, and the level of the roadway along Bundeena Drive. The topography incorporated into the TUFLOW model is shown in **Figure 5.2** and **Figure 5.3**, depending on outlet configuration being partially blocked versus scoured (*see* **Section 5.3.3** *for further details*).

The locations of all bridge crossings and other structures across watercourses and flowpaths within the model were determined using the available aerial photography and Council's GIS information. They were also confirmed during site inspections. A total of five structures were identified, as listed in **Table 5.1** and shown in **Figure 5.4**.

These structures were predicted to be submerged during some or all of the design flood events and it was necessary to include these in the final model network. They have been modelled as flow constrictions within the TUFLOW model. Data was entered into the TUFLOW network that defined the dimensions of the structure (*e.g., bridge deck level or culvert dimensions*) as well as a corresponding rise in the hydraulic roughness value of the stream in the vicinity of the crossing to account for hydraulic losses.

Table 5.1 STRUCTURES WITHIN HYDRODYNAMIC MODEL

LOCATION	DETAILS
Scarborough Street Culvert	Single culvert (deck level approx. 1.60 mAHD)
Bundeena Drive Culvert	Four culverts (deck level approx. 1.93 mAHD)
Pedestrian Footbridge 1 (located between Lot DP4733 and Bundeena Drive)	Deck level of 1.3 m AHD
Pedestrian Footbridge 2 (located between Lots DP202961 and DP4733)	Deck level of 1.8 m AHD
Pedestrian Footbridge 3 (at Horderns Beach)	Arched footbridge connecting eastern bank to Horderns Beach with deck level varying from 1.5 – 2.8 mAHD

5.2.2 Model Roughness

Main channel and overbank roughness values were estimated for the study area using aerial photographs and field observations of channel and floodplain vegetation density. The adopted roughness values were determined by comparing vegetation density and soil types observed in the field, with standard photographic records of stream and floodplain condition for which roughness values are documented.

Buildings within the floodplain were also assigned a high roughness factor across their footprint in order appropriately model flood behaviour through urban areas. Assigned roughness polygons within the active boundary of the 2D grid are shown in **Figure 5.5**.

5.2.3 1D Model Network Development

During flood events, high water levels within Bundeena Creek can cause a "backing-up" of flow through the sub-surface drainage network surcharging from local drainage pits and inundating low lying areas prior to, or simultaneously with the overtopping of the creek channel. The stormwater pits and pipes also provide drainage from these areas in lesser storm events. The sub-surface drainage network survey data was used to create a pits and pipes one-dimensional network that incorporates selected areas along Laurence Avenue, Thompson Street, Horderns Lane, Liverpool Street and Bundeena Drive (*refer* **Figure 5.4**). This was incorporated into the TUFLOW model to enable the simulation of pit surcharge. A total of 45 pits and 1 kilometre of pipe network have been incorporated into the TUFLOW model.

5.2.4 Model Boundary Conditions

Flood models require inflow boundaries to define stream discharges entering the model at the upstream limits, local inflows to define runoff that enters the model from subcatchments located within the network itself and a relationship to define the hydraulic conditions at the downstream boundary. The locations of these boundaries are shown in **Figure 5.6**.

Upstream Inflow Boundaries

As discussed in **Section 4**, the upstream boundary conditions for the hydrodynamic model are provided by discharge hydrographs generated from hydrologic modelling of the upstream subcatchments. Discharge hydrographs were generated at each of the upstream inflow locations identified in **Figure 5.6** from the results of the hydrologic modelling that was undertaken using the XP-RAFTS model. These inflow locations correspond to the locations where the hydrologic model intersects with the TUFLOW model for Bundeena Creek.

The XP-RAFTS model layout was structured to ensure discharge hydrographs were generated at these locations. The XP-RAFTS model nodes corresponding to these inflow locations are listed in **Table 5.2**.

Table 5.2 UPSTREAM BOUNDARY CONDITIONS FOR HYDRODYNAMIC MODEL

TRIBUTARY	LOCATION (*refer* Figure 5.6)	XP-RAFTS MODEL NODE (*refer* Figure 4.1)
Eastern Branch	Approximately 200 metres west of the corner of Eric Street and Beachcomber Avenue	Junction of 1E & 2E
Western Branch	Approximately 750 metres south of the Bundeena Bowling and Sports Club	2W

Local Inflow Boundaries

Runoff that is generated within subcatchments downstream of the upstream boundaries enter the model as local inflows directly into the network. The local inflow polygons are shown in in **Figure 5.6**, which represent those parts of the corresponding subcatchment polygon that intersect with the TUFLOW model network. The discharge hydrograph calculated for each subcatchment is distributed directly into watercourses within the inflow polygons.

Downstream Boundary

Flows from Bundeena Creek discharge to the Pacific Ocean at Horderns Beach. As shown in **Figure 5.6**, the water level at the downstream extent of the hydraulic model is governed by the variation in ocean level at the creeks outlet in Bundeena Bay.

For calibration simulations ocean levels have been based on recorded data from Fort Denison and Port Hacking as no recordings have been made at the mouth of Bundeena Creek during major flood events. While this approach is deemed appropriate for calibration, design events will adopt design ocean levels as well as incorporated storm surge and wave set up influences.

5.3 TUFLOW MODEL CALIBRATION

Calibration and verification of the hydrodynamic flood model is an important step in the model development process. If an acceptable calibration of the model to recorded events can be achieved, it demonstrates the reliability of the results of the subsequent design flood simulations.

Calibration of the hydrodynamic model was undertaken for the November 1969, November 1984 and March 2012 historical floods. Streamflows derived from hydrologic modelling of rainfall-runoff processes across the upper and local subcatchment areas for each of these historic storm events were simulated in the hydrodynamic flood model.

Flood levels generated from the simulations were then compared to historical flood recollections. Calibration of the model was achieved by adjusting floodplain roughness parameters within acceptable limits to obtain the best 'fit' between simulated and recorded peak flood levels.

5.3.1 Available Historic Flood Level Information

A flooding questionnaire was distributed to residents within the study area as part of the study. A total of 86 responses were received to the questionnaire, which requested respondents provide details of any specific recollections they may have with respect to observed peak flood levels or known debris marks. Three observations were provided that could reliably be used to determine peak flood levels or extents during the calibration process for the three chosen historical flood events.

Similar data was also obtained during the Cameron McNamara Bundeena Flood Management Study (*1993*). The most useful information was extracted to complement the questionnaire feedback.

The historical flood level data chosen for calibration is summarised in **Table 5.3**.

Table 5.3 HISTORIC FLOOD LEVEL INFORMATION USED IN MODEL CALIBRATION

EVENT	LOCATION (*refer* Figures 5.7 to 5.9)	PEAK FLOOD LEVEL *[mAHD]*	SOURCE OF INFORMATION
14 November 1969	Bundeena Service Station	~ 2.30	Community Questionnaire
14 November 1969	Bundeena Drive	2.00 – 2.06	Previous study[1]
14 November 1969	Downstream of Scarborough Street	2.01 – 2.20	Previous Study[1]
8 November 1984	Cnr Simpson Rd & Bundeena Dr	~ 2.10	Community Questionnaire
8 November 1984	Upstream of Bundeena Drive	1.20	Previous study[1]
8 November 1984	Downstream of Scarborough Street	1.55 – 1.90	Previous study[1]
8 March 2012	Scarborough Street	~ 2.00	Community Questionnaire

[1] *Bundeena Flood Management Study Cameron McNamara (1993)*

5.3.2 Boundary Condition Data

Historic pluviograph rainfall data is required in order to calibrate hydrologic and hydrodynamic models to historic flood levels. In this instance there was a distinct lack of rainfall data for the Bundeena Creek catchment. The most reliable and accessible daily read rainfall data is recorded at the Cronulla South Bowling Club gauge, located 1.5 kilometres north of Bundeena. In order to generate appropriate record of continuous rainfall experienced in Bundeena during each historical flood, Cronulla South Bowling Club rainfall totals were applied to the temporal patterns recorded at the nearest pluviograph at Sydney Airport, located 16 kilometres north of Bundeena. This provided an estimation of varying rainfall intensity across a 24 hour period, which was considered necessary for the calibration of a small sized catchment with a low time of concentrations. Graphs showing the estimated cumulative rainfall recorded during these periods in the vicinity of Bundeena are presented in **Appendix B**.

The adopted continuous rainfall data was routed through the XP-RAFTS hydrologic model to generate inflow hydrographs for the November 1969, November 1984 and March 2012 flood events at the appropriate upstream and local inflow boundary locations in the TUFLOW model.

Tidal information for Sydney Harbour (*Fort Denison*) and Port Hacking was used to generate maximum still water levels within Bundeena Bay for all three calibration events (*refer* **Table 5.4**). These peak tidal levels were applied as downstream boundary conditions for each respective calibration event.

Table 5.4 HISTORIC PEAK TIDAL LEVEL INFORMATION USED IN MODEL CALIBRATION

EVENT	LOCATION	PEAK TIDAL LEVEL *[mAHD]*	SOURCE OF INFORMATION
November 1969	Fort Denison	0.94	Sydney Port Corporation
November 1984	Fort Denison	0.79	Sydney Port Corporation
March 2012	Port Hacking	1.16	Manly Hydraulics Laboratory

5.3.3 Calibration Simulations

The TUFLOW flood model was used to simulate the November 1969, November 1984 and March 2012 flood events. Final calibrated modelling results for these historic events are presented in **Appendix C**.

Some modifications were made to the model network during the calibration process, which primarily included the checking of boundary conditions and the minor adjustment of floodplain roughness parameters (*within reasonable limits*). These changes were made to achieve an improved "fit" between simulated and observed flood levels throughout the study area.

It was noted that the geometry of the creek mouth may have influenced peak water levels experienced throughout Bundeena during historical flooding. During both the November 1969 and March 2012 events, minimal rainfall had fallen prior to the high intensity storms that caused flooding along Bundeena Creek. As such, the potential for scour at the outlet would have been minimal prior to the respective flood events. Accordingly, for these events the creek outlet was modelled as defined by the existing LiDAR, with a slight beach berm (*0.5 – 1.0 metre rise*) aligned across the outlet, providing very low outflow.

However, four days prior to the November 1984 event Bundeena received 100 mm of rainfall (*refer* **Appendix B**). As such, it is likely that some form of scour would have occurred at the outlet during the days prior to flooding and therefore, it is reasonable to assume that the outlet would have been "free-draining" during the November 1984 flood. This is reflected in the 0.7 metre difference in flood levels observed between Scarborough Street and Bundeena Drive during the 1984 event (*refer* **Table 5.3**), which indicates that there was a significant grade on the flood surface profile, typical of fully open entrance conditions. A terrain alteration was made in the model to remove the berm across the outlet to account for the scour as part of this simulation.

A comparison of the final calibrated model results and the observed flood levels at Bundeena Drive and Scarborough Street is provided in **Table 5.5** and also in **Figures C.1** to **C.3**. Depth and velocity mapping for the calibration events is shown in **Figures C.4** to **C.6**.

Table 5.5 COMPARISON OF OBSERVED AND MODELLED PEAK LEVELS FOR HISTORIC FLOOD EVENTS

LOCATION	PEAK FLOOD LEVEL [*mAHD*]					
	November 1969		November 1984		March 2012	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
Bundeena Drive	2.00 – 2.06	2.02	1.20	1.30	N/A	2.00
Scarborough Street	2.01 – 2.20	2.13	1.55 – 1.90	1.90	2.00	2.09

5.3.4 Summary

The modelling results for all three calibration events indicate that generally good agreement between observed and simulated flood levels was obtained using the TUFLOW model. The differences between the upper limit of the observed levels and simulated levels in the vicinity of Scarborough Street and Bundeena Drive were within 100 millimetres for all three calibration events.

As discussed, flood levels in the vicinity of Bundeena Drive were highly influenced by the adopted creek mouth geometry at Horderns Beach. The relevant outlet geometry applied at the downstream boundary resulted in peak flood levels at Bundeena Drive that closely matched those observed during all three events.

In order to ensure uniformity between the three events, a single set of final roughness was chosen to represent the modelled area for the three selected events. Accordingly, it was necessary to select parameters that resulted in the best overall “fit” for the modelled results in relation to the observed data across the three events.

In conclusion, it is considered that the TUFLOW model provides a reliable and suitably calibrated tool for the simulation of design floods for the study area. The final roughness values applied to all three calibrated events are listed in **Table 5.6**. These values are in general agreement with the calibrated roughness parameters derived during the *Bundeena Flood Management Study* (*1993*), where values for the one-dimensional cross-sections of the creek were generally between 0.025 and 0.1.

Table 5.6 FINAL ROUGHNESS VALUES USED IN TUFLOW MODEL

MATERIAL TYPE (*refer* Figure 5.5)	ROUGHNESS PARAMETER *[Manning's 'n']*
Urban Areas	0.06
Open Watercourses	0.04
Grass / Lawns	0.03
Forested Areas / National Park / Swamp	0.10
Roads	0.02
Fencing at Scarborough Street	0.1
Buildings	1

6. DESIGN FLOOD ESTIMATION

6.1 GENERAL

Design floods are hypothetical floods that are commonly used for planning and floodplain risk management investigations. Design floods are based on statistical analysis of rainfall and flood records and are defined by their probability of occurrence. For example, a flood with an Average Recurrence Interval of 100 years (*or 100 year ARI flood*) is the best estimate of a flood that will likely occur, on average, once in every one hundred years.

It should be noted that there is no guarantee that the design 100 year ARI flood will occur just once in a one hundred year period. It may occur more than once, or at no time at all in a given one hundred year period. This is because the design floods are based upon a statistical 'average'. There is a 1% chance that a flood of the magnitude will occur each year. Notes on the terminology of storm probabilities are provided in **Appendix D**.

The computer models identified in **Sections 4** and **5** were used to derive design flood estimates for the 50%, 20%, 10%, 5%, 2%, 1% and 0.5% AEP floods as well as an extreme flood known as the Probable Maximum Flood (*PMF*) event. The procedures employed in deriving these design floods are outlined in the following sections.

6.2 HYDROLOGIC MODELLING

6.2.1 Design Flood Simulations

The XP-RAFTS hydrologic model described in **Section 4** was used to simulate runoff from the catchment for design storm conditions. The design storm conditions were based on rainfall intensities and temporal patterns for the study area, which were derived using standard procedures outlined in *'Australian Rainfall and Runoff – A Guide to Flood Estimation'* (*1987*) (*ARR 87*). The design storm rainfall data was generated by applying the principles of rainfall intensity estimation described in Chapter 2 of ARR 87.

It should be noted that Engineers Australia and the Bureau of Meteorology published updated intensity-frequency-duration (*IFD*) data and recommendations (*Engineers Australia, 2013*) during the course of the study. This included additional information in relation to the derivation and implementation of areal reduction factors (*ARFs*) (*Engineers Australia, 2013*).

However, following discussions with the OEH and Engineers Australia, it was recommended that the latest information was not suitable for the study. This was primarily because the temporal patterns within the XP-RAFTS hydrologic model for the catchment are based on the ARR 87 methods and are considered incompatible with the 2013 IFD data. Accordingly, it was decided that the most appropriate approach was to continue to adopt the IFD data, temporal patterns and ARF methodology from the ARR 87 documentation.

Due to the small catchment area, spatially varying intensity-frequency-duration (*IFD*) data was not required. Hence IFD data for the catchment was adopted at one location. A summary of the IFD data and the adopted rainfall loss, roughness and lag time data that has been applied to each of the subcatchments in the XP-RAFTS model is contained in **Appendix A**. Design temporal patterns outlined in ARR 87 were also applied within the XP-RAFTS model. These temporal patterns specify the variation in rainfall intensity over the duration of the design storms.

Critical Storm Duration

The critical storm duration was previously determined during the validation of the hydrologic model for Bundeena Creek. (*Refer* **Section 4.1.3**) The 90 minute storm was deemed to be critical for all design events.

Discharge hydrographs were generated throughout the catchment for all design events using the appropriate critical storm duration and the appropriate rainfall intensities and design temporal patterns.

Probable Maximum Precipitation Event

An estimate of Probable Maximum Precipitation (*PMP*) rainfall was also derived for the catchment. The PMP is defined as the greatest depth of precipitation that is meteorologically possible for a given duration at a specific location at a particular time of year. The PMP can be routed through the hydrologic model to provide discharge hydrographs for the Probable Maximum Flood (*PMF*) at specified locations throughout the catchment.

The catchment of Bundeena Creek covers an area of 2.8 square kilometres. As such, the Generalised Short-Duration Method (*GSDM*) method for estimating PMP was employed. According to guidance contained within the '*Guidebook to the Estimation of Probable Maximum Precipitation: Generalised Short-Duration Method*', the catchment lies within the coastal zone. Therefore the maximum duration of the PMP event to be tested was 6 hours. Total catchment flow calculations indicated that the 30 minute storm duration was deemed to be critical for the PMP event.

6.2.2 Hydrologic Modelling Results

Design discharge hydrographs determined using the XP-RAFTS hydrologic model and based on the derived critical durations were used to define inflows into the TUFLOW hydrodynamic model. A summary of the peak discharges for each upstream model boundary location is provided in **Table 6.1**.

Table 6.1 PEAK UPSTREAM INFLOWS USED IN TUFLOW MODEL

LOCATION (*refer* Figure 5.6)	XP-RAFTS MODEL NODE	PEAK DISCHARGE[1] (m^3/s)							
		PMF	0.5% AEP	1% AEP	2% AEP	5% AEP	10% AEP	20% AEP	50% AEP
		30 min Storm	90 min Storm	90 min Storm	90 min Storm	90 min Storm	90 min Storm	90 min Storm	90 min Storm
Eastern Branch	Junction 1E & 2E	43.6	18.5	16.4	14.4	12.7	10.6	9.2	6.5
Western Branch	2W	48.5	13.7	11.9	10.1	8.1	6.5	5.3	3.4

1. Peak discharges listed do not necessarily occur simultaneously.

6.3 HYDRODYNAMIC MODELLING

6.3.1 Design Flood Simulations

The TUFLOW hydrodynamic model was used to simulate each of the design flood events. The design simulations were based on a range of boundary condition data which is described in the following.

Catchment Runoff

Upstream boundary conditions were defined for each design flood based on the inflow hydrographs generated using the XP-RAFTS hydrologic model (*refer* **Table 6.1**). For example, design 1% AEP flood discharge hydrographs for river inflows were extracted from the XP-RAFTS hydrologic model output and used to define the rate of flow into the area covered by the flood model.

A further seventeen local element inflows were specified throughout the model network allowing localised flows to be input into the hydraulic model (*refer* **Figure 5.6**). These local element inflows were representative of sub-catchments defined in the XP-RAFTS hydrologic model.

Downstream Boundary

As previously stated, flows from Bundeena Creek discharge to the Pacific Ocean at Horderns Beach. The water level at the downstream extent of the hydraulic model is governed by the variation in ocean level at the creek mouth in Bundeena Bay.

The level of the ocean at this location was assumed to be constant for each design simulation using a level that corresponds to the Highest Astronomical Tide + storm surge level, as identified in the '*Sea Level Rise Risk Assessment*' (2011) published by GHD. The adopted levels correspond to the Average Recurrence Interval of the design storm investigated; for example, a 10% AEP storm with a 10% AEP tide + storm surge sea level. It should be noted that the adopted tailwater levels have a maximum range of 0.22 metres between all adopted design tide + surge events (*i.e. 1.33 to 1.55 mAHD*).

6.3.2 Hydrodynamic Modelling Results and Discussion

Extent of Inundation

The predicted extent of inundation across the floodplain of the study area for the design events have been extracted from the modelling results and are presented in **Figures E.1** to **E.8**. The figures also indicate the peak flood levels at each location in the study area via flood level contour lines. The figures cover only the residential areas of Bundeena contained within the flood extents in order to ensure sufficient detail can be seen for the township.

Specific peak flood levels at four key locations throughout the study area are listed in **Table 6.2**.

Table 6.2 PREDICTED PEAK DESIGN FLOOD LEVELS

LOCATION	PEAK FLOOD LEVEL (*mAHD*)							
	PMF	0.5% AEP	1% AEP	2% AEP	5% AEP	10% AEP	20% AEP	50% AEP
Horderns Beach (*At footbridge*)	2.10	1.87	1.83	1.79	1.75	1.71	1.67	1.55
Bundeena Drive (*Upstream*)	2.71	2.15	2.10	2.02	1.92	1.83	1.76	1.59
Bundeena Drive (*Opposite Service Station*)	2.75	2.33	2.32	2.31	2.30	2.28	2.28	2.24
Scarborough Street (*Upstream*)	2.75	2.25	2.18	2.11	2.00	1.91	1.85	1.74

The figures indicate that a large proportion of the modelled network area is at risk of flooding during events up to and including the Probable Maximum Flood (*PMF*) event. Floodwaters generally tend to pond across the swampy storage area south of Scarborough Street prior to inundating this roadway and the properties located directly north. Floodwater also spills out across areas west of Liverpool Street, inundating low lying areas located in the vicinity of Bundeena Oval and the Bowling Club. It is noted that the width of the floodplain downstream of Scarborough Street is generally lower as the channel becomes narrower and more defined by slightly higher ground on either side.

The modelled flood extents indicate some form of overtopping of Scarborough Street and Liverpool Street for all events in excess of a 50% AEP flood. While localised areas of ponding occur along the western extent of Bundeena Drive during storms in excess of a 50% AEP, Bundeena Creek floodwaters only begin to overtop Bundeena Drive at the location of the creek crossing during events in excess of a 2% AEP.

Floodwater Depths

Peak floodwater depths were also extracted from the modelling results for each of the design flood events and are presented in **Appendix F**.

The figures indicate that flooding within Bundeena during events up to and including the 1% AEP event is generally shallow.

Flood depths within the residential areas of Bundeena during the 1% and 0.5% AEP events are typically less than 0.6 metres in most areas (*refer* **Figure F.6** *and* **Figure F.7**). Depths can be significantly higher during the PMF; rising to around 1.5 metres in places (*refer* **Figure F.8**).

Flow Velocities

Peak floodwater flow velocities for the adopted design flood events have also been extracted from the modelling results for each of the design flood events and are presented for Bundeena in **Appendix G**. These figures indicate that the peak flow velocities are largest at the outlet of Bundeena Creek as it drains to the ocean. During the 1% AEP flood, the maximum peak velocity at this location is 1.3 m/s (*refer* **Figure G.6**). Peak velocities are also largest within the main channel of the Bundeena Creek as it passes through the culvert structures beneath Scarborough Street and Bundeena Drive. For example, during the 1% AEP event, the peak in-channel velocities within Bundeena Creek at these two locations are typically greater than 0.9 m/s (*refer* **Figure G.6**).

Peak flow velocities within residential areas located in the general floodplain areas of Bundeena are typically less than 0.2 m/s during the 1% AEP event but can be as high as 0.8 m/s in isolated areas along Bundeena Drive and Scarborough Street. Peak flow velocities in these areas are typically less than 0.3 m/s during the PMF event; however, the velocities along Bundeena Drive, Scarborough Street and Liverpool Street are typically greater than 1.0 m/s (*refer* **Figure G.8**).

6.3.3 Sensitivity Analysis

Sensitivity analysis was carried out in order to assess the influence that the creek mouth geometry has on the overall flood behaviour within Bundeena. Sensitivity to roughness parameters and rainfall losses were investigated as part of the model calibration process.

As indicated during the calibration process, the geometry of the creek mouth has the ability to influence peak water levels experienced throughout Bundeena. The geometry adopted in design flood simulations documented in Appendices E, F and G is based on the recent LiDAR data, as was used in model calibration to the 1969 and 2012 events.

Simulations were run to determine the impact that outlet geometry has on upstream flood levels. In this instance two scenarios were assessed; one with a completely scoured "free draining" creek outlet, the other ensured that the creek outlet remained completely "blocked" (*i.e., representing a shoaled entrance*). Flood level difference mapping has been generated to display the total increase/decrease at each location in the network (*i.e., the peak flood level under the revised outlet geometry minus the corresponding adopted peak flood level*). This difference mapping is considered a meaningful method in assessing the impact of revising the geometry of the creek outlet as is shown for each scenario in **Figure H.1** and **Figure H.2**.

A simulation of the 1% AEP flood event was run with a "free draining" outlet. A terrain alteration was made to remove the existing berm across the outlet to account for scour as part of this simulation. Difference mapping revealed a reduction in peak flood level of 0.35 – 0.45 metres downstream of Bundeena Drive during the 1% AEP event (*refer* **Figure H.1**). The free draining outlet had a lesser impact on peak flood levels experienced upstream of Bundeena Drive, reducing levels by 0.08 – 0.30 metres between Bundeena Drive and Scarborough Street, and by 0.05 – 0.07 metres in a selected area upstream of Scarborough Street. As such the free draining scenario creates a higher grade on the flood surface profile, typical of fully open entrance conditions. While the reduction in flood level was significant in areas close in proximity to the creek outlet, the revised outlet geometry only reduced flood levels experienced in selected upstream areas of the broader floodplain of up to 0.05 metres.

Conversely, geomorphic processes also have the ability to significantly block the creek outlet. It is perceived that a blocked creek outlet would generate the "worst case" flooding scenario for Bundeena Creek. A terrain alteration was made in order to extend the berm across the outlet at a height of 3 mAHD. This level was deemed appropriate to ensure the prevention of creek outflow as catchment runoff progressed downstream. Difference mapping revealed a increase in flood level of 0.2 to 0.4 metres downstream of Bundeena Drive and 0.13 metres in the areas immediately upstream of Scarborough Street during the peak of the 1% AEP flood event (*refer* **Figure H.2**). Additionally, a small portion of land located between Lawrence Street and Thompson Street was inundated solely as a result of blocking the creek outlet during the 1% AEP event (*indicated by red cross hatching in* **Figure H.2**). This increase in flood extent is related to the inability of local runoff to drain to the ocean, and also the potential for ponded water behind the blocked outlet to back-up into low-lying residential areas.

In light of the above findings, it is considered that the outlet geometry does have a significant impact on flood levels experienced across the broader floodplain.

7. FLOOD HAZARD AND HYDRAULIC CATEGORIES

7.1 GENERAL

The personal danger and physical property damage caused by a flood varies both in time and place across the floodplain. Accordingly, the variability of flood patterns across the floodplain over the full range of floods, needs to be understood by flood prone landholders and by floodplain risk managers.

Representation of the variability of flood hazard across the floodplain provides floodplain risk managers with a tool to assess the existing flood risk and to determine the suitability of land use and future development. The hazard associated with a flood is represented by the static and dynamic energy of the flow, which is in essence, the depth and velocity of the floodwaters. Therefore, the flood hazard at a particular location within the floodplain is a function of the velocity and depth of the floodwaters at that location.

The NSW Government's *'Floodplain Development Manual'* (*2005*), characterises hazards associated with flooding into a combination of three hydraulic categories and two hazard categories. Hazard categories are broken down into high and low hazard for each hydraulic category as follows:

- Low Hazard – Flood Fringe
- Low Hazard – Flood Storage
- Low Hazard – Floodway
- High Hazard – Flood Fringe
- High Hazard – Flood Storage
- High Hazard - Floodway

As a result, the manual effectively divides hazard into two categories, namely, high and low. An interpretation of the hazard at a particular site can be established from Figure L1 and L2 on the following page, which have been taken directly from the manual.

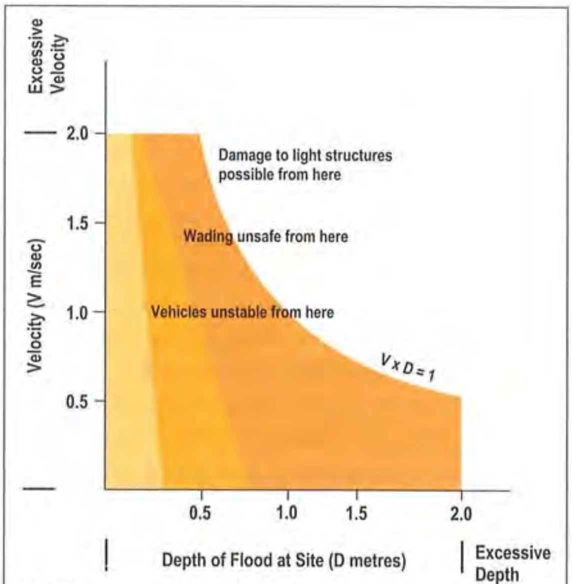
The first of these graphs shows approximate relationships between the depth and velocity of floodwaters and resulting hazard. This relationship has been used to define the provisional low and high hazard categories represented in the second of these plots.

7.2 FLOOD HAZARD

7.2.1 Adopted Provisional Hazard Categorisation

As shown in Figures L1 and L2 of the manual, flood hazard is a measure of the degree of difficulty that pedestrians, cars and other vehicles will have in egressing flooded areas, and the likely damage to property and infrastructure. At low hazard, passenger cars and pedestrians (*adults*) are able to move out of a flooded area. At high hazard, wading becomes unsafe, cars are immobilised and damage to light timber-framed houses would occur.

Flood hazard is categorised according to a combination of the flow velocity and the depth of floodwater. The categories are defined by lower and upper bound values for the product of flow velocity and floodwater depth.

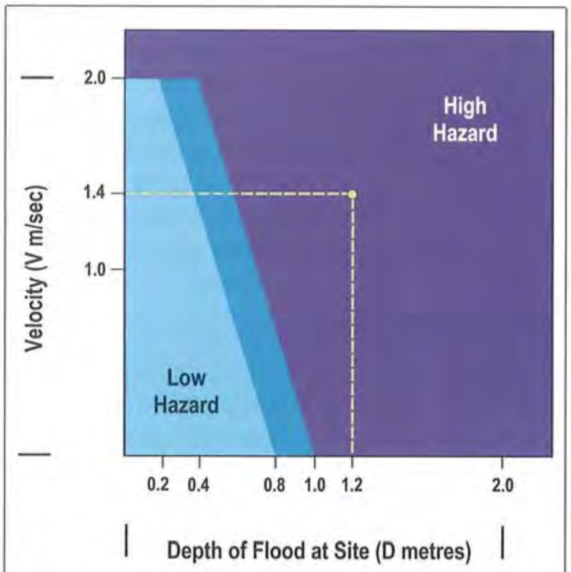


Notes

1. At velocities in excess of 2.0 m/s, the stability of foundations and poles can be affected by scour. Also, grass and earth surfaces begin to scour and can become rough and unstable
2. The velocity of floodwaters passing between buildings can produce a hazard, which may not be apparent if only the average velocity is considered. For instance, the velocity of floodwaters in a model test has risen from an average of 1 m/sec to 3 m/sec between houses.
3. Vehicle instability is initially by buoyancy.
4. At floodwater depths in excess of 2.0 meters and even at low velocities, there can be damage to light-framed buildings from water pressure, flotation and debris impact.

Derived from laboratory testing and flood conditions which caused damage.

FIGURE L1 - Velocity & Depth Relationships



Notes

The degree of hazard may be either -

- reduced by establishment of an effective flood evacuation procedure.
- increased if evacuation difficulties exist.

In the transition zone highlight by the median colour, the degree of hazard is dependant on site conditions and the nature of the proposed development.

Example:

If the depth of flood water is **1.2 m**
and the velocity of floodwater is **1.4 m/sec**
then the provisional hazard is **high**

FIGURE L2 - Provisional Hydraulic Hazard Categories

Spatial and temporal distributions of flow, velocity and water level determined from the computer modelling undertaken as part of this study were used to determine the flood hazard categorisation of the Bundeena floodplain. Interpretation of this data indicates that for large events such as the 1% AEP flood event, the majority of flooded land would fall within the low hazard category defined in the *'Floodplain Development Manual'* (*2005*).

7.2.2 Provisional Flood Hazard

The criteria presented in **Section 7.2.1** were used to develop provisional hazard mapping for the floodplain of Bundeena Creek. Provisional flood hazard mapping generated for the catchment during the 1% AEP and PMF events is presented in **Appendix I**.

The mapping indicates that a large proportion of the floodplain would be subject to a low hazard during the 1% AEP event. This is predominantly a function of the shallow floodwater depths and low velocities experienced across much of the floodplain at the peak of the event (*refer* **Figure I.1**). It should be noted that higher flood hazards are experienced across the floodplain during the peak of the PMF event. Mapping indicates that key areas experiencing "High" Hazard are located along sections of Liverpool Street and Scarborough Street (*refer* **Figure I.2**).

The hazard represented in this mapping is provisional only. This is because it is based only on an interpretation of the flood hydraulics and does not reflect the effects of other factors that influence hazard (*see clause L6 to Appendix L of the Floodplain Development Manual*). For example, access to an otherwise low hazard area may be through a high hazard area and this may present an unacceptable risk to life and limb and as such the provisional low hazard area may be changed to high hazard.

Accordingly, modification of the hazard mapping presented in **Appendix I** will be required as part of investigations that will need to be undertaken in the future to develop / prepare an updated Floodplain Risk Management Plan for Bundeena Creek.

7.3 HYDRAULIC CATEGORIES

7.3.1 Adopted Hydraulic Categorisation

The NSW Government's *'Floodplain Development Manual'* (*2005*) also characterises flood prone areas according to the hydraulic categories presented in **Table 7.1**. The hydraulic categories provide an indication of the potential for development across different sections of the floodplain to impact on existing flood behaviour.

Unlike for the hazard categorisation outlined in **Section 7.2**, the *'Floodplain Development Manual'* (*2005*) does not provide explicit quantitative criteria for defining hydraulic categories. This is because the extent of floodway, flood storage and flood fringe areas is largely dependent on the geomorphic characteristics of the floodplain in question.

Table 7.1 HYDRAULIC CATEGORY CRITERIA

HYDRAULIC CATEGORY	DESCRIPTION
FLOODWAY	• those areas where a significant volume of water flows during floods • 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 redistribution of flood flow, which may in turn adversely affect other areas • they are often, but not necessarily, areas with deeper flow or areas where higher velocities occur.
FLOOD STORAGE	• 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 substantially 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 redistribution of flood flows.
FLOOD FRINGE	▪ the remaining area of land affected by flooding, after floodway and flood storage areas have been defined. ▪ Development in flood fringe areas would not have any significant effect on the pattern of flood flows and/or flood levels.

Although there are no specific procedures for identifying or determining hydraulic categories, a rigorous methodology involving several stages of analytical analysis in conjunction with flood modelling has been developed by Thomas & Golaszewski (*2012*). This methodology has been applied with success to similar floodplains in NSW and has been shown to provide a robust procedure for defining floodway extent. Most recently, this methodology was successfully applied to the Lower Hastings River floodplain as part of investigations for the '*Hastings Floodplain Risk Management Study*' (*2012*).

The hydraulic category mapping that was prepared for Bundeena Creek is provided in **Appendix J**.

The following sections describe the methodology that was employed to determine the hydraulic category mapping.

7.3.2 Adopted Methodology for Determination of Floodway Corridors

The adopted methodology for determination of hydraulic categories for Bundeena Creek involved several stages of assessment that relied on analysis of all available hydraulic, topographic, cadastral and geomorphic data-sets.

Once the detailed investigations to determine the extents of floodway corridors were completed, an assessment was also undertaken to determine the extent of flood storage and flood fringe areas. Each of these hydraulic categories was then combined to develop hydraulic category mapping for the study area which can be incorporated into future mapping layers linked to Council's Local Environmental Plan.

A preliminary floodway extent was firstly determined based on an assessment of aerial photography, topographic data and existing 1% AEP flood and PMF modelling results. Determination of this extent or "line" considered the following:

- The location of flood storages that are readily identifiable from aerial photography;
- The location and potential impact of hydraulic controls and geomorphic features that could influence floodwater movement and flood characteristics (*e.g., velocity*);
- Mapping of contours of 'velocity-depth' product (*V x D*); and,
- Mapping of the variation in peak flow velocity.

Because of the ponding nature of flooding across the Bundeena Creek catchment, establishment of a standard set of criteria was <u>not</u> considered appropriate for the determination of the floodway extent. For example, definition of the floodway extent based on a single target value for velocity or velocity-depth product (*V x D*) would limit the reliability of the investigation findings.

Accordingly, to ensure the assessment of floodway extent was completed reliably, a time series analysis of the 1% AEP flood and the lesser 50% AEP flood was used in order to establish initial flow paths within the study area prior to the peak flood level "washing out" these areas.

A set of interactive flood maps was produced for each of these precincts to show key hydraulic data including the variation in V x D, peak flow velocities and peak flood depths. The results of modeling of the design 1% AEP flood were used as the benchmark for the analysis.

The interactive flood maps were used to identify areas of the floodplain representing:

- High depth and high velocities; i.e., high V x D (*generally considered floodway*);
- High depth and low velocities (*generally considered flood storage*); and
- Low depth and low velocity (*generally considered flood fringe*).

In this regard, a typical "first pass" assessment of floodway extents was undertaken to identify areas where the velocity-depth product is greater than 0.4 m^2/s and where flow velocities are greater than 1 m/s. The alignment of significant flow paths across the floodplain (*i.e., potential flood runners*), as inferred by the velocity and V x D contour mapping, was also considered in determining the preliminary floodway extents.

The Preliminary Floodway Extent was further verified by comparison with mapping of the width of the floodplain that would be required to convey 80% of the peak flow. Trial analyses for this project and similar floodplain risk management studies have shown a good correlation between the transitions in velocity-depth product contour mapping, geomorphic characteristics and the width of the floodplain that conveys about 80% of the flood flow. A discussion of this criteria and its appropriateness for defining floodway extent is provided in Thomas & Golaszewski (*2012*).

The width occupied by 80% of the flow was readily determined for any location within the lower reaches of the floodplain using the *Flow Extraction* tool within waterRIDE™. This width was then used to verify and adjust the Preliminary Floodway Extent where appropriate. The resultant floodway mapping is shown in **Appendix J**.

7.3.3 Adopted Methodology for Determining Flood Storage and Flood Fringe

Following determination of those areas of the floodplain categorised as floodway, investigations were focused towards identifying the remaining hydraulic categories, namely flood storage and flood fringe. As outlined in the NSW *'Floodplain Development Manual'* (*2005*), flood storage and flood fringe make up the remainder of the floodplain outside of the floodway corridor.

Flood storage areas are typically defined as those flood prone areas that afford significant temporary storage of floodwaters during a major flood. If filled or obstructed (*through the construction of levees or road embankments*) the reduction in storage would be expected to result in a commensurate increase in flood levels in nearby areas. The remaining flood prone areas not classified as floodway or flood storage are termed flood fringe.

In order to determine the boundary between flood storage and flood fringe, the variation in peak flood depths in areas outside of the floodway extent was mapped to identify areas inundated to depths of approximately 0.3 metres. A depth of 0.3 metres was selected as it is considered to be the transitionary point between flood storage and flood fringe.

In terms of the Bundeena Creek floodplain, peak depths below 0.3 metres are generally considered to correspond to areas where negligible flow is conveyed and represent a relatively small proportion of storage for floodwaters.

In accordance with the Floodplain Development Manual (*2005*), this represents areas which are unlikely to have any significant impact on the pattern of floodwater distribution through a river and floodplain system and associated flood levels. Accordingly, the boundary between flood storage and flood fringe was defined by a peak 1% AEP flood depth of 0.3 metres.

Flood storage and flood fringe mapping for the floodplain of the Bundeena Creek within the study area is presented within **Appendix J**.

8. IMPACT OF FUTURE CLIMATE CHANGE

8.1 GENERAL

The NSW government has published a number of documents which provide guidance to account for climate change impacts on flooding. The Department of Environment and Climate Change (*DECC*) Floodplain Risk Management Guideline titled: 'Practical Consideration of Climate Change' (*2007*) is most relevant to the present study.

This guideline provides an estimate of the range for increases in sea level associated with climate change and provides estimates for the change in "Extreme Rainfall" under future climate change conditions for different parts of NSW. The guideline recommends consideration of increased rainfall intensities of 10%, 20% and 30%. Similarly, the guideline recommends consideration of 2050 and 2100 sea levels for coastal catchments. Accordingly, it was agreed with Council that following six climate change scenarios would be tested:

- 1% AEP rainfall event with 20% increase in rainfall intensity;
- 1% AEP rainfall event with 2050 year sea level;
- 1% AEP rainfall event with 2100 year sea level;
- PMF event with 20% increase in rainfall intensity;
- PMF event with 2050 year sea level;
- PMF event with 2100 year sea level;

8.2 HYDROLOGIC MODELLING

In order to derive the inflow hydrographs for the two increased rainfall intensity scenarios, the XP-RAFTS hydrologic model was updated to include intensity-frequency-duration (*IFD*) data with the appropriate percentage increases to intensities applied.

Updated inflow hydrographs for all upstream boundary locations and local subcatchment inflows were derived for the two increased rainfall intensity scenarios. A summary of the peak discharges for each upstream model boundary location is provided in **Table 8.1**.

Table 8.1 PEAK UPSTREAM INFLOWS USED IN TUFLOW MODEL (CLIMATE CHANGE)

LOCATION	XP-RAFTS MODEL NODE	PEAK DISCHARGE[1] (m^3/s)			
		PMF	PMF +20%	1% AEP	1% AEP +20%
		30 min Storm	30 min Storm	90 min Storm	90 min Storm
Eastern Branch	Junction 1E & 2E	43.6	53.1	16.4	20.2
Western Branch	2W	48.5	60.5	11.9	15.3

1. *Peak discharges listed do not necessarily occur simultaneously.*

It should be noted that the remaining four climate change scenarios relating to sea level rise did not require updated inflow hydrographs.

8.3 HYDRODYNAMIC MODELLING

8.3.1 Increased Rainfall Intensity Scenarios

The updated inflow hydrographs were used within two further simulations of the TUFLOW hydrodynamic model. The results from these two scenarios provide a suitable indication of the flooding characteristics that could be expected within the study under the assumed climate change conditions.

8.3.2 Sea Level Rise Scenarios

Updated downstream boundary conditions were used within four further simulations of the TUFLOW hydrodynamic model to reflect the impact of increased tailwater levels as a result of climate change. The following 1% AEP Highest Astronomical Tide + storm surge levels, as identified in the '*Sea Level Rise Risk Assessment*' (GHD, 2011) were used in order to simulate the effects of sea level rise:

- Year 2050 – 1.79 mAHD
- Year 2100 – 2.41 mAHD

Existing design upstream and local subcatchment inflow hydrographs were used for all four simulations (i.e. with no increases in rainfall intensity).

8.4 OBSERVED IMPACTS ON FLOODING

The predicted impact on peak flood levels resulting from the increased rainfall intensities due to climate change have been extracted from the modelling results and are presented in **Appendix K** for each design event. One set of figures display the flood level experienced at the peak of each scenario. Another set of figures display the total increase at each location in the network (*i.e., the peak flood level under climate change conditions minus the corresponding present day peak flood level*). It should be noted that 'hatching' has been used on the difference mapping to display areas of land inundated during the climate change scenario that remains dry during the present day scenario.

8.4.1 Increased Rainfall Intensity Scenarios

The observed impacts were generally consistent between the two base events tested (*i.e., similar impacts between the 1% AEP and PMF events when 20% rainfall added*). Levels across a majority of the floodplain will typically increase by 0.12 metres during the 1% AEP event and by 0.18 metres across the entire floodplain during the PMF (*refer* **Figure K.2** *and* **Figure K.4**). The flood extent remains almost unchanged as a result of the increases in rainfall intensity during both simulations. However, a small portion of land located between Lawrence Street and Thompson Street was inundated solely as a result of the increase in rainfall intensity during the 1% AEP event (*indicated by red cross hatching in* **Figure K.2**).

The observed impacts were typically lower in the vicinity of the Horderns Beach, where flood levels are typically governed by ocean conditions. Levels within the outlet of the creek channel near the Horderns Beach footbridge increased by 0.05 metres during the 1% AEP event and increased by 0.07 metres during the PMF event.

8.4.2 Sea Level Rise Scenarios

The observed impacts were relatively minor for the Year 2050 sea level rise scenarios. Raising the downstream boundary condition from 1.51 mAHD to 1.79 mAHD led to minimal flood level increases across the broader floodplain. The level of influence was restricted to areas of the channel located downstream of Bundeena Drive during the 1% AEP event. Levels in this area of the creek channel generally increased by 0.02 metres as a result of this rise in sea level (*refer* **Figure K.6**). The increase in sea level to the Year 2050 tidal level does not have any impact on flood levels in the broader floodplain during the PMF event (*refer* **Figure K.8**).

Contrastingly, the observed impacts were large for the Year 2100 sea level rise scenarios. As a majority of the Bundeena Creek floodplain lies at an elevation of around 2 mAHD, raising the downstream boundary condition from 1.51 mAHD to 2.41 mAHD led to large flood level increases. Under this scenario, ocean levels would be expected to significantly "back up" the creek system, inundating a majority of the floodplain. Flooding would then be expected to be exacerbated by Bundeena Creek local flooding. Levels across the floodplain generally increased by 0.4 to 0.65 metres during the 1% AEP event and 0.45 metres during the PMF as a result of the Year 2100 sea level rise (*refer* **Figure K.10** *and* **Figure K.12**).

Generally, peak flood levels experienced across the broader floodplain during the 1% AEP event and the PMP event under the Year 2100 sea level rise scenario were 2.68 mAHD and 3.19 mAHD respectively (*refer* **Figure K.10** *and* **Figure K.12**). As 2.41 metres of this level can be attributed to tidal inundation, it can be deduced that rainfall within the Bundeena Creek catchment would have contributed an additional 0.27 metres and 0.78 metres to the overall flood levels experienced during the 1% AEP and PMF, respectively.

9. PRELIMINARY FLOOD PLANNING AREAS

Preliminary Flood Planning Area Mapping for the Bundeena Creek study area have been determined for the present-day conditions and also the 2050 and 2100 sea level rise scenarios. Flood Planning Levels have been determined according to the 1% AEP flood level (*with either present day, 2050 or 2100 sea level rise predictions*) plus a 0.5 metre freeboard. WorleyParsons' *waterRIDE* software has been used to apply the 0.5 metre freeboard to the detailed flood modelling results detailed in **Section 6** and **Section 8**.

Flood Planning Area Mapping is presented in **Appendix L**. Comparison between the maps shows that the flood planning area would remain largely the same under a Year 2050 sea level rise scenario. However, under a Year 2100 sea level rise scenario, there are some notable increases in the flood planning area, particularly in the eastern side of Bundeena Drive, between Liverpool Street and the creek.

10. PRELIMINARY FLOOD EMERGENCY RESPONSE MANAGEMENT

10.1 GENERAL

The NSW State Emergency Service (*SES*) is the legislated Combat Agency for floods and it is responsible for coordinating other agencies involved with emergency management.

To allow SES to manage the emergency response to flood risk and undertake evacuation planning the SES, along with NSW Office of Environment and Heritage (*OEH*) (*formerly the Department of Environment, Climate Change and Water*), have developed guideline documents which detail their desired outcomes from the Floodplain Risk Management process. These guidelines are titled:

- *'SES Requirements from the Floodplain Risk Management Process'* (*2007*); and,
- *'Flood Emergency Response Planning Classification of Communities'* (*2007*).

Given the potential for loss of life or damage to property during flooding and in light of the emergency response guidelines, it is considered appropriate to assess the risk to the potentially flood affected community of Bundeena. Preliminary requirements involve the identification of Flood Management Communities in light of the guidelines and recent flood modelling results (*where appropriate*).

It is envisaged that the subsequent Floodplain Risk Management Study will use these Flood Management Communities as starting point to identify those who are at risk from flooding and to assess measures that could be implemented to reduce the exposure of the community to flood risk.

In addition, information contained in the Floodplain Risk Management Study will be of assistance to the SES in the verification and refinement of existing flood emergency response procedures or the development of additional protocols, if required.

10.2 INUNDATION MAPPING

The flood inundation maps prepared as part of this study using the TUFLOW flood model provide a range of useful information for emergency management, including flood depths, levels, velocities, flood hazard and the location of affected properties for a range of flood events.

In addition to informing the following assessment of emergency response communities, it is envisaged that this mapping could be used directly by SES and Council operational staff to inform decisions during a flood. This would help to target flood responses to where they are most effective.

Furthermore, the set of inundation maps could also be compiled into a waterRIDE software package for use by SES and Council, which would allow the flood model results to be more closely interrogated, including step-by-step visualisation of the progress of flooding through the study area to identify the most critical areas in need of urgent attention.

10.3 DURATION OF FLOODING

The results of the TUFLOW modelling indicate that the typical duration of local catchment flooding across Bundeena would be between around 5 hours. It is accepted that periods of prolonged rainfall and hence prolonged inundation could occur, but an inundation period of this order is considered typical for this size catchment.

This short duration of flooding indicates that any residents evacuating from flood prone areas would not remain isolated for an extended period of time. Accordingly, the evacuated residents are unlikely to need any on-going assistance from the SES which can often be required in cases of extended isolation, such as food drops or air/water rescue. Local refuge at nearby higher ground, either to the east or north-west of Bundeena Creek, is always available.

If residents are unable to return to damaged properties following a flood, then it would not be long before floodwaters recede further and access routes are again open to allow travel to flood recovery centres.

10.4 FLOOD-FREE ACCESS & FLOOD MANAGEMENT COMMUNITIES

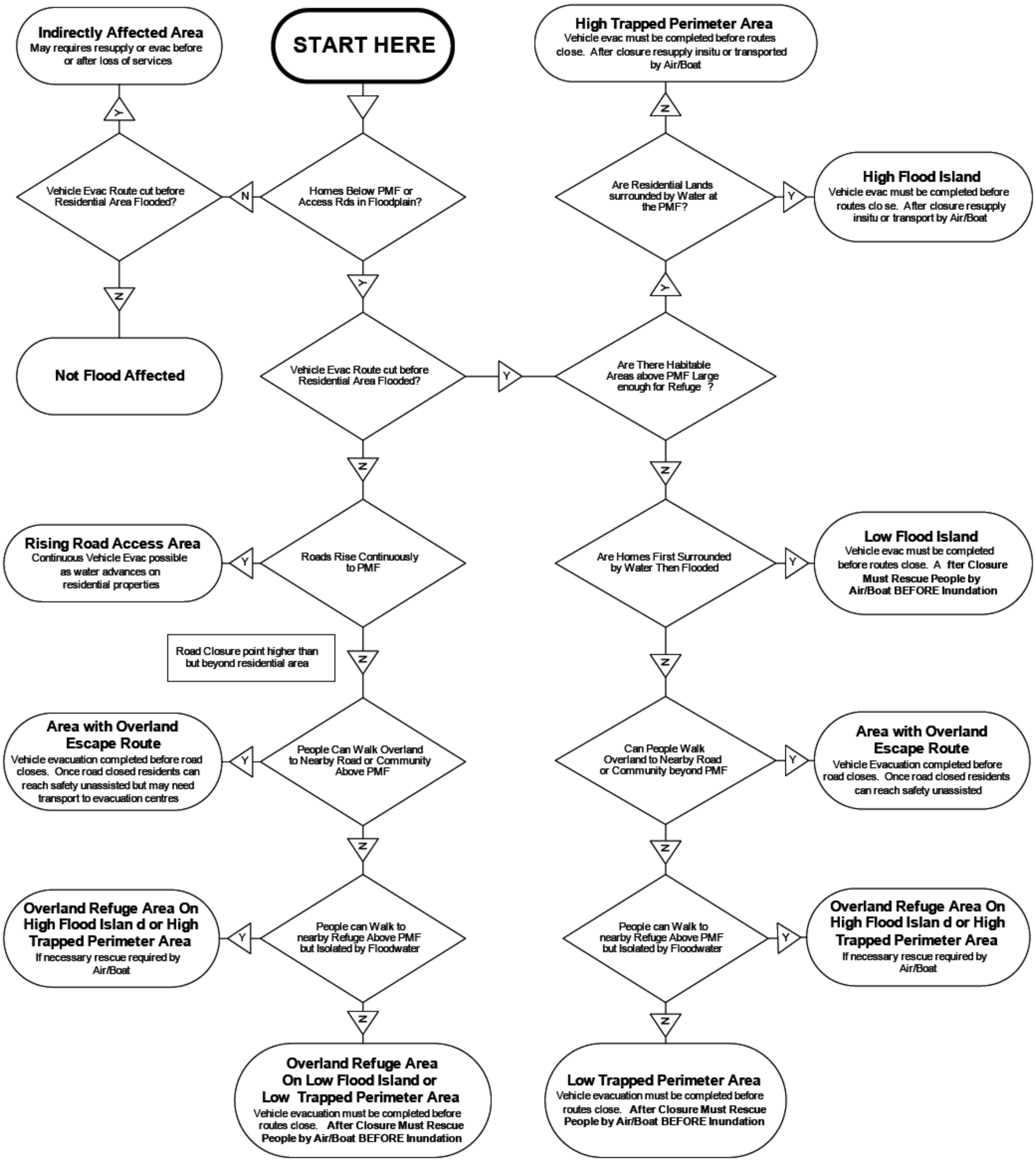
The SES guidelines highlight the need to identify Flood Management Communities (*refer* **Figure 10.1** *overleaf*). The delineation of communities within the SES' wider Operational Areas allows emergency response to be tailored for areas with differing degrees of vulnerability. Classification provides an indication of the relative vulnerability of communities located on the floodplain and helps identify the information required by SES to manage the risk. Community risk may be influenced by such factors as flood behaviour, topography and the provision of safe access and egress routes.

Flood Management Communities for Bundeena Creek are presented in **Appendix M**.

The crossings that will <u>most frequently</u> become cut by floodwaters are as follows:

- Scarborough Street becomes inaccessible in events larger than the 50% AEP event.
- Sections of Bundeena Drive become inaccessible in events larger than the 5% AEP event.

Due to the rapid onset of flooding in the catchment (*i.e. within an hour of the onset of rainfall*), residents would have little warning prior to the inundation of properties and key access roads. Bundeena Drive is the only road offering access in and out of Bundeena and would provide safe access during events up to a 5% AEP event, when a low point on the route out of town would become cut off. There are no guarantees that Bundeena Drive would remain completely accessible during a major flood event. Accessibility would obviously depend on the time of evacuation.



Classification of Floodplain Communities for Emergency Management Planning

Figure 10.1 SES PROCESS FOR CLASSIFICATION OF COMMUNITIES FOR FLOOD EMERGENCY RESPONSE PLANNING

As such, it is inappropriate to assume that Bundeena Drive can always be used as a vehicle evacuation route (*refer* **Figure M.1**). Hence, a majority of the township contained within the PMF flood extent has been classified as 'High Flood Island' as residents looking to evacuate west of Bundeena Creek may be forced to head to the isolated high ground to the north and to wait until flood waters recede.

Residents on the east side of the creek would be able to take refuge at what is considered to be a high trapped perimeter area at the eastern portion of Bundeena (*refer* **Figure M.1**)

11. REFERENCES

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- NSW Government *(2007), 'Flood Emergency Response Planning Classification of Communities'*.

REPORT FIGURES

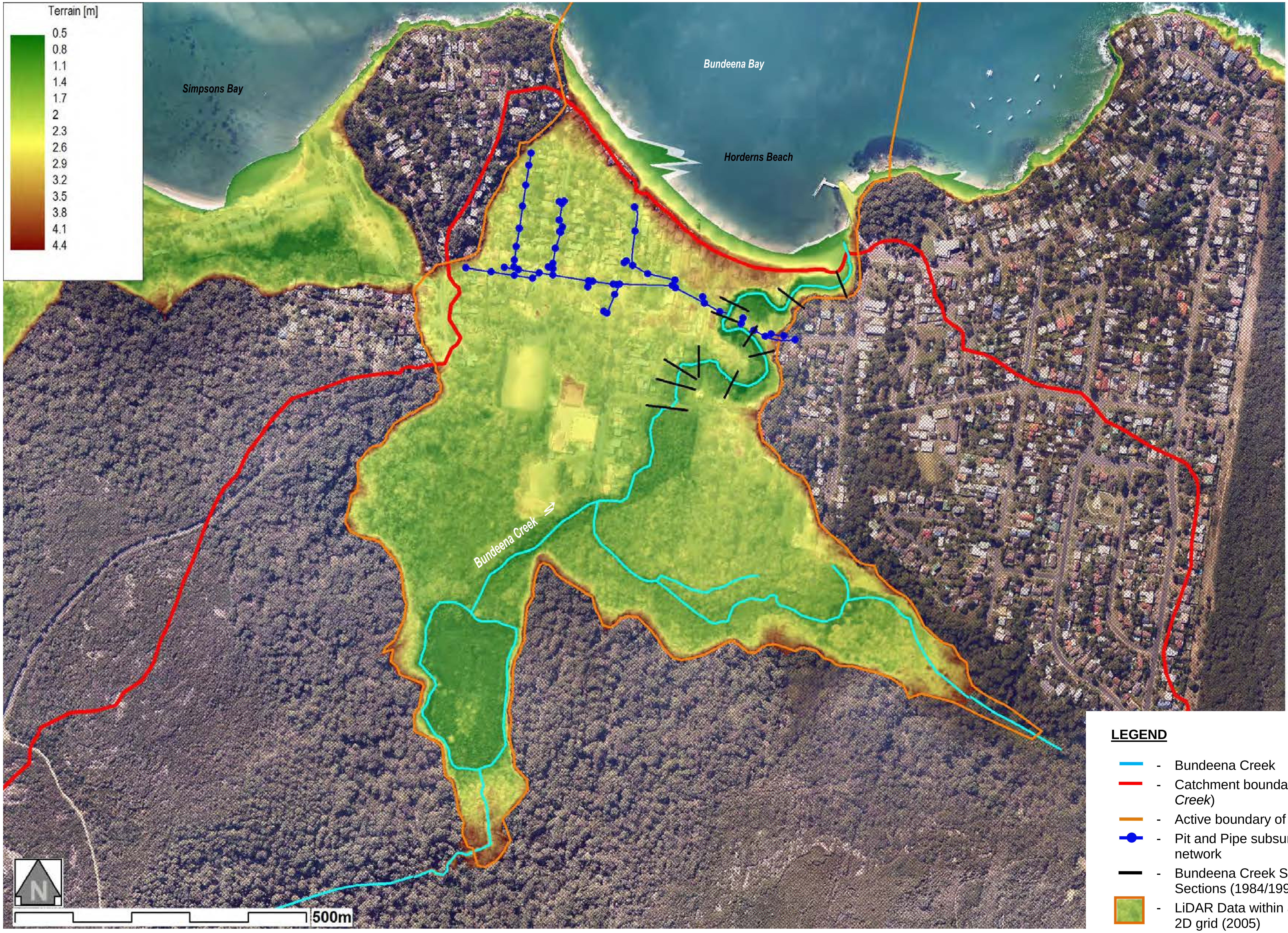
FIGURE 1.1

LEGEND

- Watercourse
- Catchment boundary

LOCATION OF STUDY AREA

FIGURE 3.1



LEGEND

- Bundeena Creek
- Catchment boundary (*Bundeena Creek*)
- Active boundary of 2D grid
- Pit and Pipe subsurface drainage network
- Bundeena Creek Survey Cross Sections (1984/1992)
- LiDAR Data within active boundary of 2D grid (2005)

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301015-03182 – Bundeena Creek Flood Study
fg301015-03182sb130711-fig3.1_Acquired Data.doc

SUMMARY OF AVAILABLE DATA

FIGURE 4.1

LEGEND

- Watercourse
- Sub-catchment boundary

7E - Sub-catchment identifier

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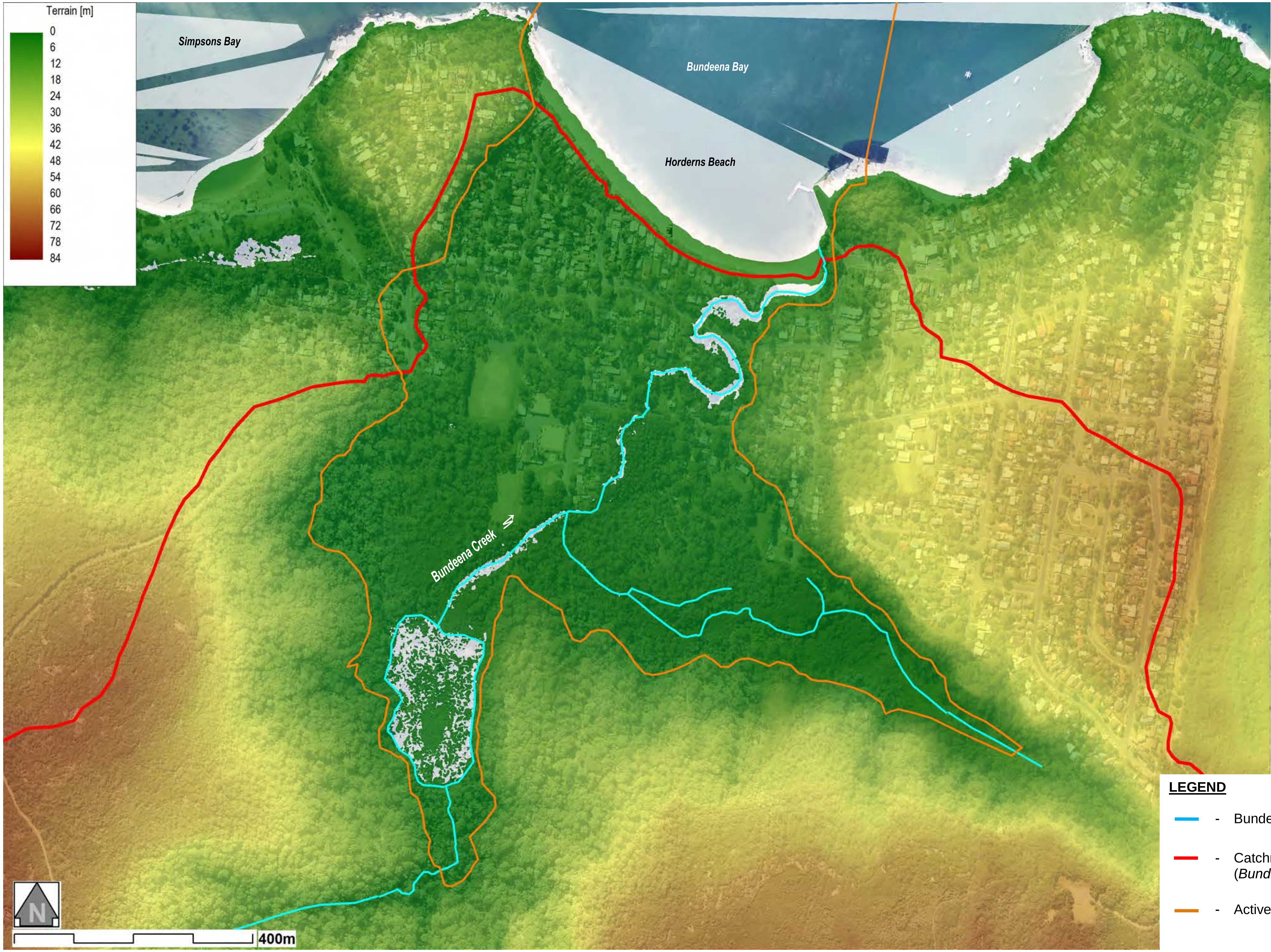
301015-03182 – Bundeena Creek Flood Study
fg301015-03182sb130628-fig4.1_Subcatchment Layout.doc

LAYOUT OF SUBCATCHMENTS
WITHIN XP-RAFTS HYDROLOGIC MODEL

FIGURE 5.1



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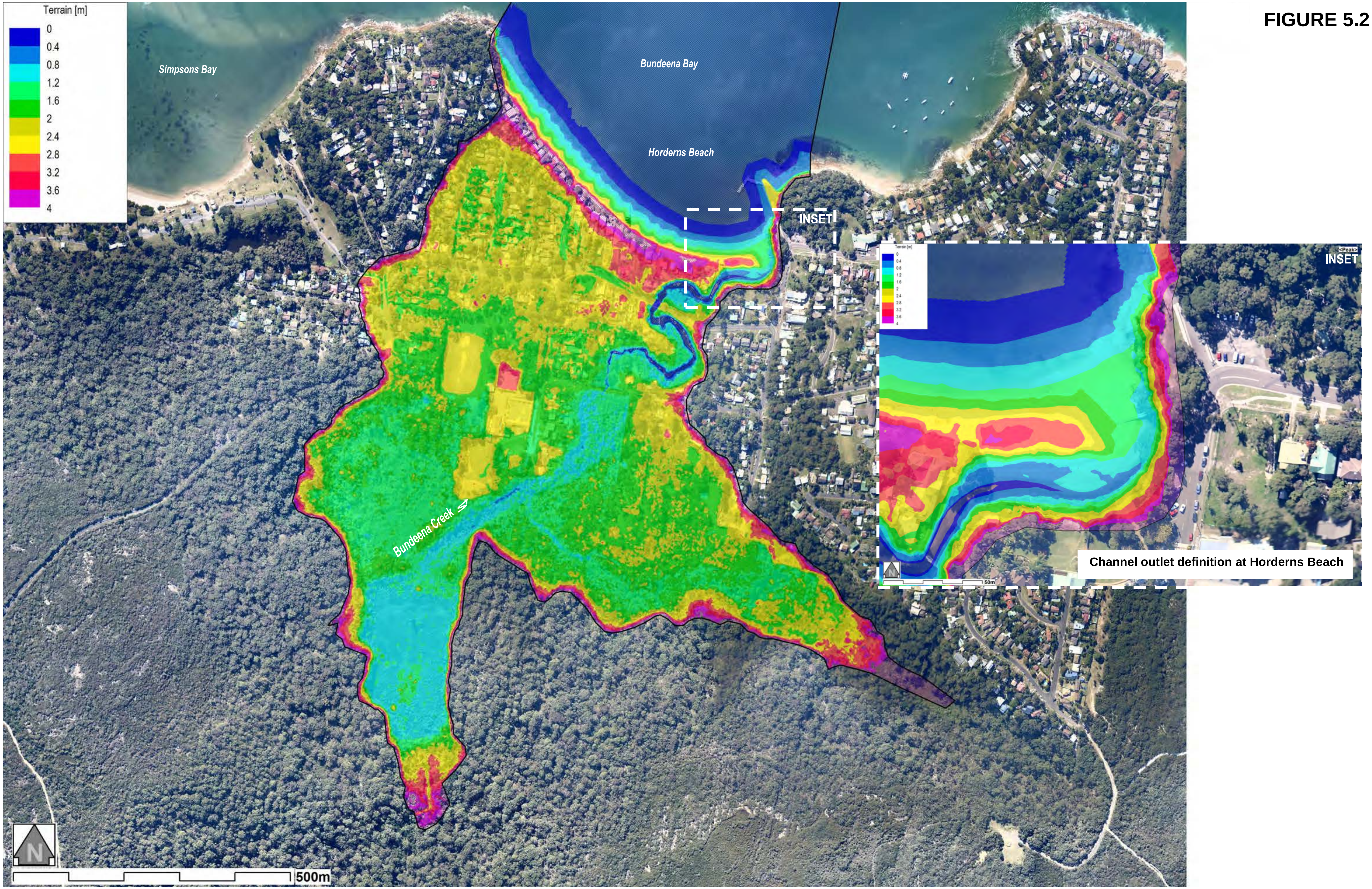
301015-03182 – Bundeena Creek Flood Study
fg301015-03182sb130711-fig5.1_Extent of TUFLOW Hydrodynamic Model.doc

EXTENT OF TUFLOW HYDRODYNAMIC MODEL

FIGURE 5.2



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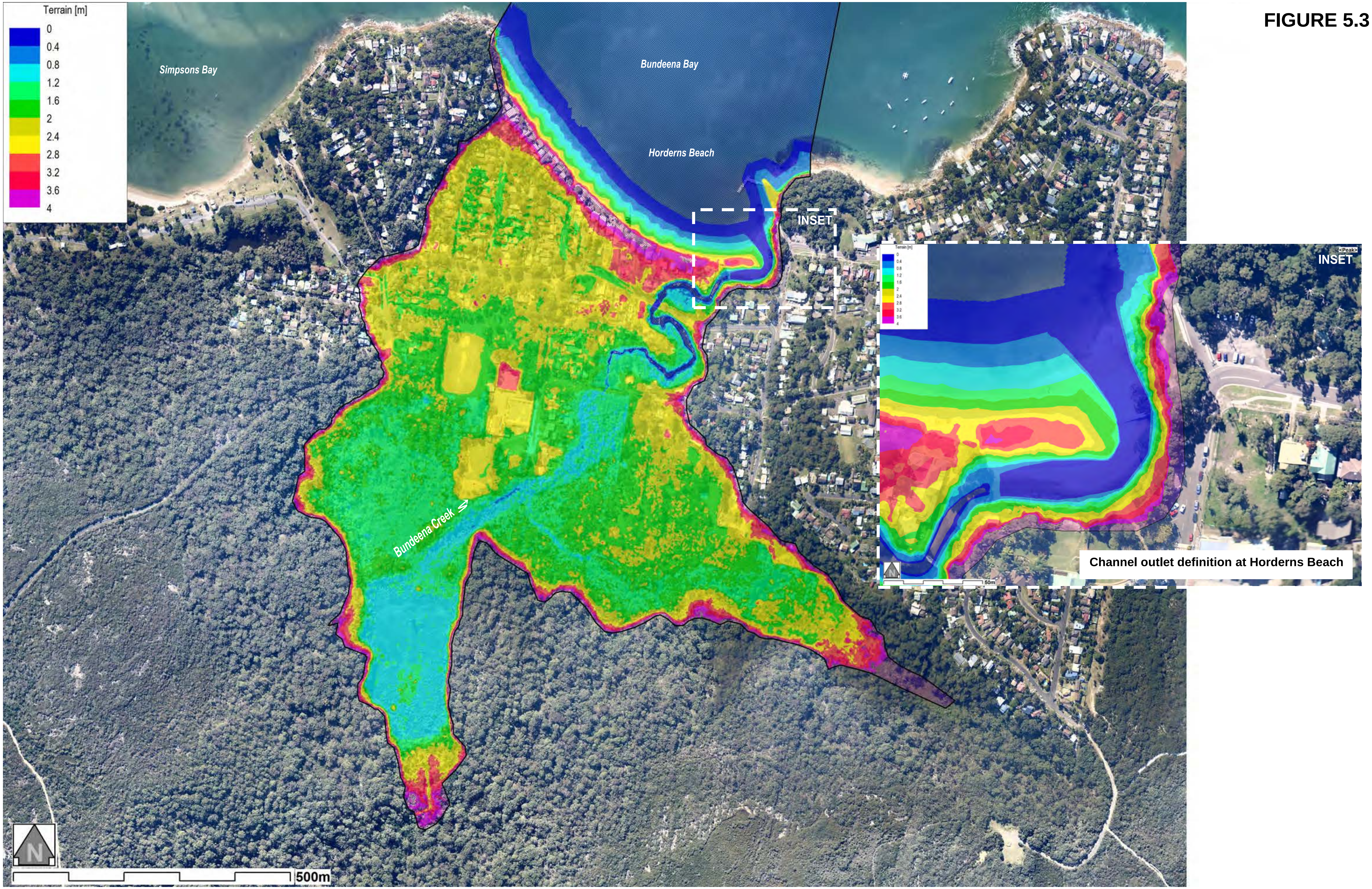
301015-03182 – Bundeena Creek Flood Study
fg301015-03182sb130711-fig5.2_TUFLOW Topography_01.doc

TOPOGRAPHIC DATA WITHIN TUFLOW HYDRODYNAMIC MODEL (1969 & 2012 EVENTS)

FIGURE 5.3



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301015-03182 – Bundeena Creek Flood Study
fg301015-03182sb130711-fig5.3_TUFLOW Topography_02.doc

TOPOGRAPHIC DATA WITHIN TUFLOW HYDRODYNAMIC MODEL (1984 EVENT)

FIGURE 5.4

Note: All structures defined within the model are located either in the vicinity, or downstream of Scarborough Street

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301015-03182 – Bundeena Creek Flood Study
fg301015-03182sb130711-fig5.4_TUFLOW Structures.doc

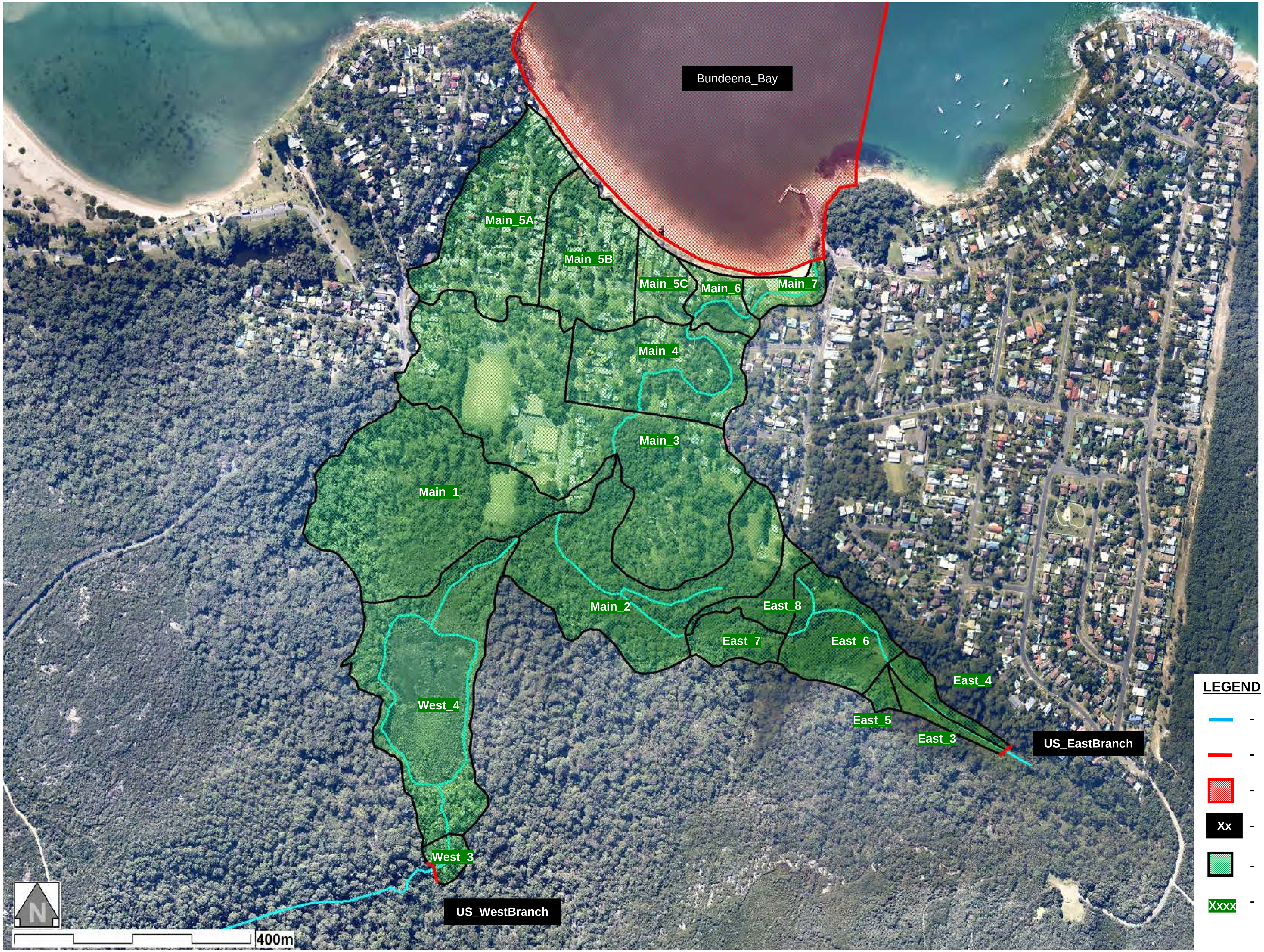
LOCATION OF HYDRAULIC STRUCTURES WITHIN TUFLOW HYDRODYNAMIC MODEL

FIGURE 5.5

Note: Only roughness polygons within the "Active boundary of 2d grid" used by TUFLOW during simulations

SCHEMATIC REPRESENTATION OF TUFLOW HYDRODYNAMIC MODEL ROUGHNESS VALUES

FIGURE 5.6



LEGEND

- Bundeena Creek
- Upstream boundary
- Downstream boundary
- Xx - Boundary condition identifier
- Local inflow area
- Xxxx - Local inflow identifier

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SCHEMATIC REPRESENTATION OF BOUNDARY CONDITIONS FOR TUFLOW HYDRODYNAMIC MODEL

APPENDIX A

SUMMARY OF HYDROLOGIC MODEL SUBCATCHMENT PARAMETERS

HYDROLOGIC MODEL PARAMETERS

Watercourse	Sub	ID	TUFLOW Boundary	Impervious	IL/CL	Mannings 'n'	Area	Stream Length	U/S Elev	D/S Elev	Slope	Reach Length	Reach U/S Elev	Reach D/S Elev	AR&R Lag	Bransby Lag	Average Lag	IFD Category
				%	[mm]		[sq km]	[km]	[mAHD]	[mAHD]	[%]	[km]	[mAHD]	[mAHD]	[mins]	[mins]	[mins]	
Eastern Branch	1	1E	US_EastBranch	20	5/1	0.025	0.2277	0.745	84	10	9.93	-	-	-	-	-	-	1
Eastern Branch	2	2E		0	10/2.5	0.100	0.0674	0.580	84	10	12.76	-	-	-	-	-	-	1
Eastern Branch	3	3E	East_3	0	10/2.5	0.100	0.1497	0.885	84	2	9.27	0.25	10	2	13	4	9	1
Eastern Branch	4	4E	East_4	40	1.5/0	0.025	0.1007	0.690	56	2	7.83	0.25	10	2	11	5	8	1
Eastern Branch	5	5E	East_5	0	10/2.5	0.100	0.1671	1.240	76	2	5.97	-	-	-	-	-	-	1
Eastern Branch	6	6E	East_6	15	5/1	0.050	0.0916	0.380	48	1.7	12.18	0.24	2	1.4	11	4	8	1
Eastern Branch	7	7E	East_7	0	10/2.5	0.100	0.1527	1.100	74	1.5	6.59	0.21	1.4	1.4	13	4	9	1
Eastern Branch	8	8E	East_8	35	1.5/0	0.025	0.0806	0.916	53	1.5	5.62	0.21	1.4	1.4	11	4	7	1
Western Branch	1	1W		0	10/2.5	0.100	0.2310	0.620	77	17	9.68	-	-	-	-	-	-	1
Western Branch	2	2W	US_WestBranch	0	10/2.5	0.100	0.3349	0.790	75	4	8.99	0.30	18.6	4	18	5	11	1
Western Branch	3	3W	West_3	0	10/2.5	0.100	0.1969	0.895	76	2.4	8.22	0.08	4	2.4	15	1	8	1
Western Branch	4	4W	West_4	0	10/2.5	0.100	0.2891	0.930	69	1	7.31	0.57	2.4	0.94	17	10	13	1
Bundeena Creek (Main channe	1	1M	Main_1	0	10/2.5	0.100	0.1954	0.900	64	1	7.00	0.24	0.94	0.92	15	4	9	1
Bundeena Creek (Main channe	2	2M	Main_2	5	5/1	0.100	0.1368	0.735	50	1	6.67	0.49	1.4	0.92	13	9	11	1
Bundeena Creek (Main channe	3	3M	Main_3	15	5/1	0.030	0.1346	0.650	19	1.65	2.67	0.10	0.92	0.64	13	2	7	1
Bundeena Creek (Main channe	4	4M	Main_4	25	1.5/0	0.025	0.0608	0.300	19	0.65	6.12	0.39	0.64	0.78	9	8	9	1
Bundeena Creek (Main channe	5A	5M_A	Main_5A	45	1.5/0	0.025	0.0515	0.350	27	2.17	7.09	-	-	-	-	-	-	1
Bundeena Creek (Main channe	5B	5M_B	Main_5B	45	1.5/0	0.025	0.0349	0.250	4.5	1.86	1.06	-	-	-	-	-	-	1
Bundeena Creek (Main channe	5C	5M_C	Main_5C	45	1.5/0	0.025	0.0113	0.190	4.5	0.84	1.93	-	-	-	-	-	-	1
Bundeena Creek (Main channe	6	6M	Main_6	10	5/1	0.025	0.0116	0.120	11	0.65	8.63	0.12	0.78	0.77	5	3	4	1
Bundeena Creek (Main channe	7	7M	Main_7	40	1.5/0	0.025	0.0557	0.430	45	1	10.23	0.18	0.77	1.21	9	3	6	1

(blue)	-upstream boundary for TUFLOW hydrodynamic model
(orange)	-local inflow on Bundeena Creek

INTENSITY-FREQUENCY-DURATION (IFD) DATA CATEGORIES FOR THE CATCHMENT

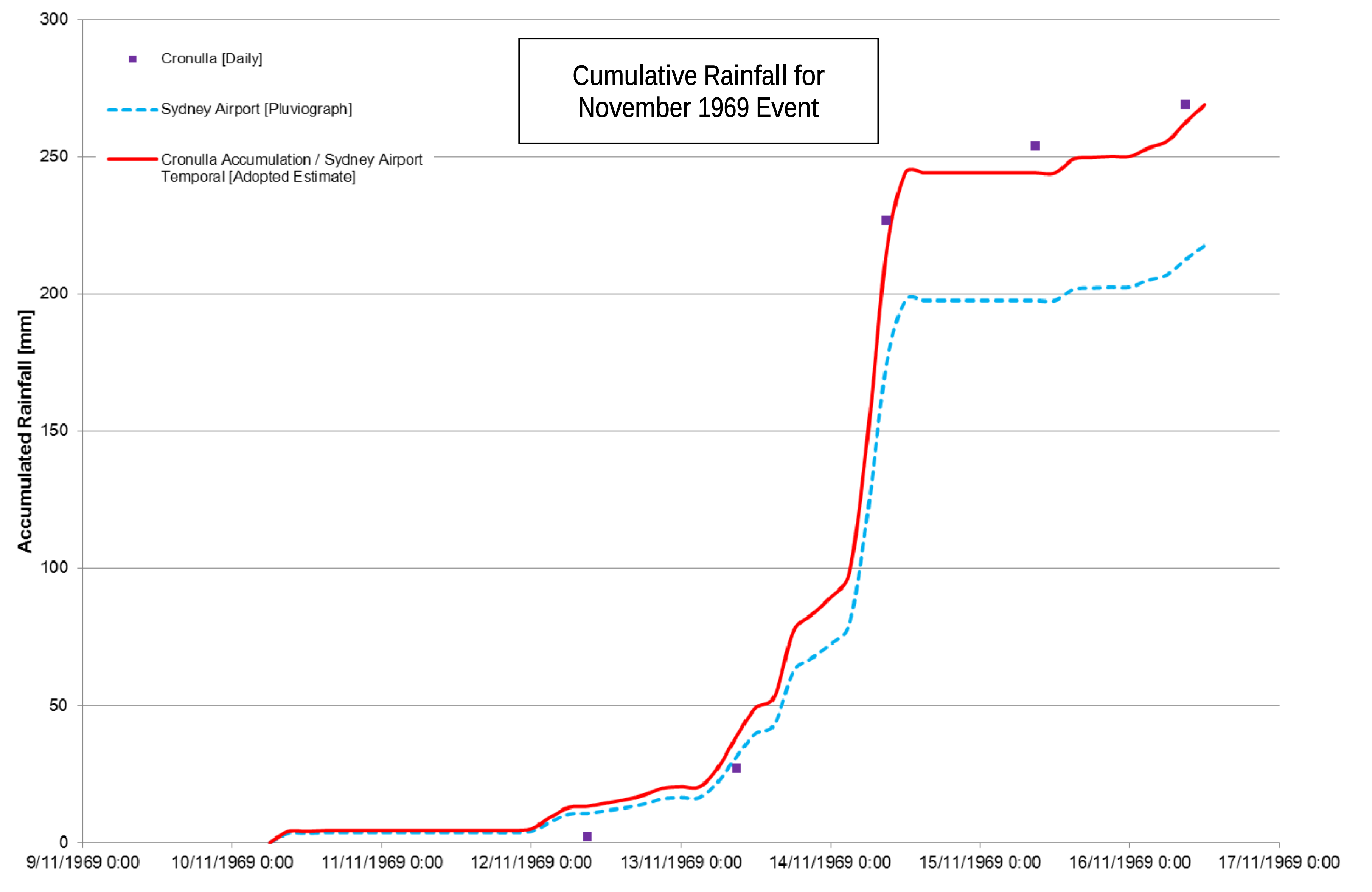
01	Long	151.150 E
	Lat	34.075 S

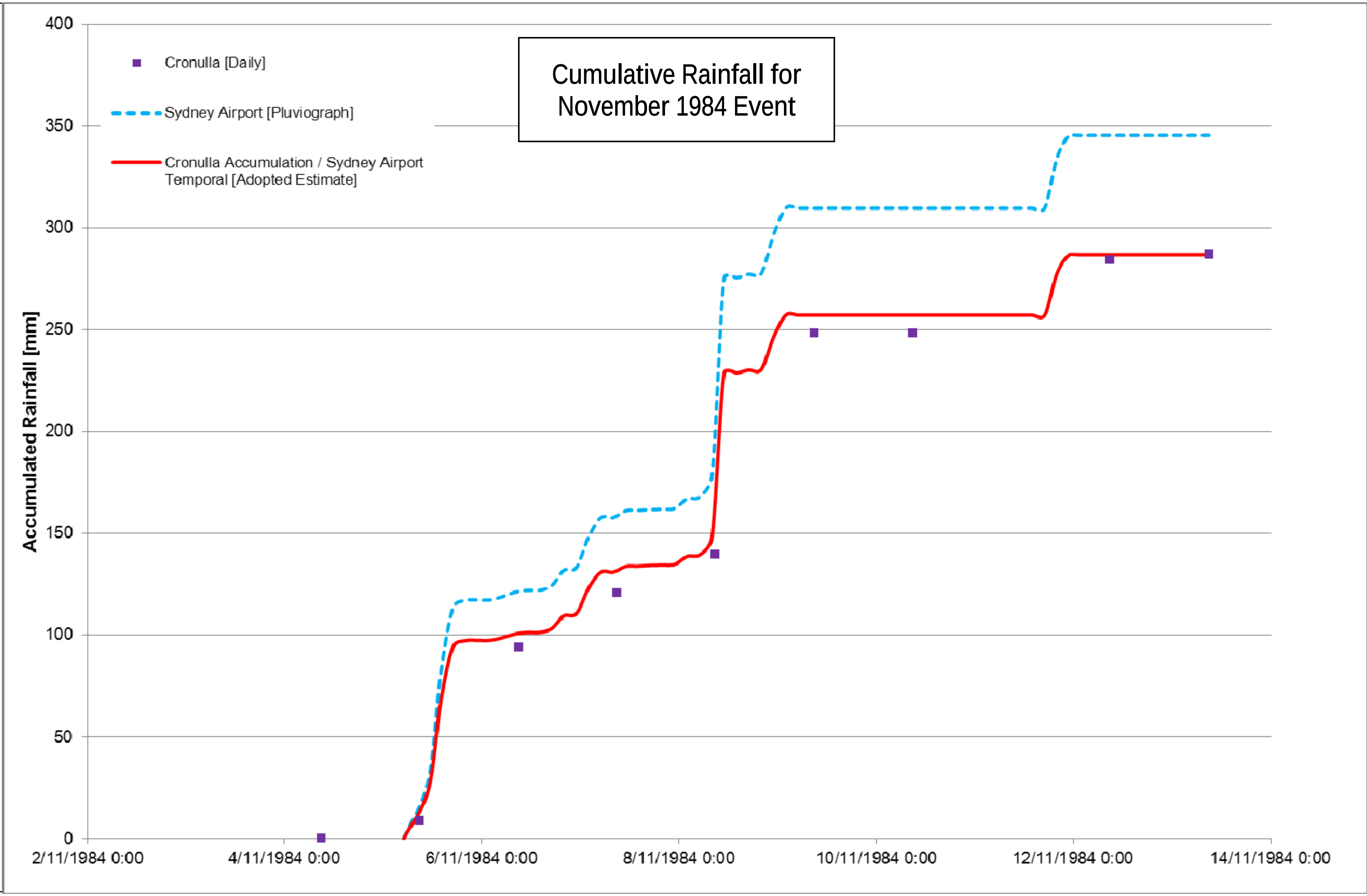
>>> From BoM DURATION	1 Year	2 years	5 years	10 years	20 years	50 years	100 years
5Mins	98.1	126	160	180	206	240	266
6Mins	91.8	118	150	169	193	225	250
10Mins	75.2	96.7	124	140	161	188	209
20Mins	55.1	71.3	92.8	105	122	144	160
30Mins	44.9	58.2	76.4	87.1	101	120	134
1Hr	30.4	39.5	52.2	59.8	69.7	82.7	92.7
2Hrs	19.8	25.7	34	39	45.4	53.8	60.3
3Hrs	15.2	19.8	26.1	29.8	34.7	41.1	46
6Hrs	9.71	12.6	16.5	18.7	21.7	25.6	28.6
12Hrs	6.24	8.06	10.5	11.9	13.8	16.2	18
24Hrs	4.05	5.23	6.78	7.69	8.89	10.5	11.7
48Hrs	2.59	3.34	4.34	4.93	5.69	6.7	7.46
72Hrs	1.93	2.49	3.23	3.66	4.21	4.95	5.51

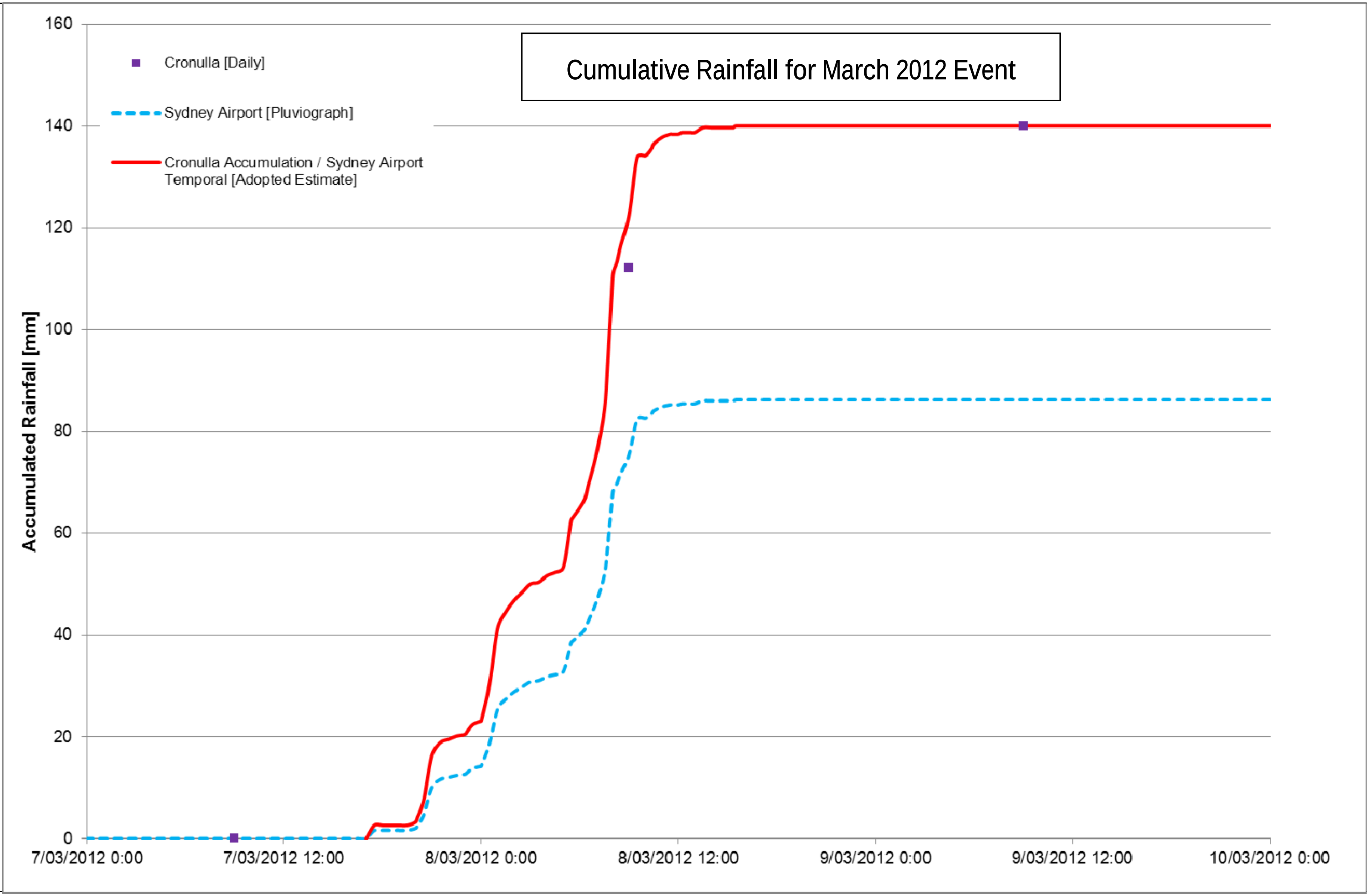
Into XP-RAFTS>>>			
	82.7	16.2	4.95
	39.5	8.06	2.49
Location Skew	0		
f2	4.29		
f50	15.85		

APPENDIX B

RECORDED RAINFALL USED IN TUFLOW MODEL CALIBRATION


Cumulative Rainfall for November 1969 Event
Cronulla [Daily]
Sydney Airport [Pluviograph]
Cronulla Accumulation / Sydney Airport Temporal [Adopted Estimate]
Accumulated Rainfall [mm]
300
250
200
150
100
50
0
9/11/1969 0:00
10/11/1969 0:00
11/11/1969 0:00
12/11/1969 0:00
13/11/1969 0:00
14/11/1969 0:00
15/11/1969 0:00
16/11/1969 0:00
17/11/1969 0:00

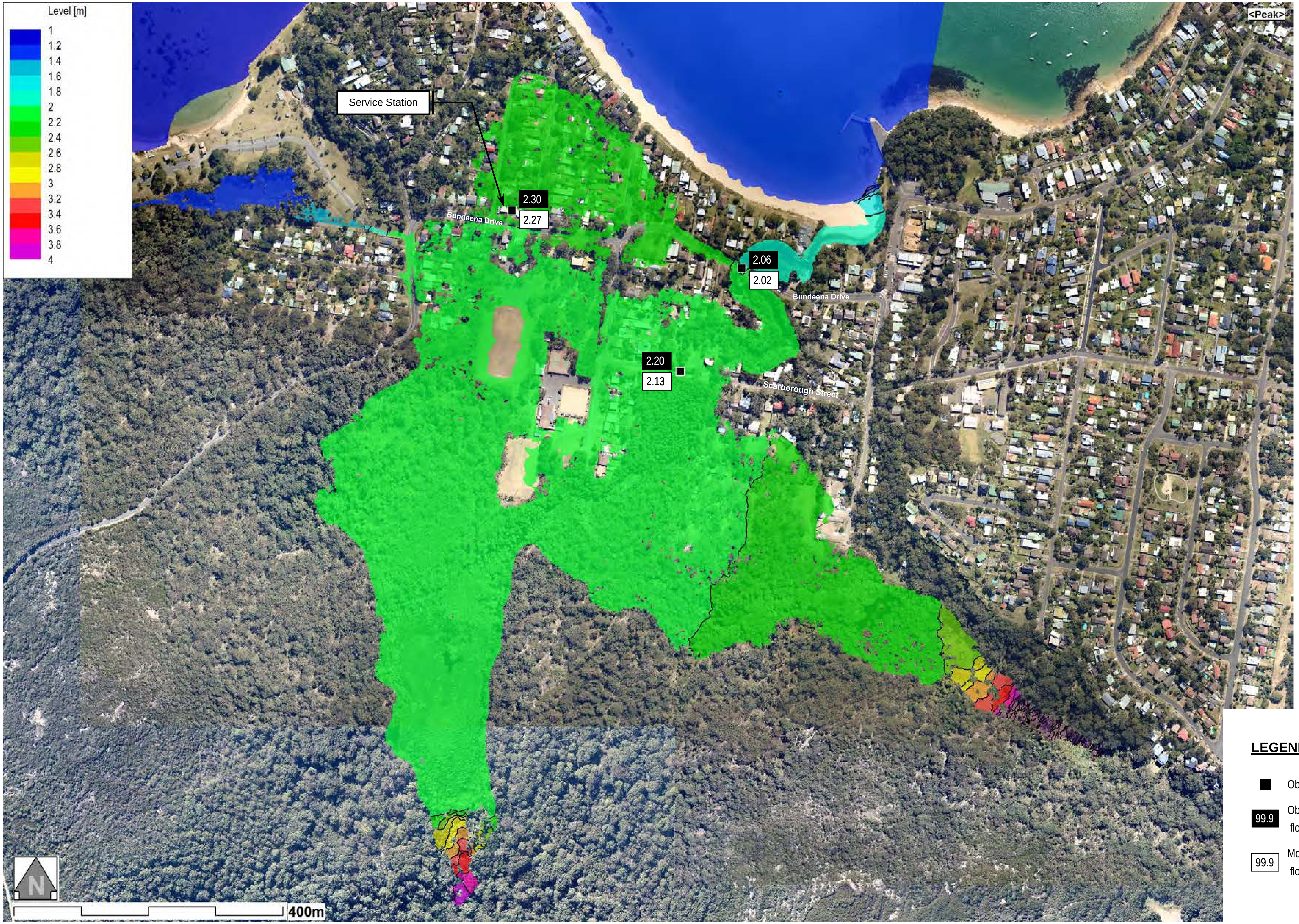

Cumulative Rainfall for November 1984 Event
Cronulla [Daily]
Sydney Airport [Pluviograph]
Cronulla Accumulation / Sydney Airport Temporal [Adopted Estimate]
Accumulated Rainfall [mm]
400
350
300
250
200
150
100
50
0
2/11/1984 0:00
4/11/1984 0:00
6/11/1984 0:00
8/11/1984 0:00
10/11/1984 0:00
12/11/1984 0:00
14/11/1984 0:00


Cumulative Rainfall for March 2012 Event
Cronulla [Daily]
Sydney Airport [Pluviograph]
Cronulla Accumulation / Sydney Airport Temporal [Adopted Estimate]
Accumulated Rainfall [mm]
160
140
120
100
80
60
40
20
0
7/03/2012 0:00
7/03/2012 12:00
8/03/2012 0:00
8/03/2012 12:00
9/03/2012 0:00
9/03/2012 12:00
10/03/2012 0:00

APPENDIX C

SUMMARY OF HYDRODYNAMIC MODEL CALIBRATION

FIGURE C.1



LEGEND:

- ■ Observed level location
- 99.9 Observed peak flood level [mAHD]
- 99.9 Modelled peak flood level [mAHD]

Note: In areas where there are more than one observed peak flow level the value listed relates to the highest of the data set observed in the vicinity

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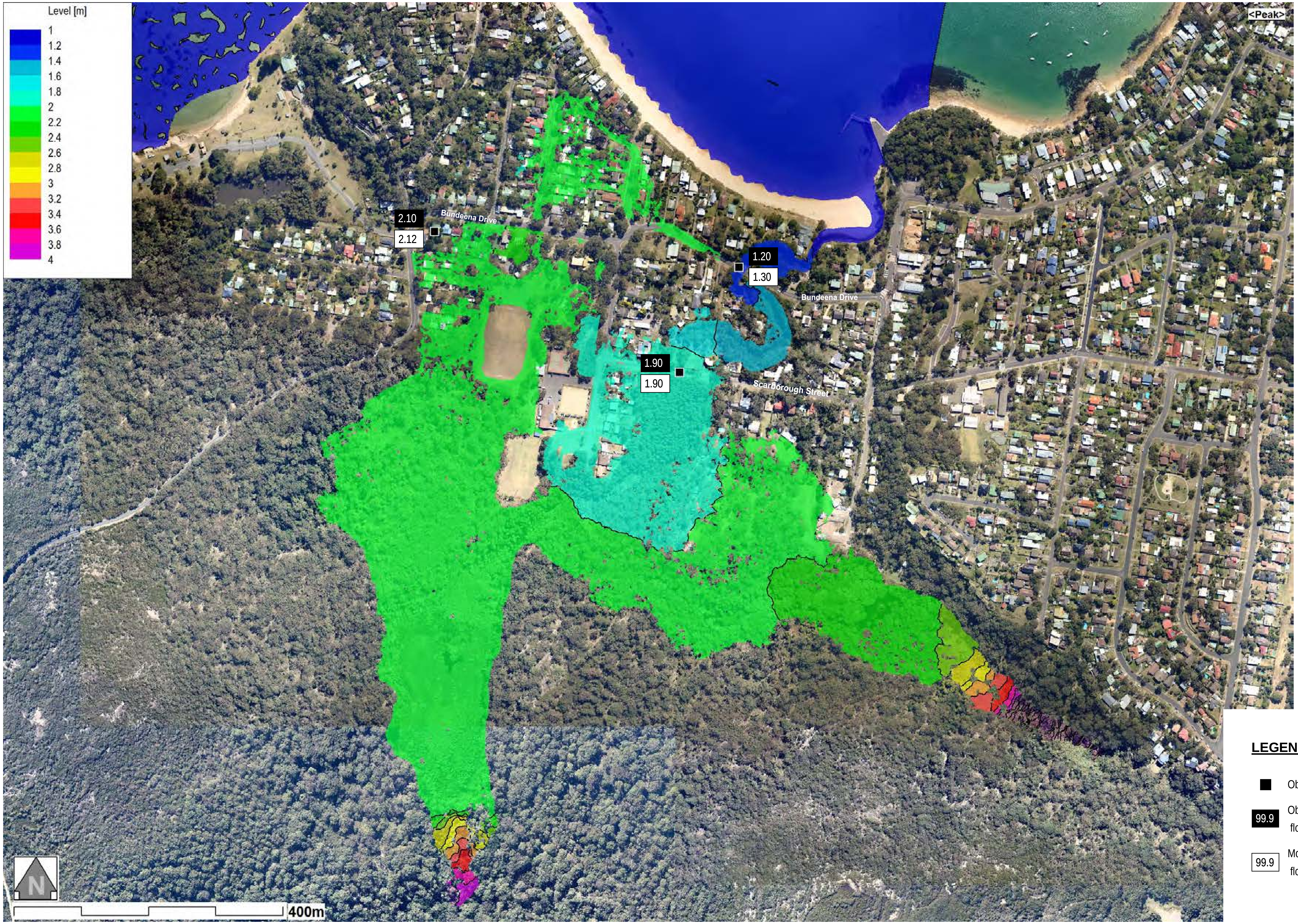
301015-03182 – Bundeena Creek Flood Study
C.1_fg301015-03182sb131209-Level_1969.doc

MODELLED FLOOD LEVELS AT THE PEAK OF THE 1969 EVENT

FIGURE C.2



Note: In areas where there are more than one observed peak flood level the value listed relates to the highest of the data set observed in the vicinity

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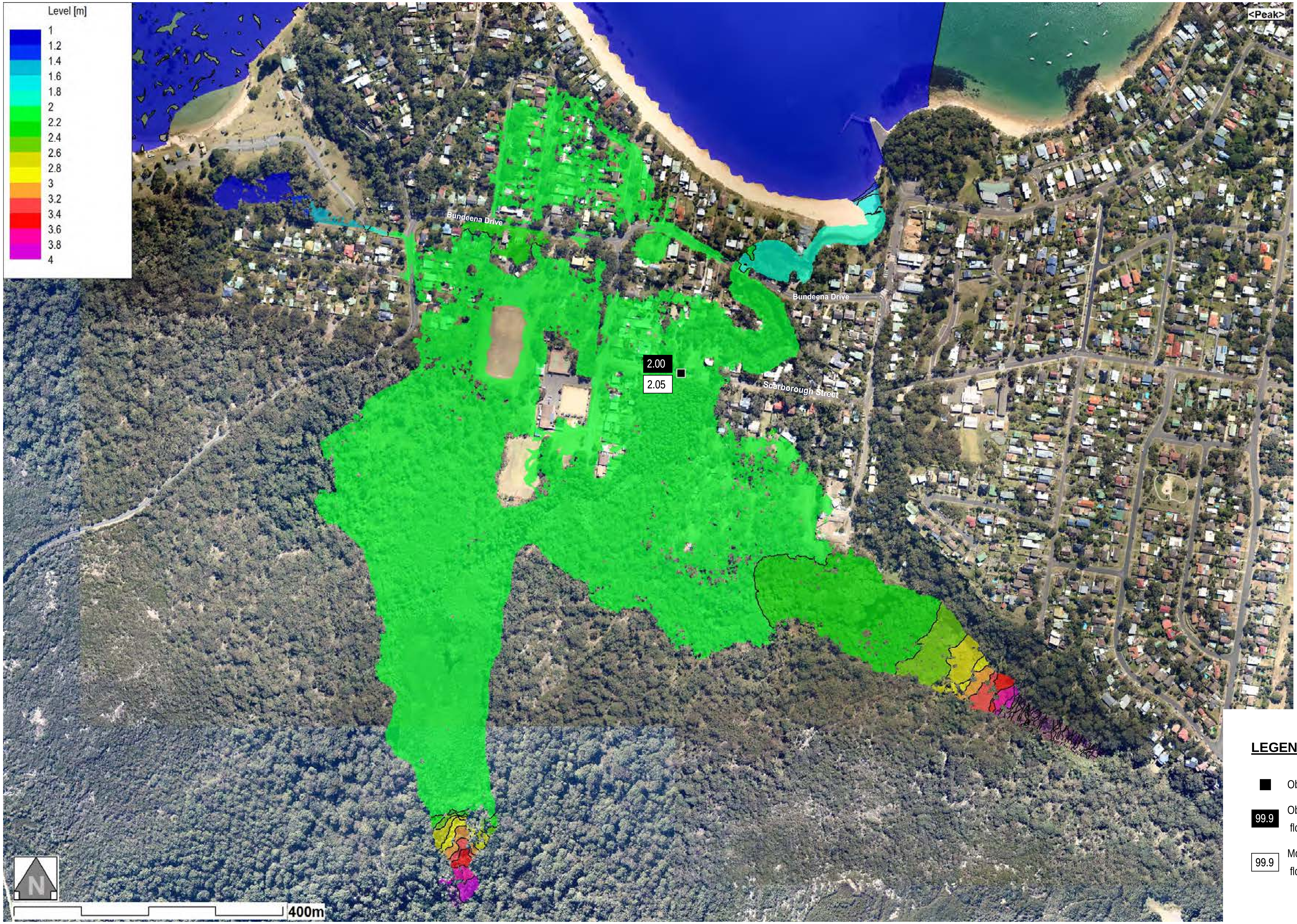
301015-03182 – Bundeena Creek Flood Study
C.2_fg301015-03182sb131129-Level_1984.doc

MODELLED FLOOD LEVELS AT THE PEAK OF THE 1984 EVENT

FIGURE C.3



LEGEND:

■ Observed level location

99.9 Observed peak flood level [mAHD]

99.9 Modelled peak flood level [mAHD]

Note: In areas where there are more than one observed peak flood level the value listed relates to the highest of the data set observed in the vicinity

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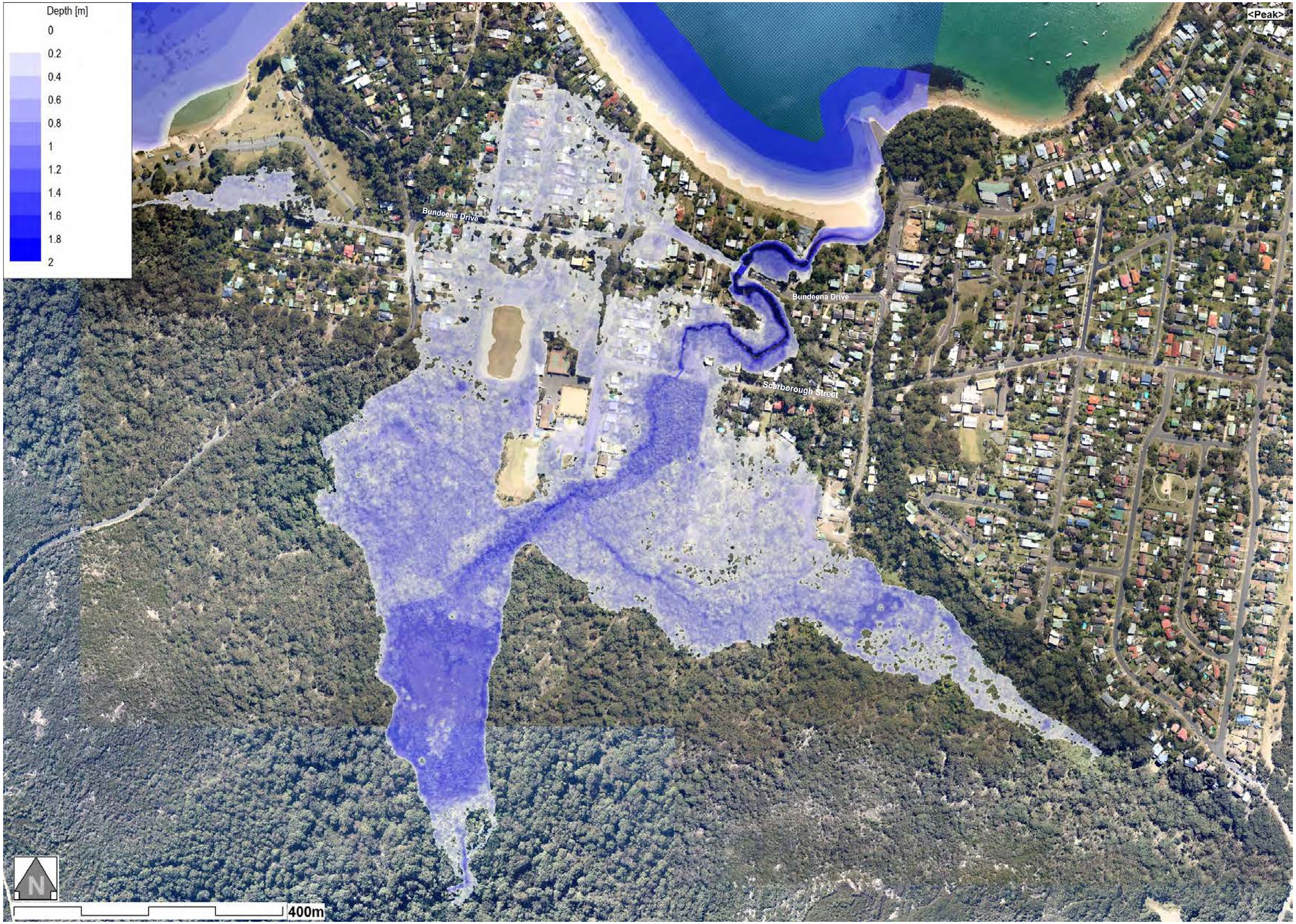
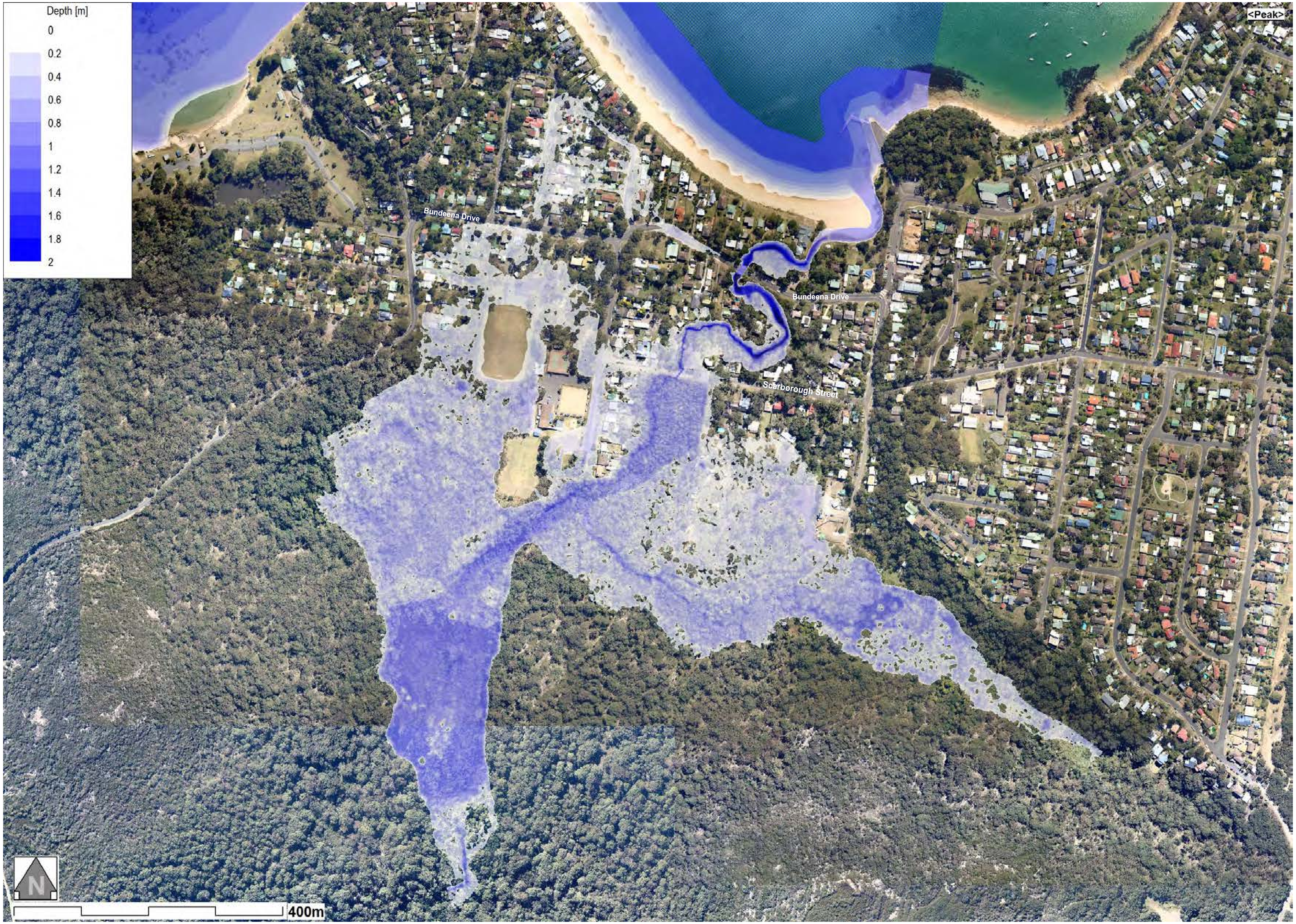
301015-03182 – Bundeena Creek Flood Study
C.3_fg301015-03182sb131209-Level_2012.doc

MODELLED FLOOD LEVELS AT THE PEAK OF THE 2012 EVENT



MODELLED FLOOD DEPTHS AT THE PEAK OF THE 1969 EVENT

FIGURE C.5



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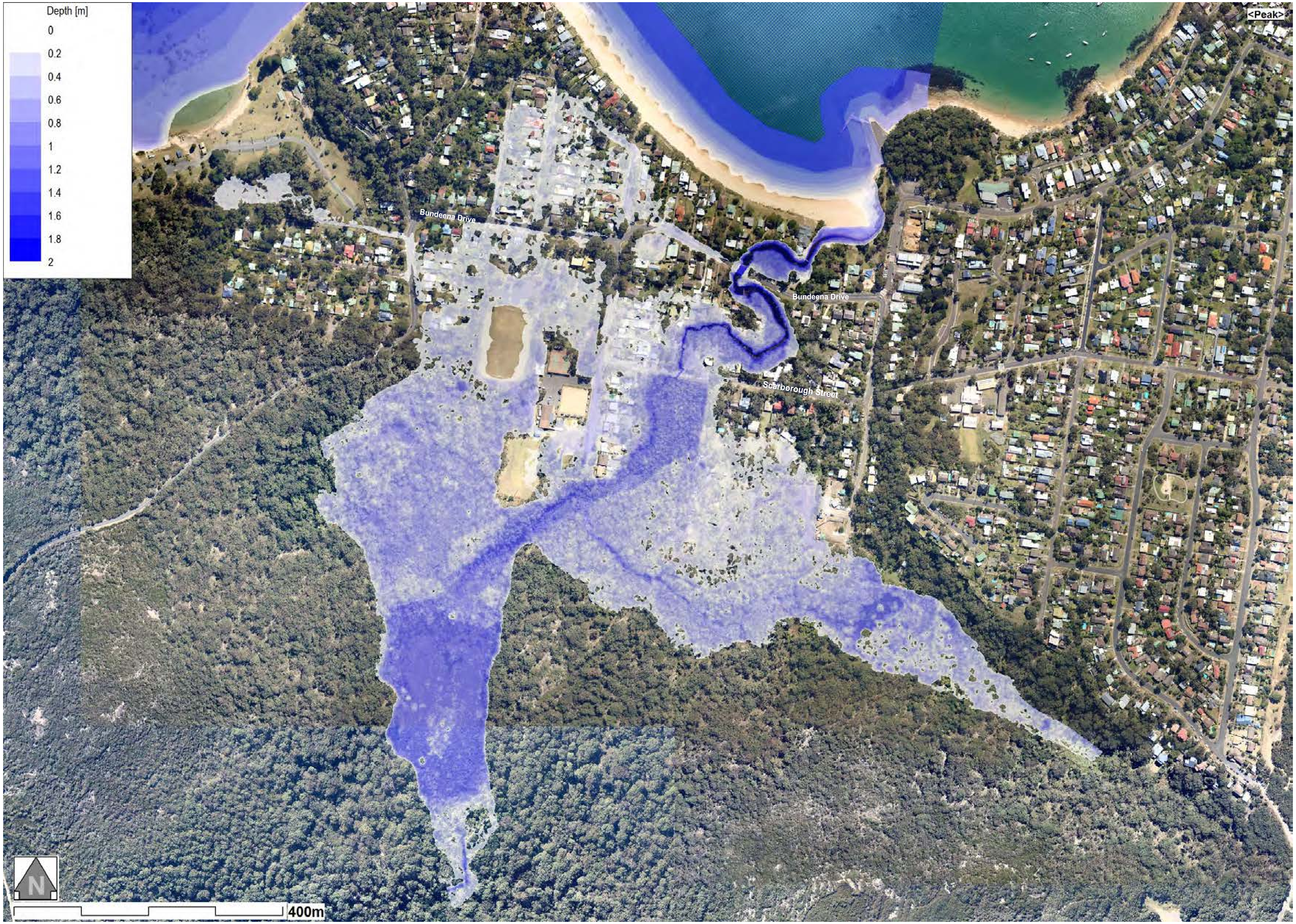
C.5_fg301015-03182sb131209-Depth_1984.doc

MODELLED FLOOD DEPTHS AT THE PEAK OF THE 1984 EVENT

FIGURE C.6



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C.6_fg301015-03182sb131209-Depth_2012.doc

MODELLED FLOOD DEPTHS AT THE PEAK OF THE 2012 EVENT

APPENDIX D

NOTES ON PROBABILITY TERMINOLOGY FOR DESIGN EVENTS

A draft discussion paper prepared as part of the current Australian Rainfall & Runoff revision project attempts to clarify the terminology currently in use and that proposed for future use (*Engineers Australia, 2013*).

The range of available terminology is shown **Table D.1** below. The terminology preferred by the National Committee on Water Engineering and the National Flood Risk Advisory Group (*NFRAG*) is highlighted in green. Annual Exceedance Probability (*AEP*) has been adopted as the preferred terminology for this study. Despite the minor discrepancies in probability shown below, the adopted 50% and 20% AEP events are assumed to be equivalent to the 2 and 5 year ARI events, respectively (*and to the 0.5 and 0.2 EY*).

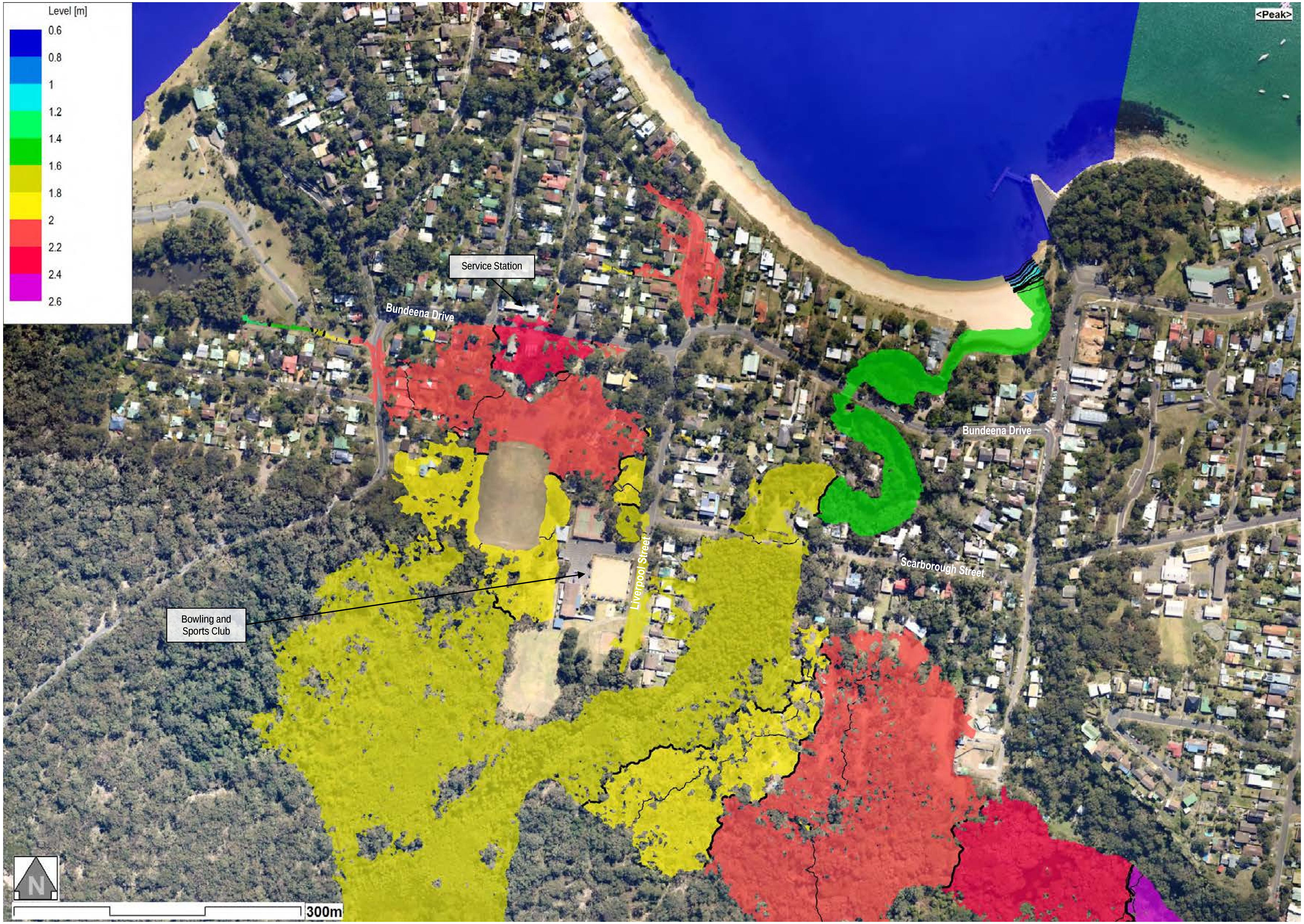
Table D.1 COMPARISON OF COMMON FLOOD PROBABILITY TERMINOLOGY

EXCEEDANCES PER YEAR (*EY*)	ANNUAL EXCEEDANCE PROBABILITY (*AEP %*)	ANNUAL EXCEEDANCE PROBABILITY (*1 in X*)	AVERAGE RECURRENCE INTERVAL (*ARI*)
6	99.75	1.002	0.17
4	98.17	1.02	0.25
3	95.02	1.05	0.33
2	86.47	1.16	0.5
1	63.21	1.58	1
0.69	50	2	1.44
0.5	39.35	2.54	2
0.22	20	5	4.48
0.2	18.13	5.52	5
0.11	10	10	9.49
0.05	5	20	19.5
0.02	2	50	49.5
0.01	1	100	99.5
0.005	0.5	200	199.5
0.002	0.2	500	499.5
0.001	0.1	1000	999.5
0.0005	0.05	2000	1999.5
0.0002	0.02	5000	4999.5

APPENDIX E

DESIGN FLOOD LEVEL MAPPING

FIGURE E.1



LEGEND:

0.1 metre contour line

0.2 metre contour line

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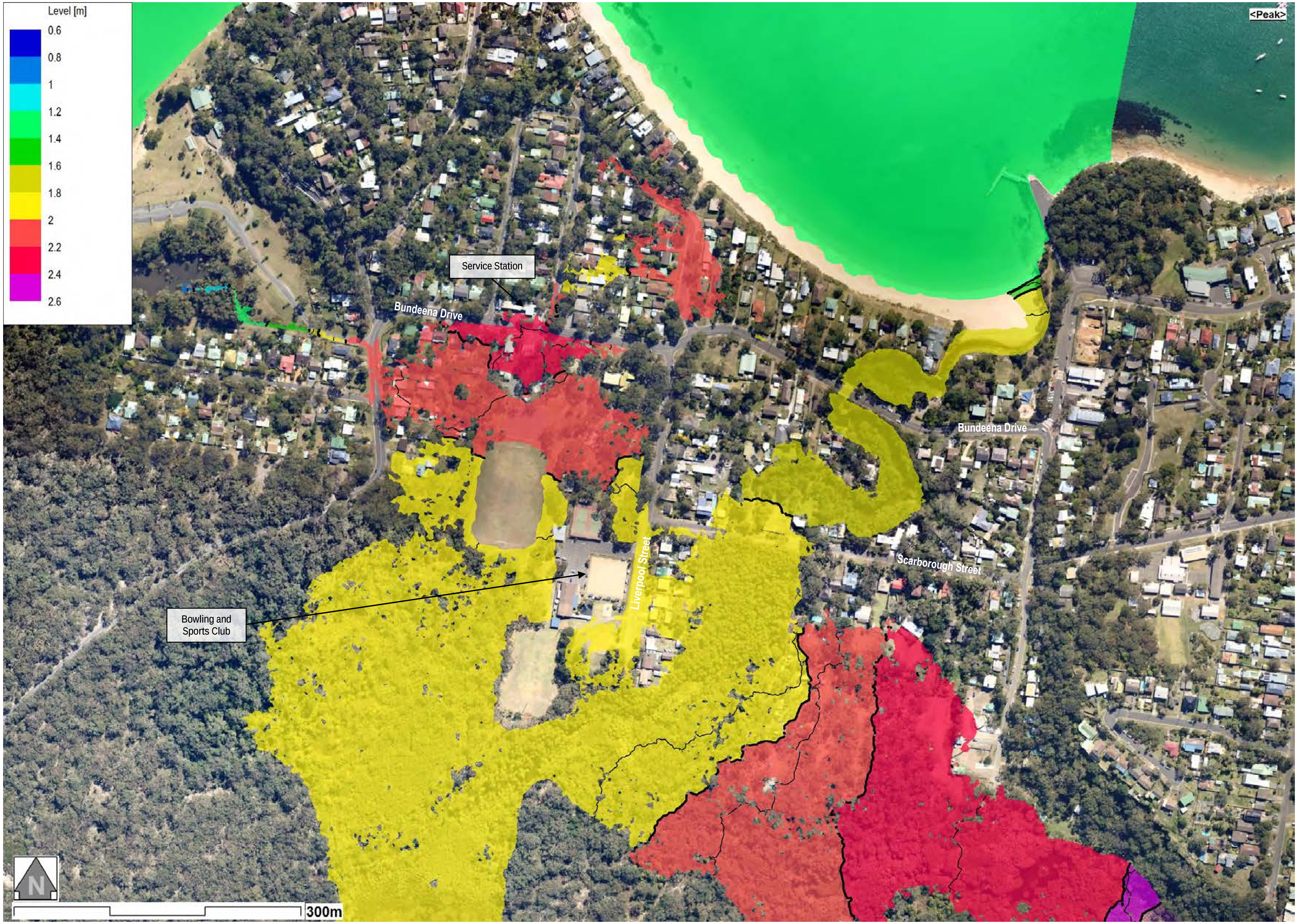
301015-03182 – Bundeena Creek Flood Study
E.1_fg301015-03182_EH131111-50%AEP_Level.doc

PEAK 50% AEP FLOOD LEVELS

FIGURE E.2



LEGEND:

0.1 metre contour line

0.2 metre contour line

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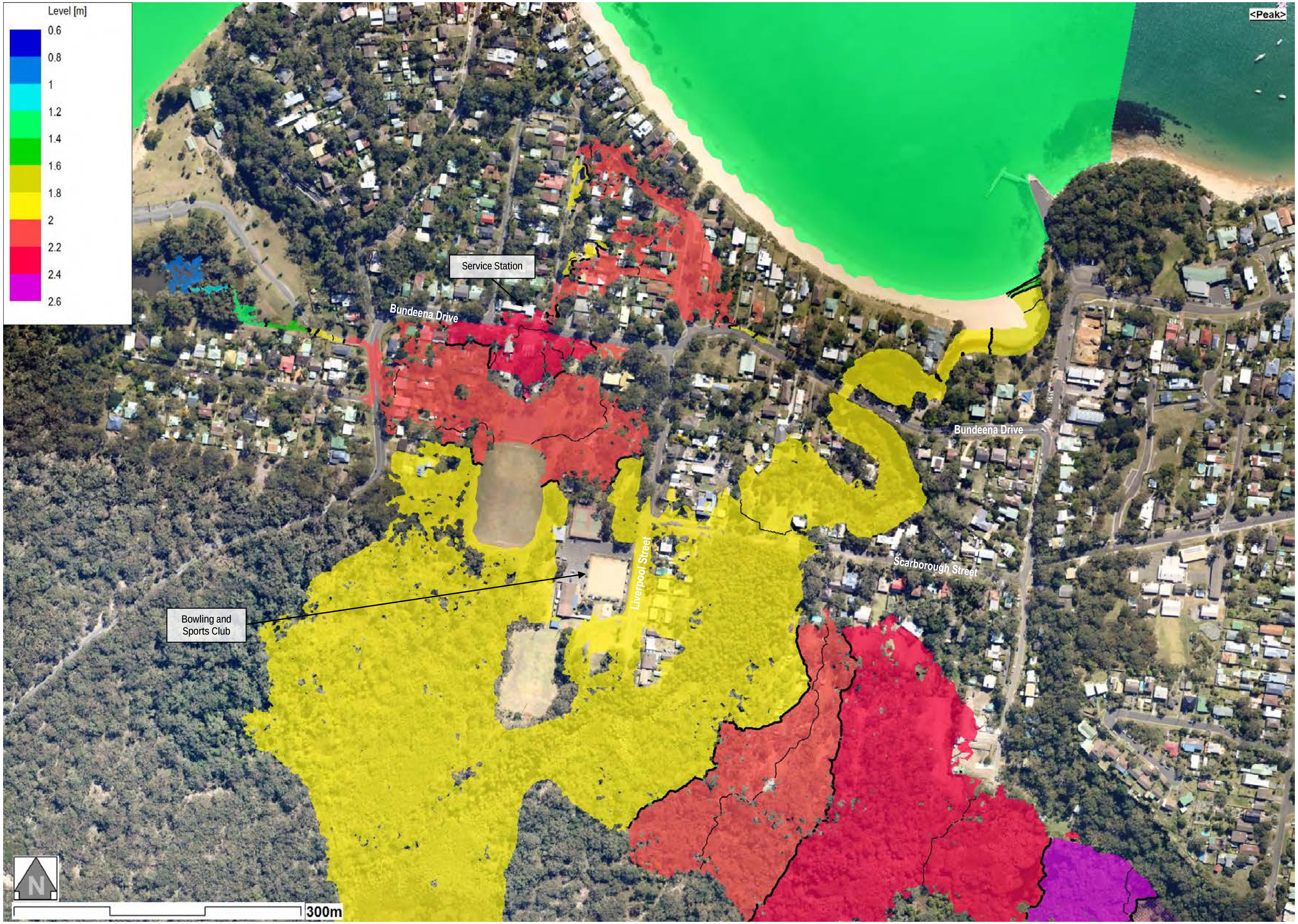
301015-03182 – Bundeena Creek Flood Study
E.2_fg301015-03182_EH131111-20%AEP_Level.doc

PEAK 20% AEP FLOOD LEVELS

FIGURE E.3



LEGEND:

0.1 metre contour line

0.2 metre contour line

WorleyParsons
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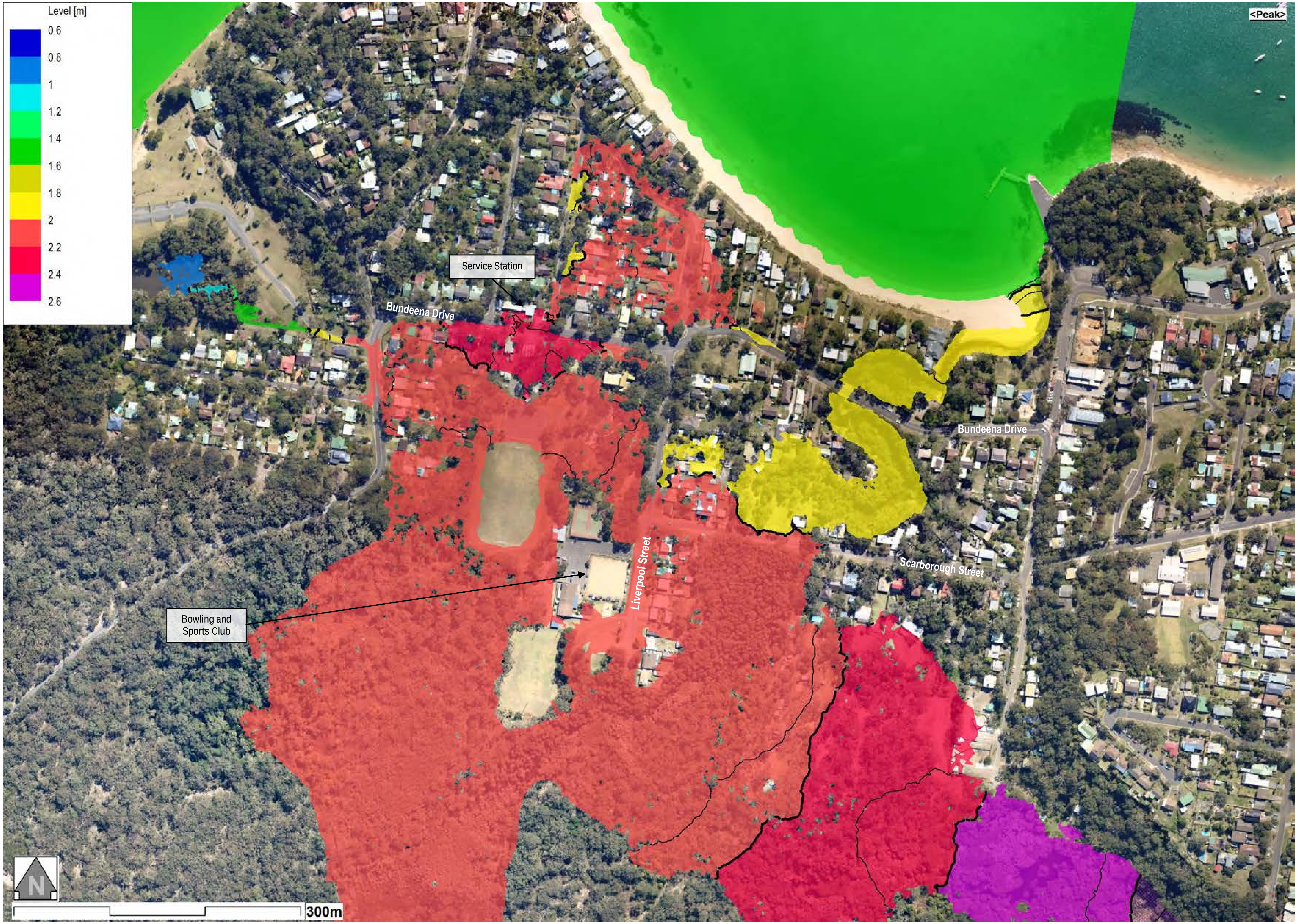
PEAK 10% AEP FLOOD LEVELS

FIGURE E.4



LEGEND:

0.1 metre contour line

0.2 metre contour line

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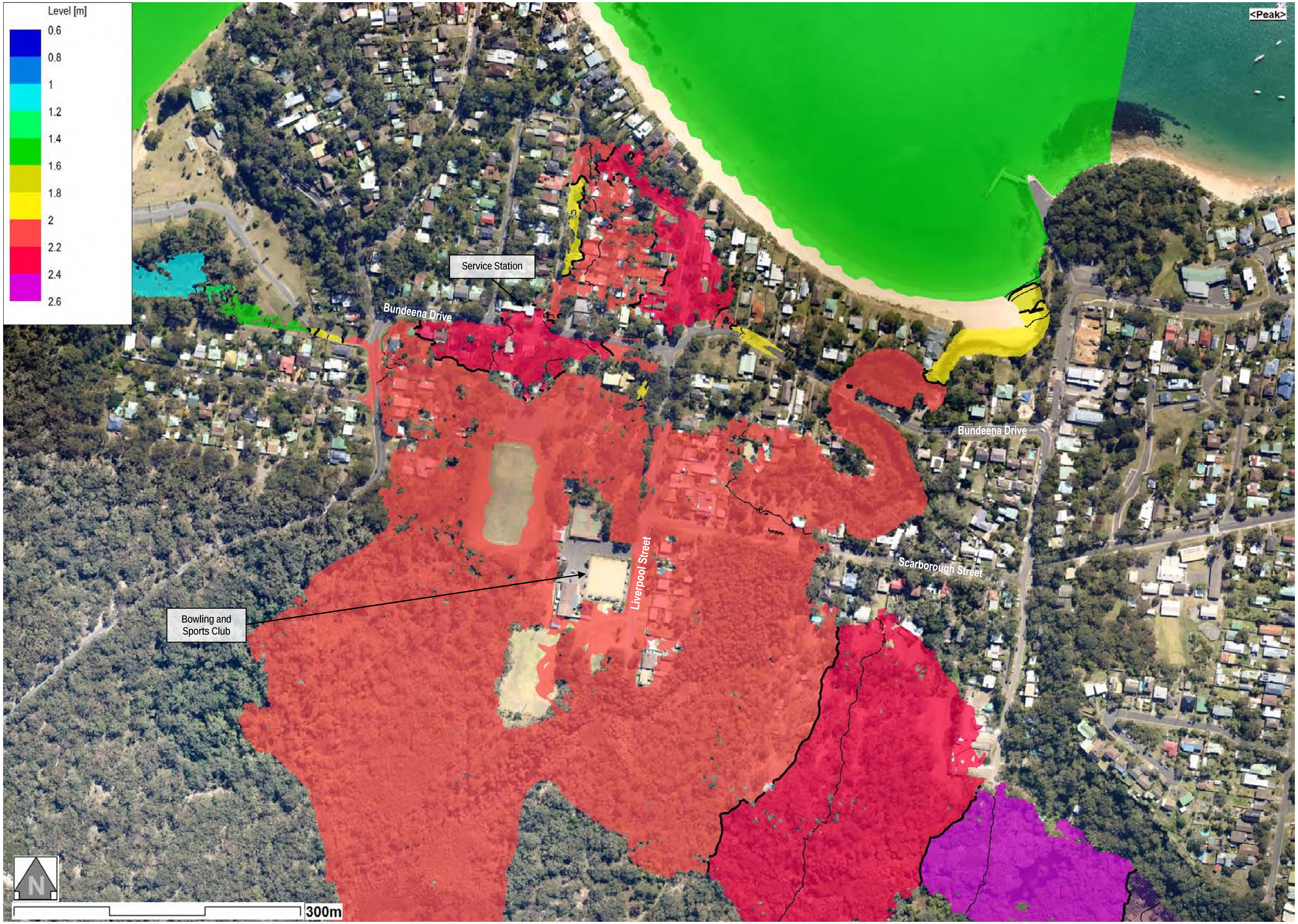
resources & energy

301015-03182 – Bundeena Creek Flood Study
E.4_fg301015-03182_EH131111-5%AEP_Level.doc

PEAK 5% AEP FLOOD LEVELS

FIGURE E.5



LEGEND:

0.1 metre contour line

0.2 metre contour line

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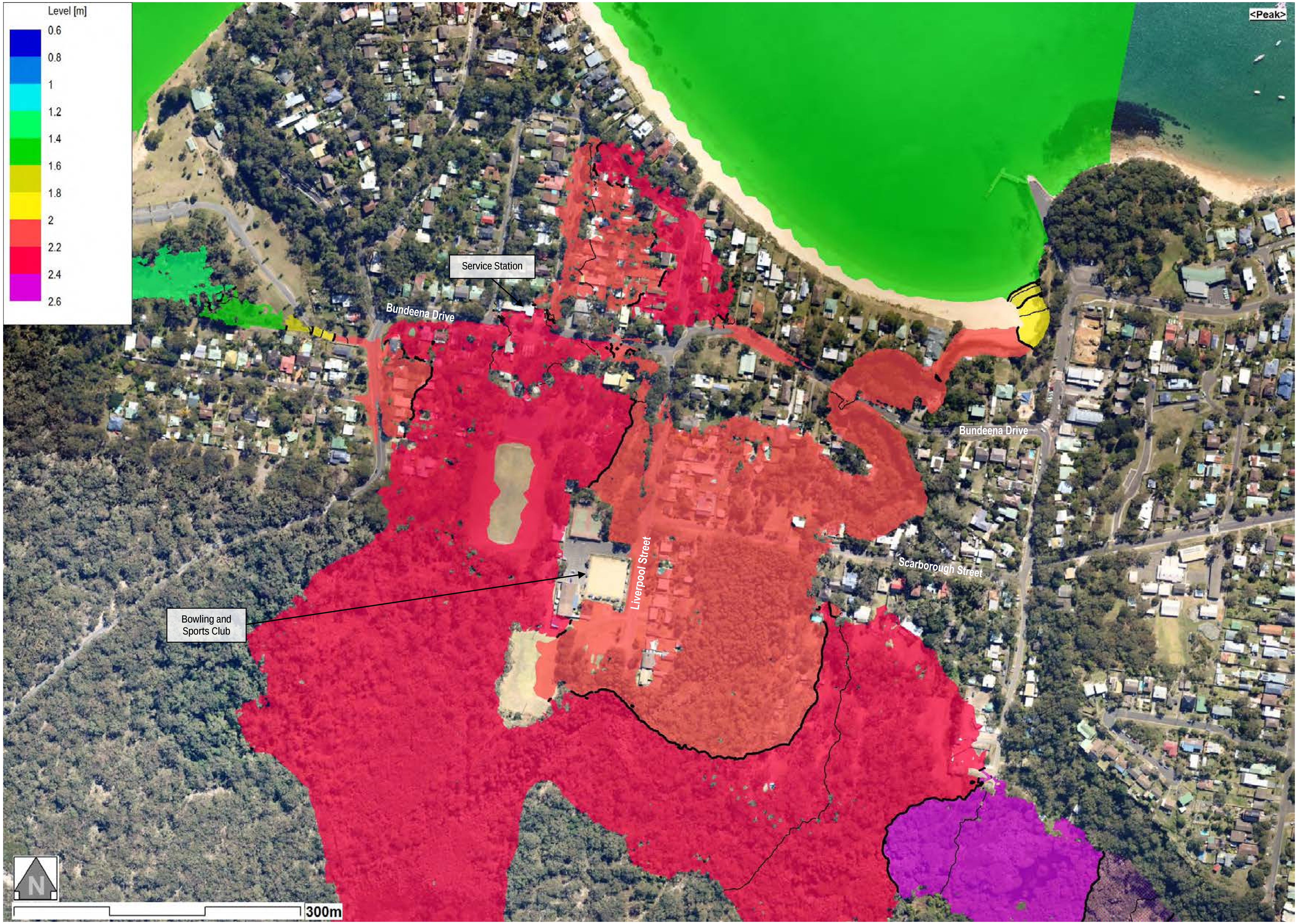
301015-03182 – Bundeena Creek Flood Study
E.5_fg301015-03182_EH131111-2%AEP_Level.doc

PEAK 2% AEP FLOOD LEVELS

FIGURE E.6



LEGEND:

- 0.1 metre contour line
- 0.2 metre contour line

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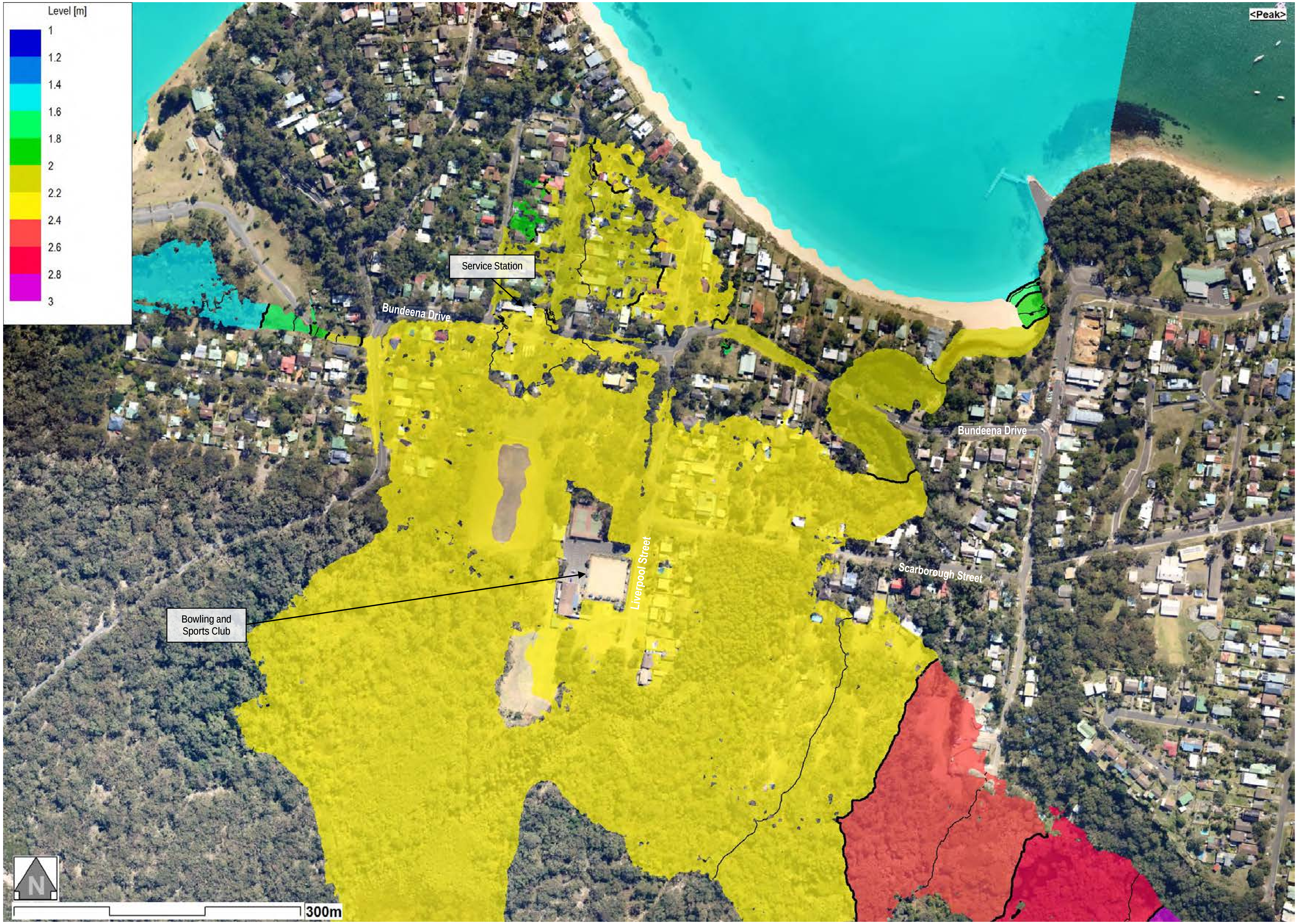
301015-03182 – Bundeena Creek Flood Study
E.6_fg301015-03182_EH131111-1%AEP_Level.doc

PEAK 1% AEP FLOOD LEVELS

FIGURE E.7



LEGEND:

0.1 metre contour line

0.2 metre contour line

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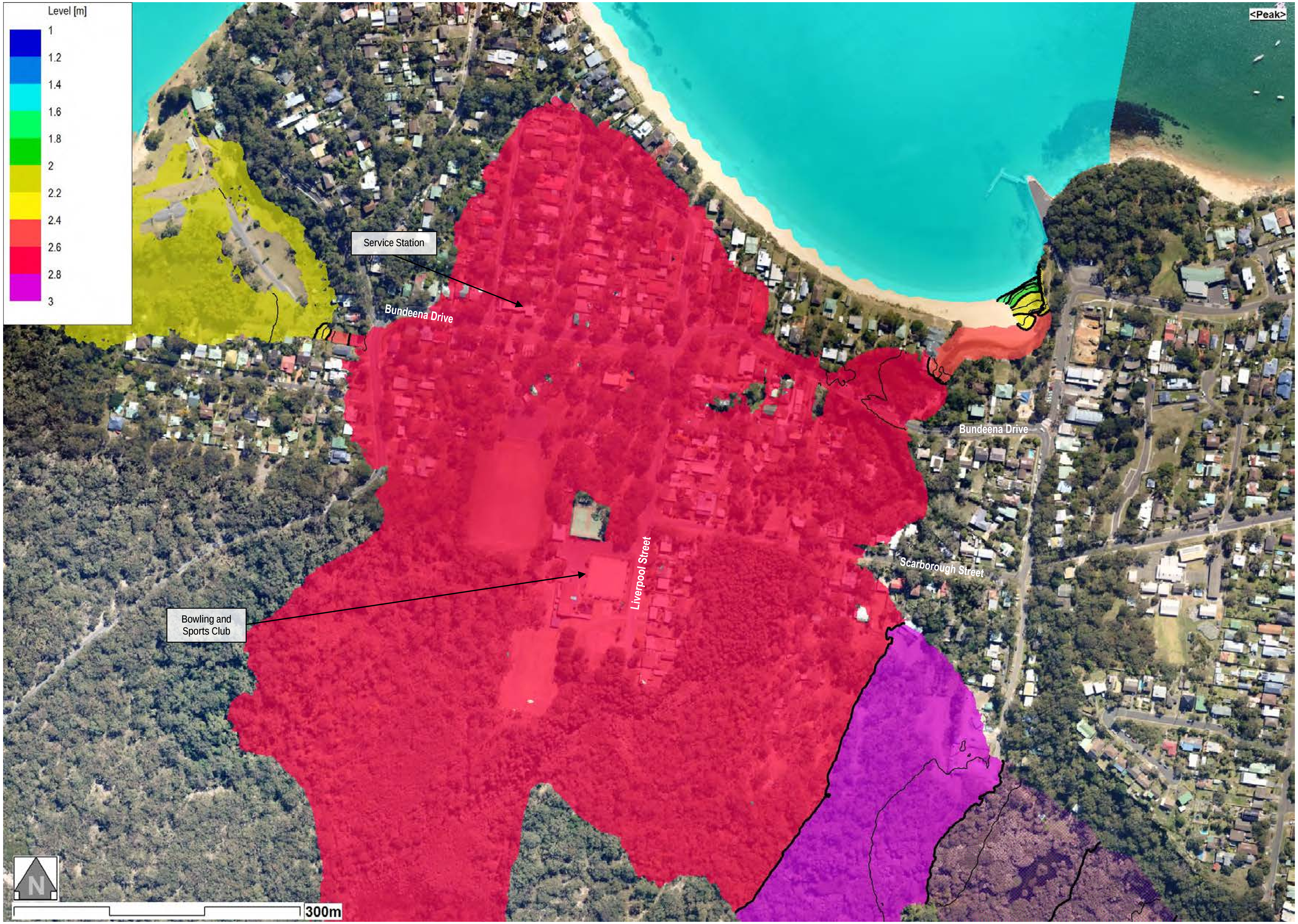
301015-03182 – Bundeena Creek Flood Study
E.7_fg301015-03182_EH131111-0.5%AEP_Level.doc

PEAK 0.5% AEP FLOOD LEVELS

FIGURE E.8



LEGEND:

0.1 metre contour line

0.2 metre contour line

WorleyParsons
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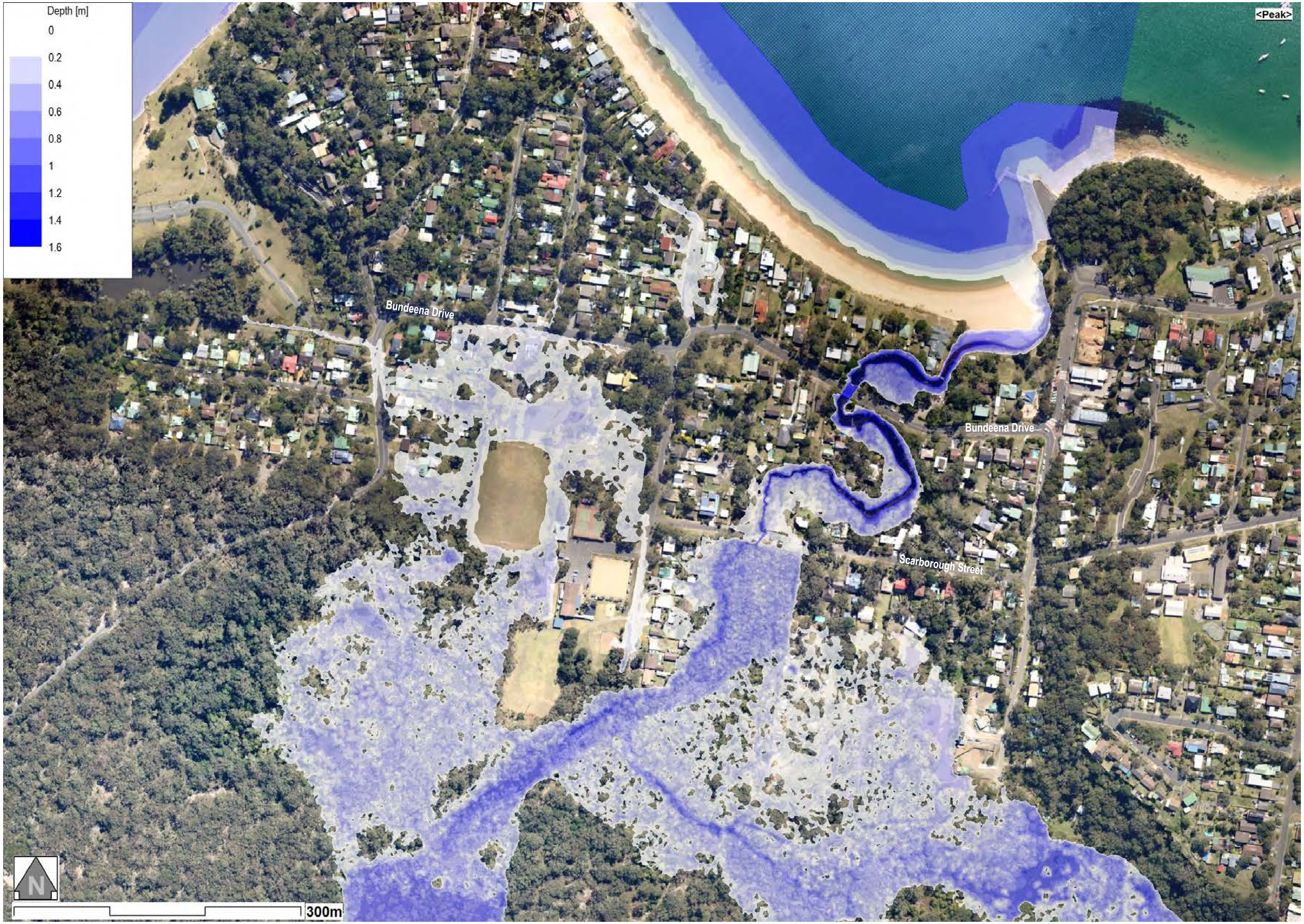
PROBABLE MAXIMUM FLOOD LEVELS

APPENDIX F

DESIGN FLOOD DEPTH MAPPING

FIGURE F.1



NOTES:

Hatching indicates flood depths greater than 1.6 metres

WorleyParsons
resources & energy

301015-03182 – Bundeena Creek Flood Study
F.1_fg301015-03182_EH131111-50%AEP_Depth.doc

PEAK 50% AEP FLOOD DEPTHS

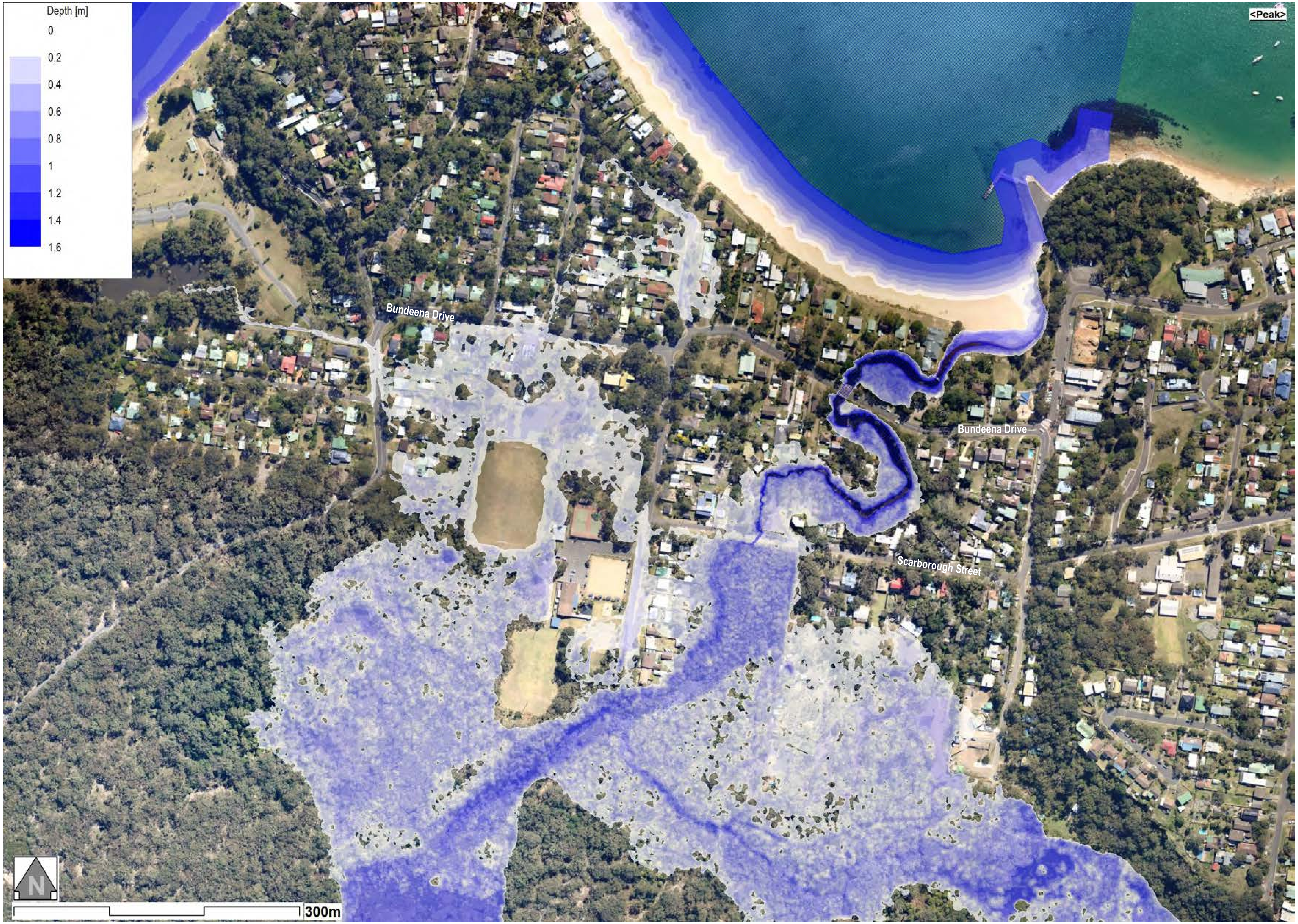


FIGURE F.2

NOTES:

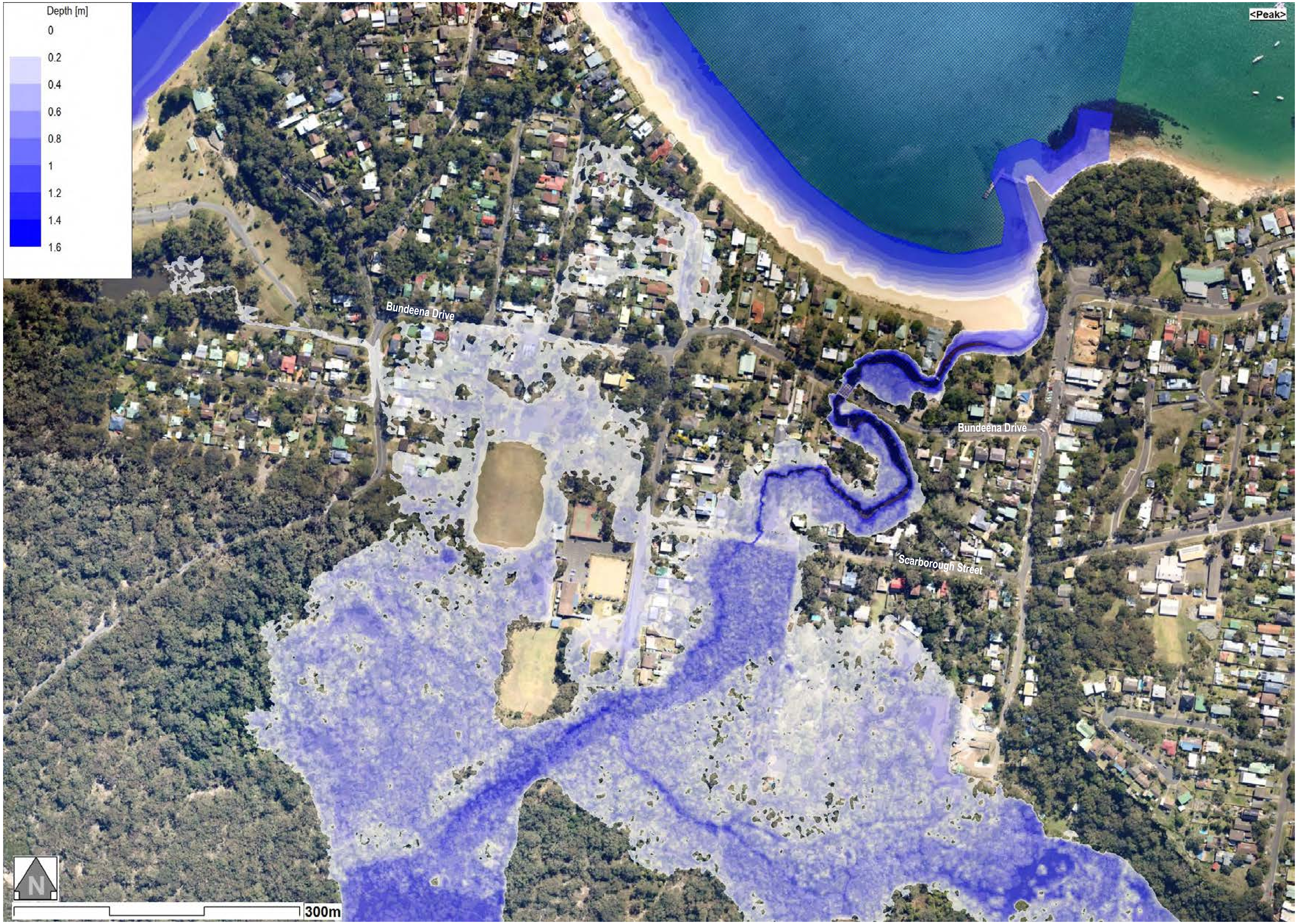
Hatching indicates flood depths greater than 1.6 metres

WorleyParsons
resources & energy

PEAK 20% AEP FLOOD DEPTHS

301015-03182 – Bundeena Creek Flood Study
F.2_fg301015-03182_EH131111-20%AEP_Depth.doc

FIGURE F.3



NOTES:

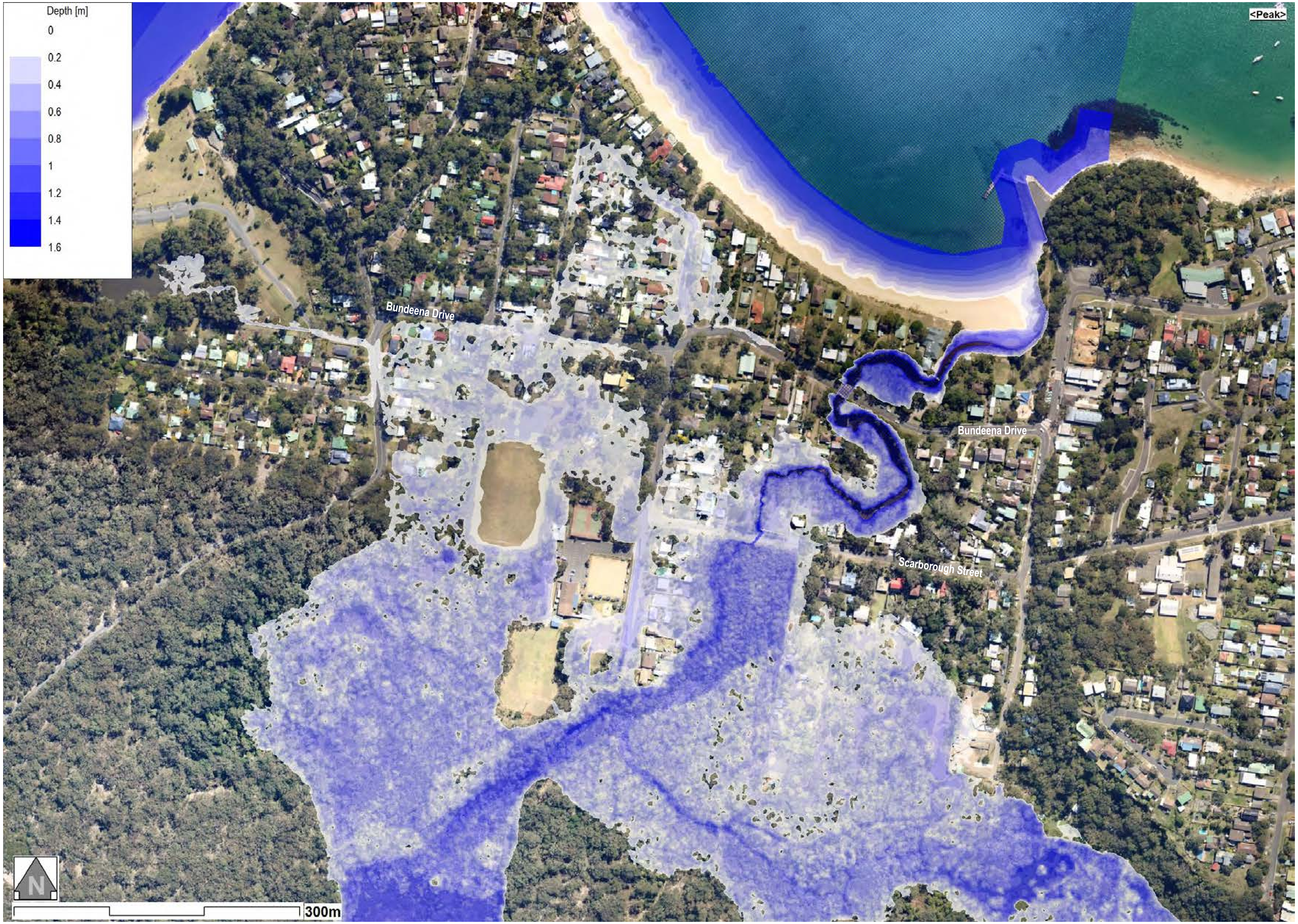
Hatching indicates flood depths greater than 1.6 metres

WorleyParsons
resources & energy

301015-03182 – Bundeena Creek Flood Study
F.3_fg301015-03182_EH131111-10%AEP_Depth.doc

PEAK 10% AEP FLOOD DEPTHS

FIGURE F.4



NOTES:

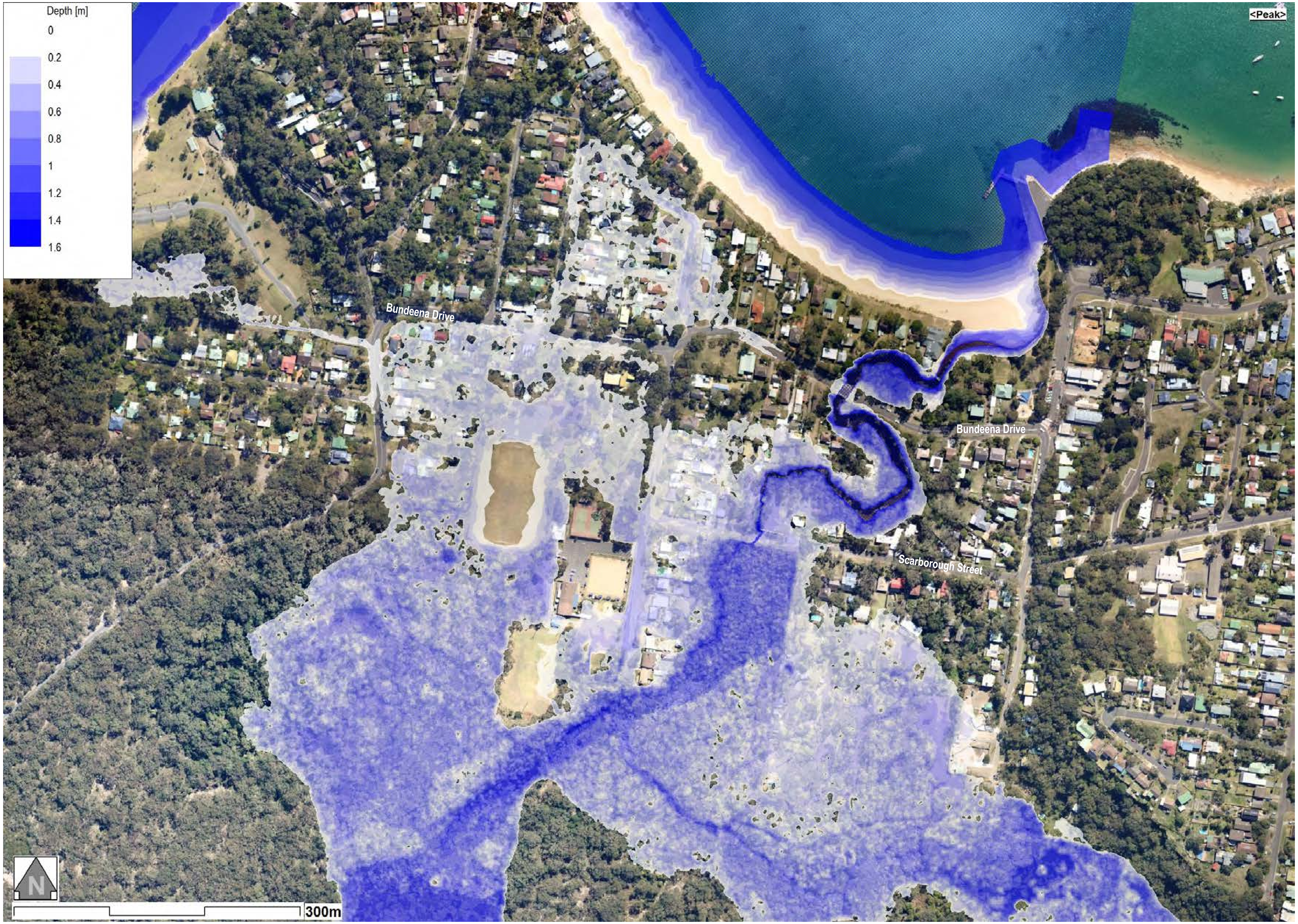
Hatching indicates flood depths greater than 1.6 metres

WorleyParsons
resources & energy

301015-03182 – Bundeena Creek Flood Study
F.4_fg301015-03182_EH131111-5%AEP_Depth.doc

PEAK 5% AEP FLOOD DEPTHS

FIGURE F.5



NOTES:

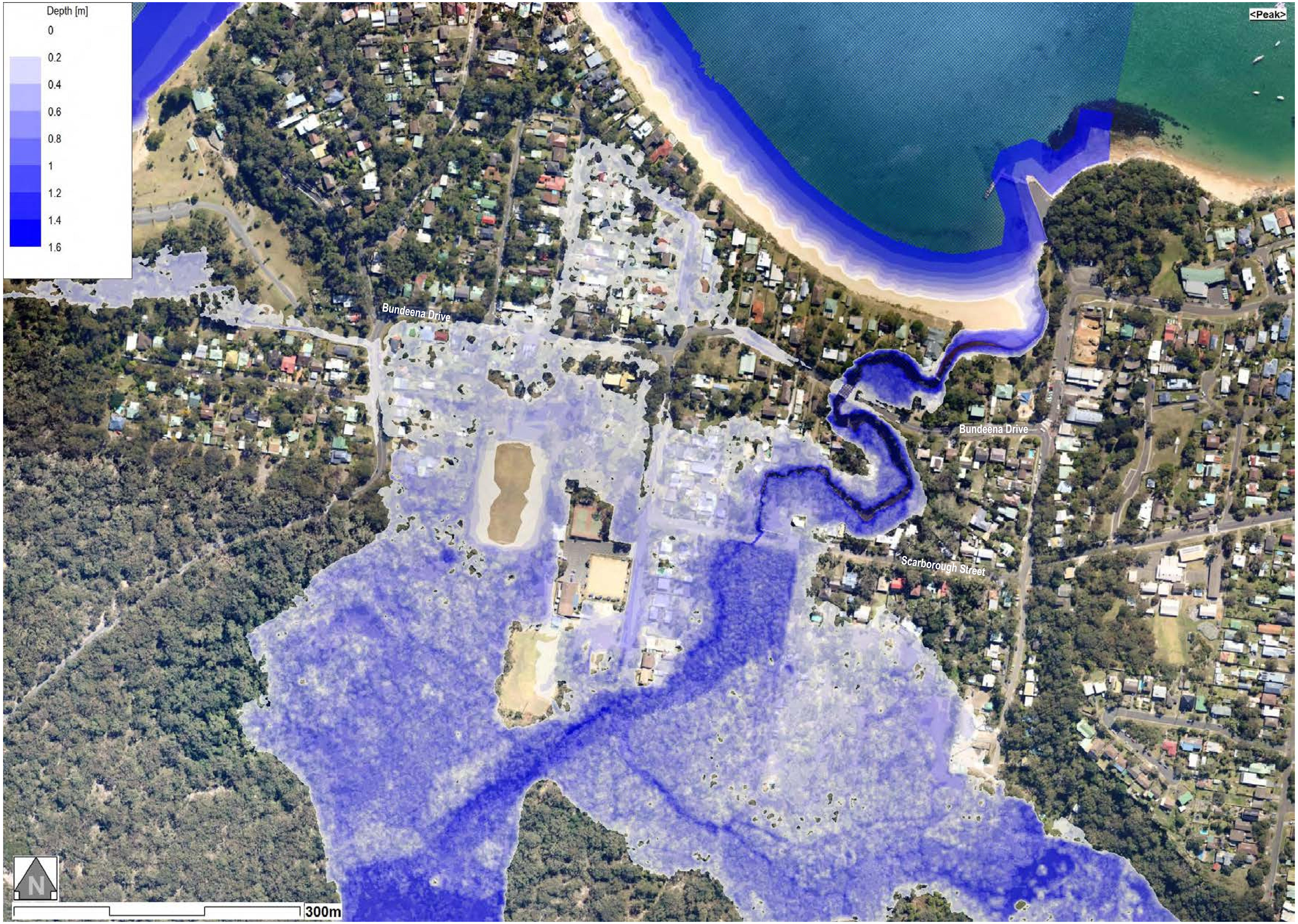
Hatching indicates flood depths greater than 1.6 metres

WorleyParsons
resources & energy

301015-03182 – Bundeena Creek Flood Study
F.5_fg301015-03182_EH131111-2%AEP_Depth.doc

PEAK 2% AEP FLOOD DEPTHS

FIGURE F.6



NOTES:

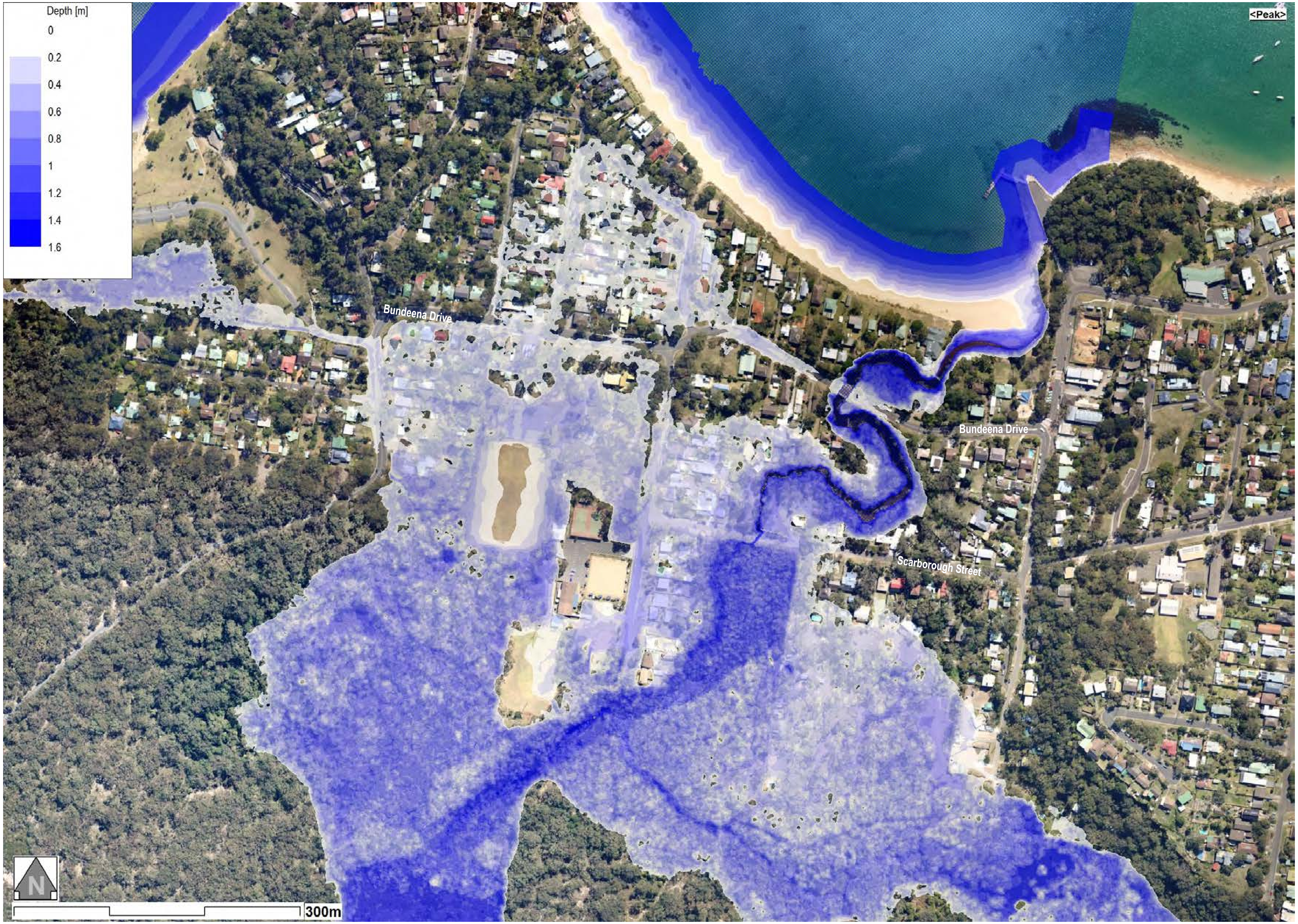
Hatching indicates flood depths greater than 1.6 metres

WorleyParsons
resources & energy

301015-03182 – Bundeena Creek Flood Study
F.6_fg301015-03182_EH131111-1%AEP_Depth.doc

PEAK 1% AEP FLOOD DEPTHS

FIGURE F.7



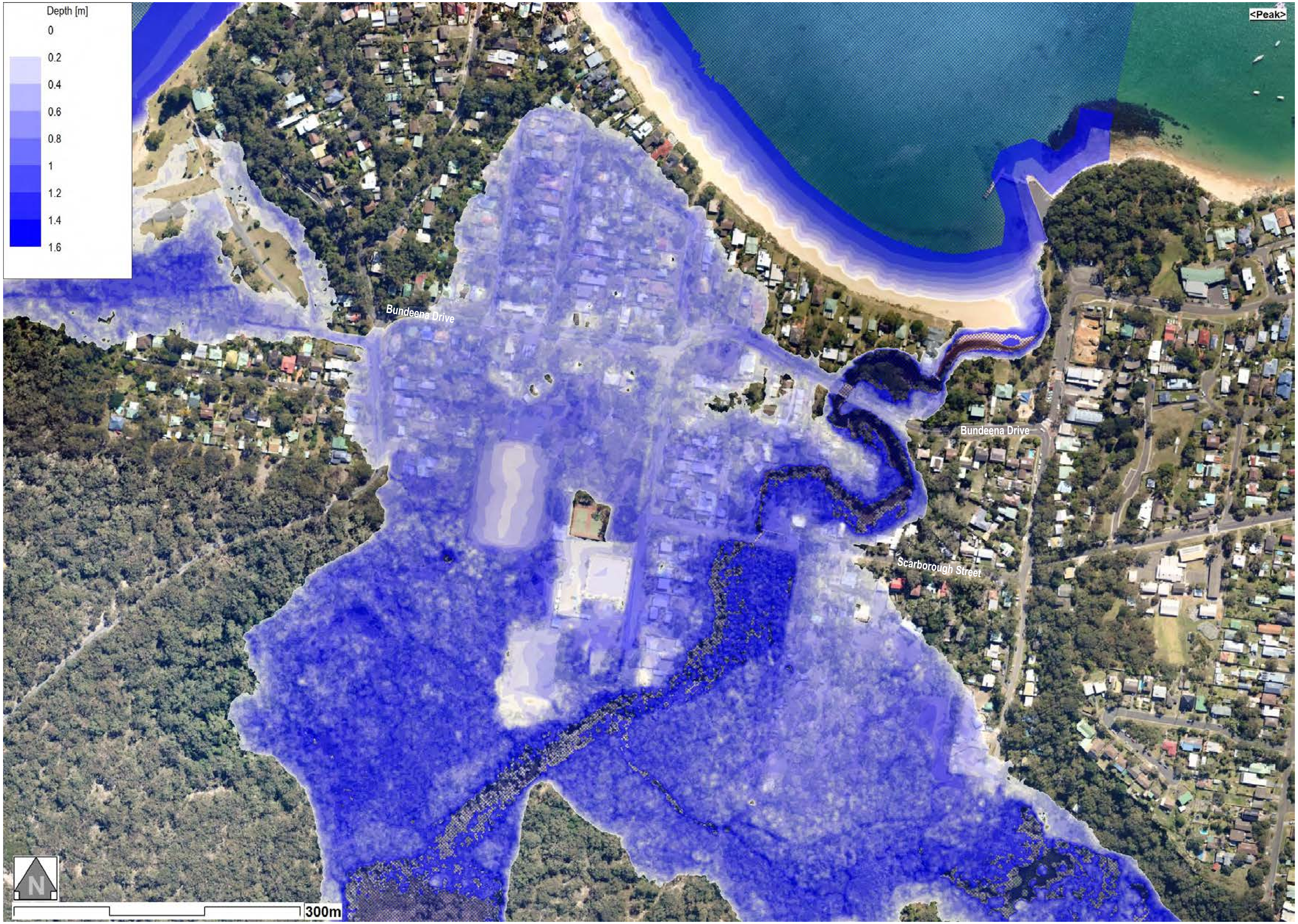
NOTES:

Hatching indicates flood depths greater than 1.6 metres

WorleyParsons
resources & energy

PEAK 0.5% AEP FLOOD DEPTHS

FIGURE F.8



NOTES:

Hatching indicates flood depths greater than 1.6 metres

WorleyParsons
resources & energy

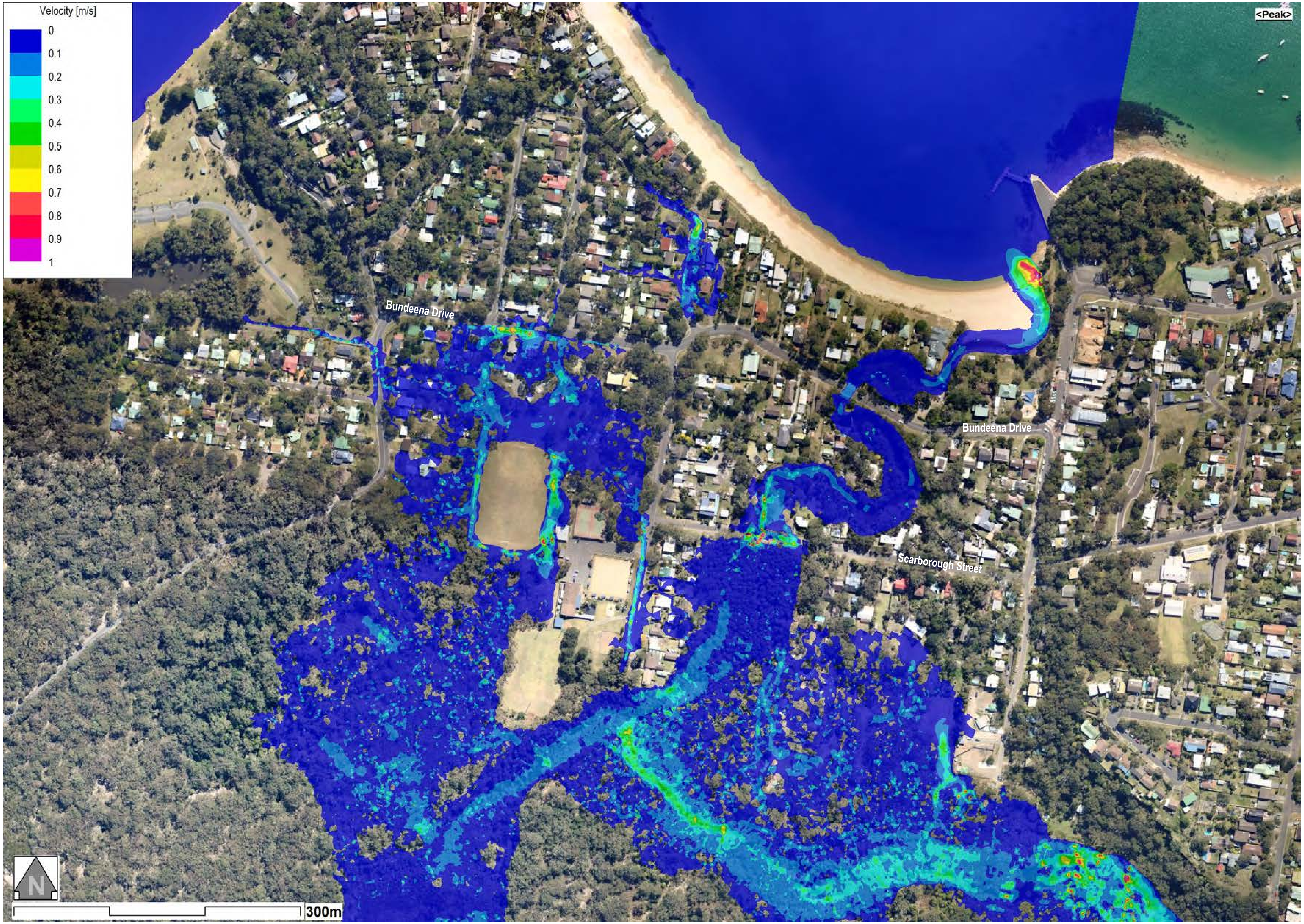
301015-03182 – Bundeena Creek Flood Study
F.8_fg301015-03182_EH131111-PMP_Depth.doc

PROBABLE MAXIMUM FLOOD LEVELS

APPENDIX G

DESIGN FLOOD VELOCITY MAPPING

FIGURE G.1



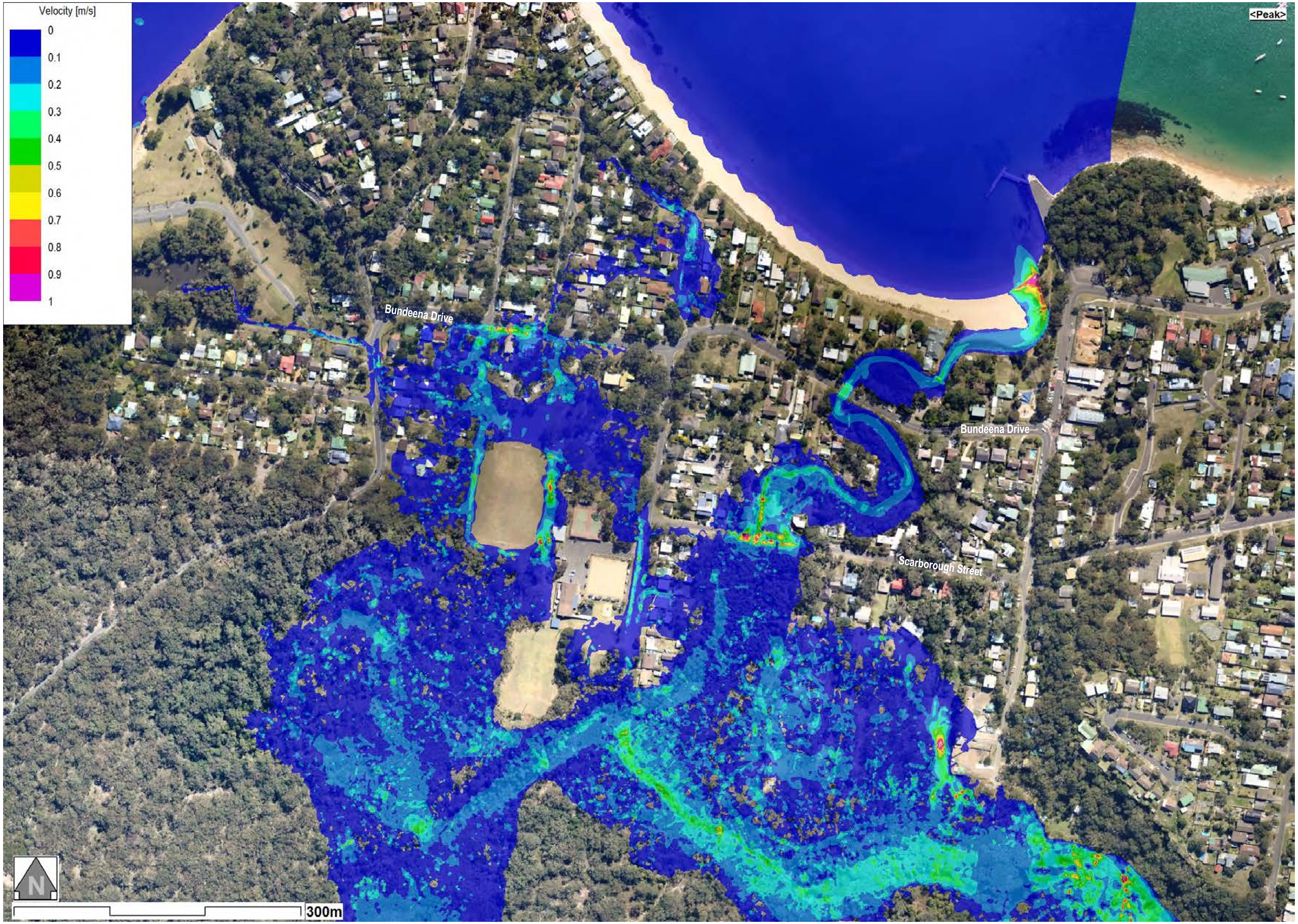
NOTES:

Hatching indicates flood velocities greater than 1 m/s

WorleyParsons
resources & energy

PEAK FLOW VELOCITIES DURING THE 50% AEP EVENT

FIGURE G.2



NOTES:

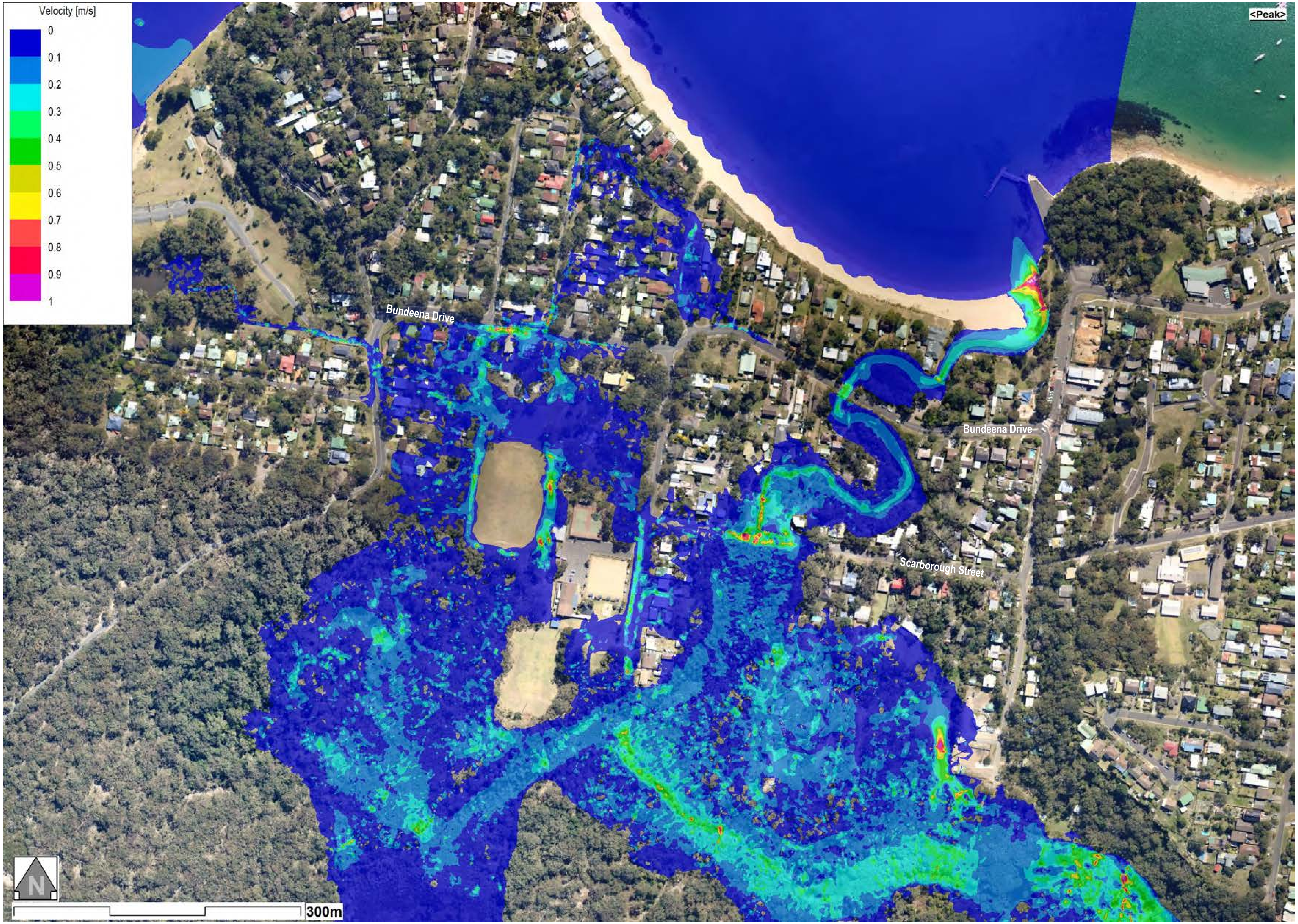
Hatching indicates flood velocities greater than 1 m/s

WorleyParsons
resources & energy

301015-03182 – Bundeena Creek Flood Study
G.2_fg301015-03182_EH131111-20%AEP_Velocity.doc

PEAK FLOW VELOCITIES DURING THE 20% AEP EVENT

FIGURE G.3



NOTES:

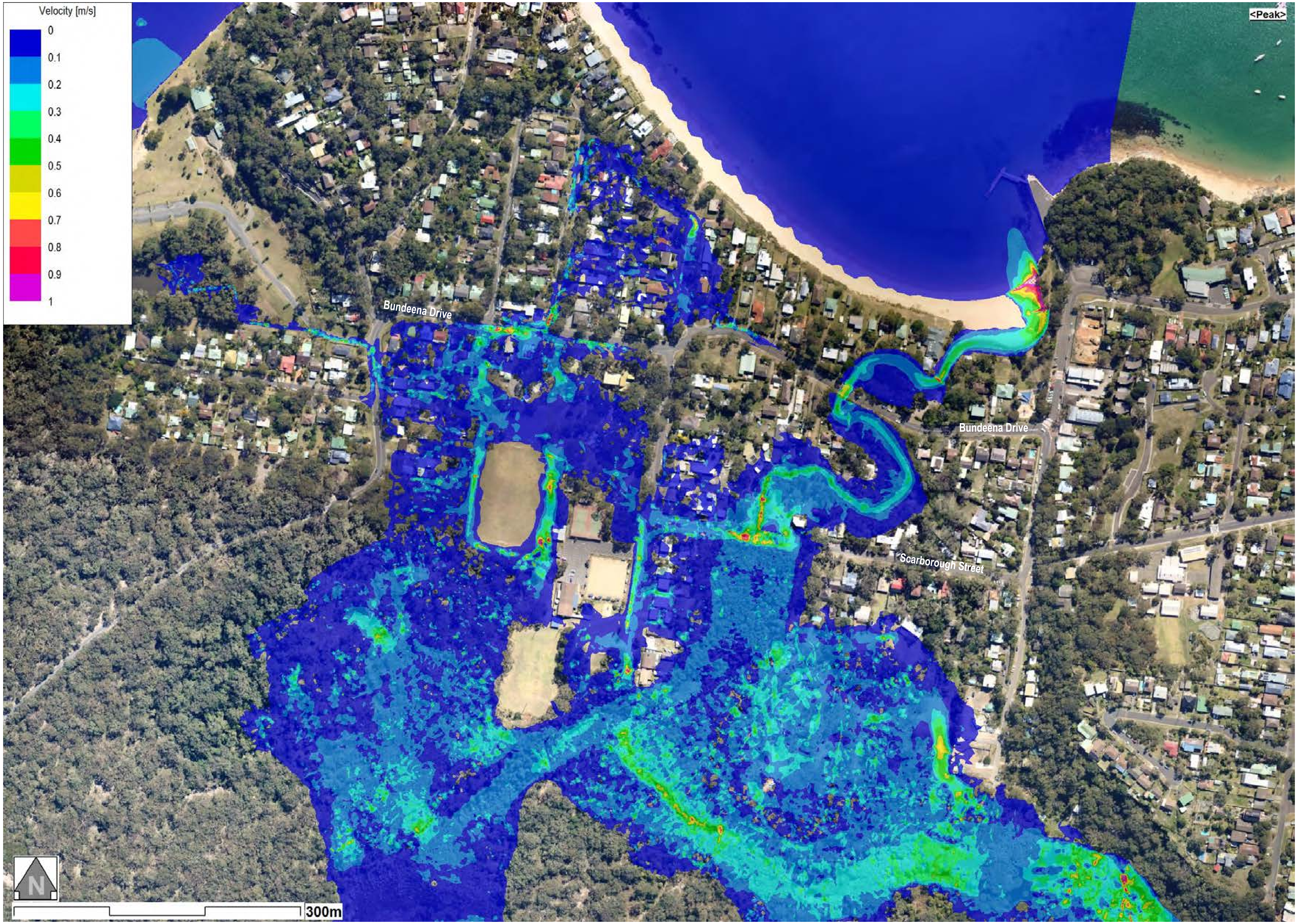
Hatching indicates flood velocities greater than 1 m/s

WorleyParsons
resources & energy

301015-03182 – Bundeena Creek Flood Study
G.3_fg301015-03182_EH131111-10%AEP_Velocity.doc

PEAK FLOW VELOCITIES DURING THE 10% AEP EVENT

FIGURE G.4



NOTES:

Hatching indicates flood velocities greater than 1 m/s

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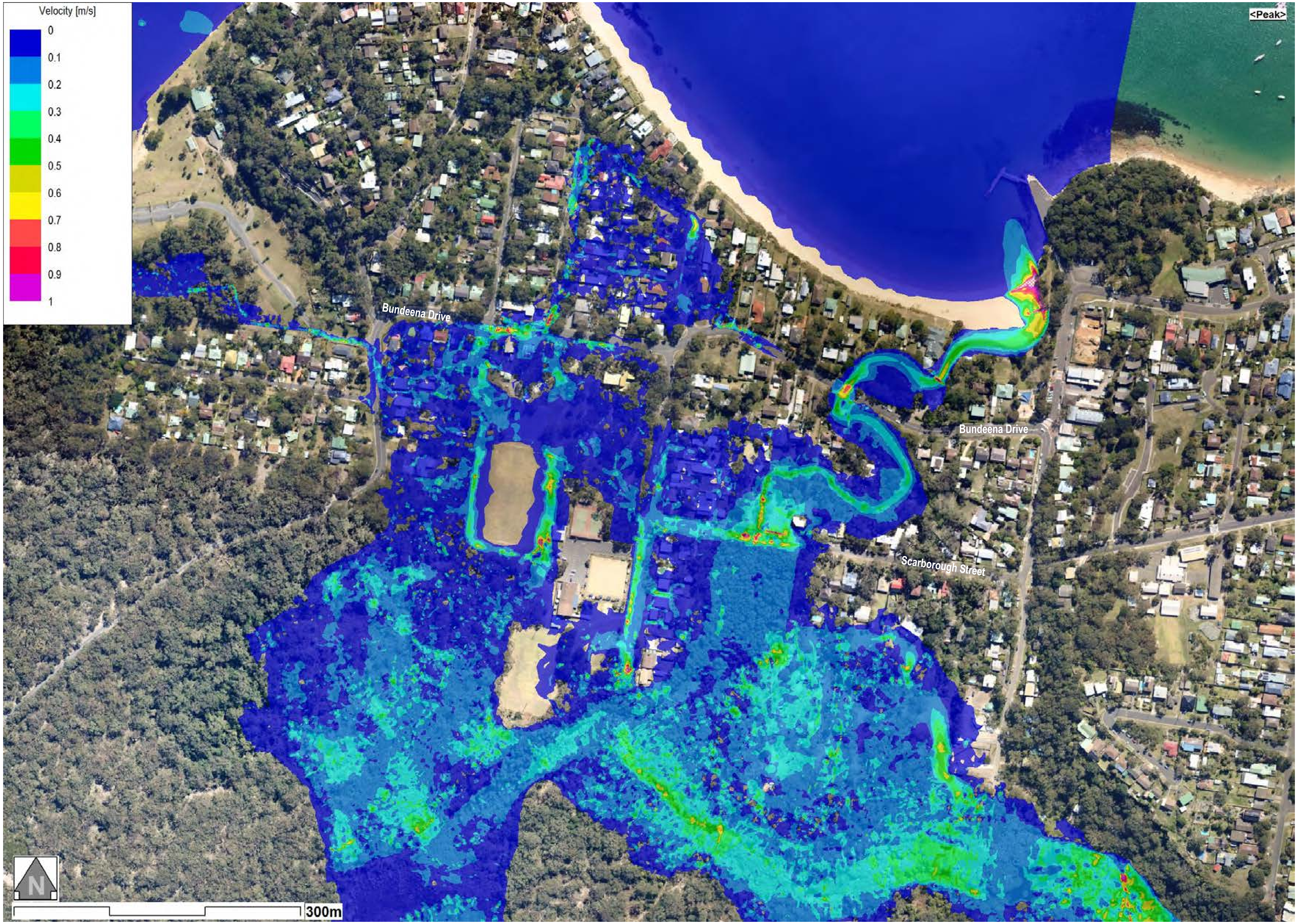
301015-03182 – Bundeena Creek Flood Study
G.4_fg301015-03182_EH131111-5%AEP_Velocity.doc

PEAK FLOW VELOCITIES DURING THE 5% AEP EVENT

FIGURE G.5



NOTES:

Hatching indicates flood velocities greater than 1 m/s

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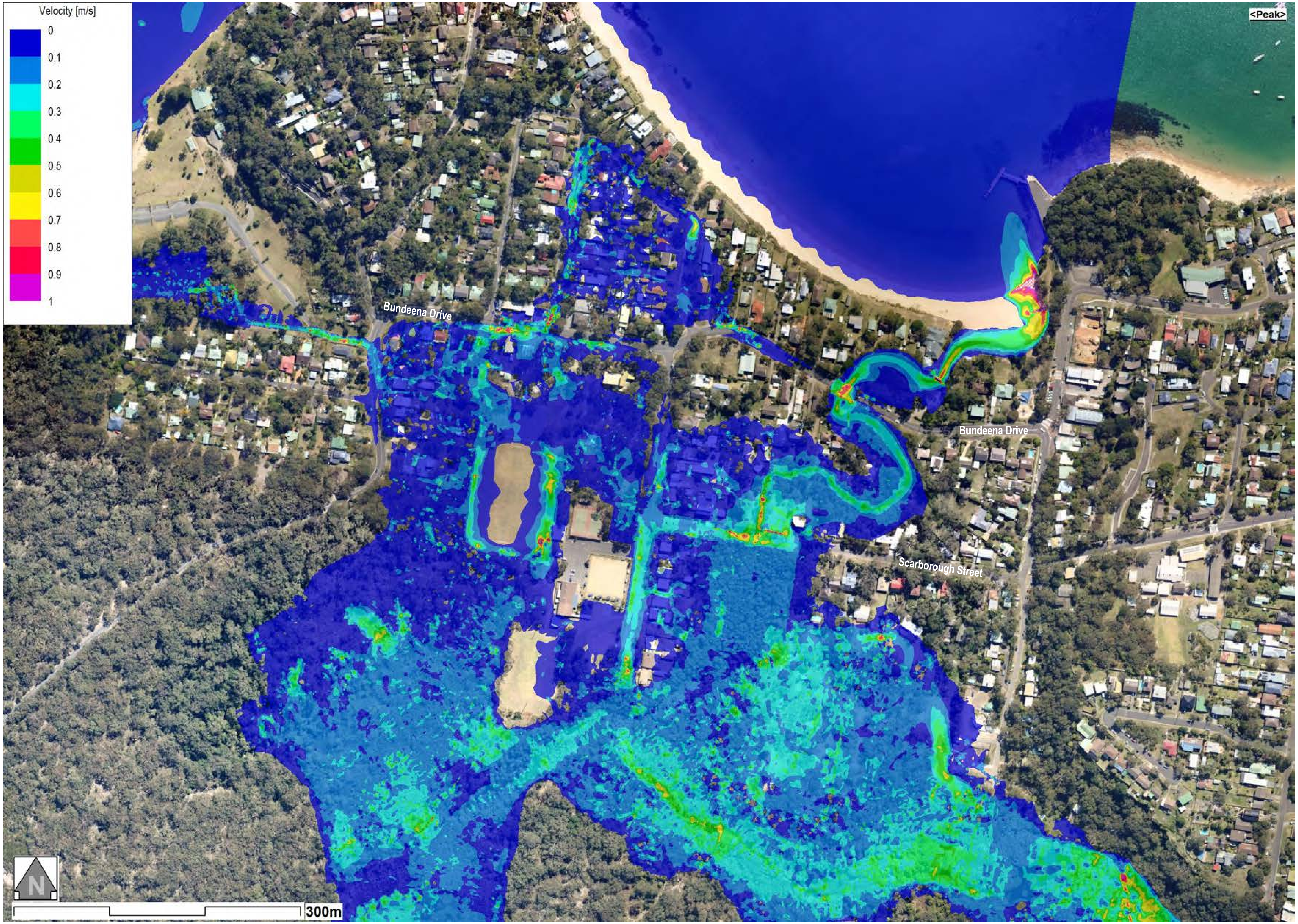
301015-03182 – Bundeena Creek Flood Study
G.5_fg301015-03182_EH131111-2%AEP_Velocity.doc

PEAK FLOW VELOCITIES DURING THE 2% AEP EVENT

FIGURE G.6



NOTES:

Hatching indicates flood velocities greater than 1 m/s

WorleyParsons
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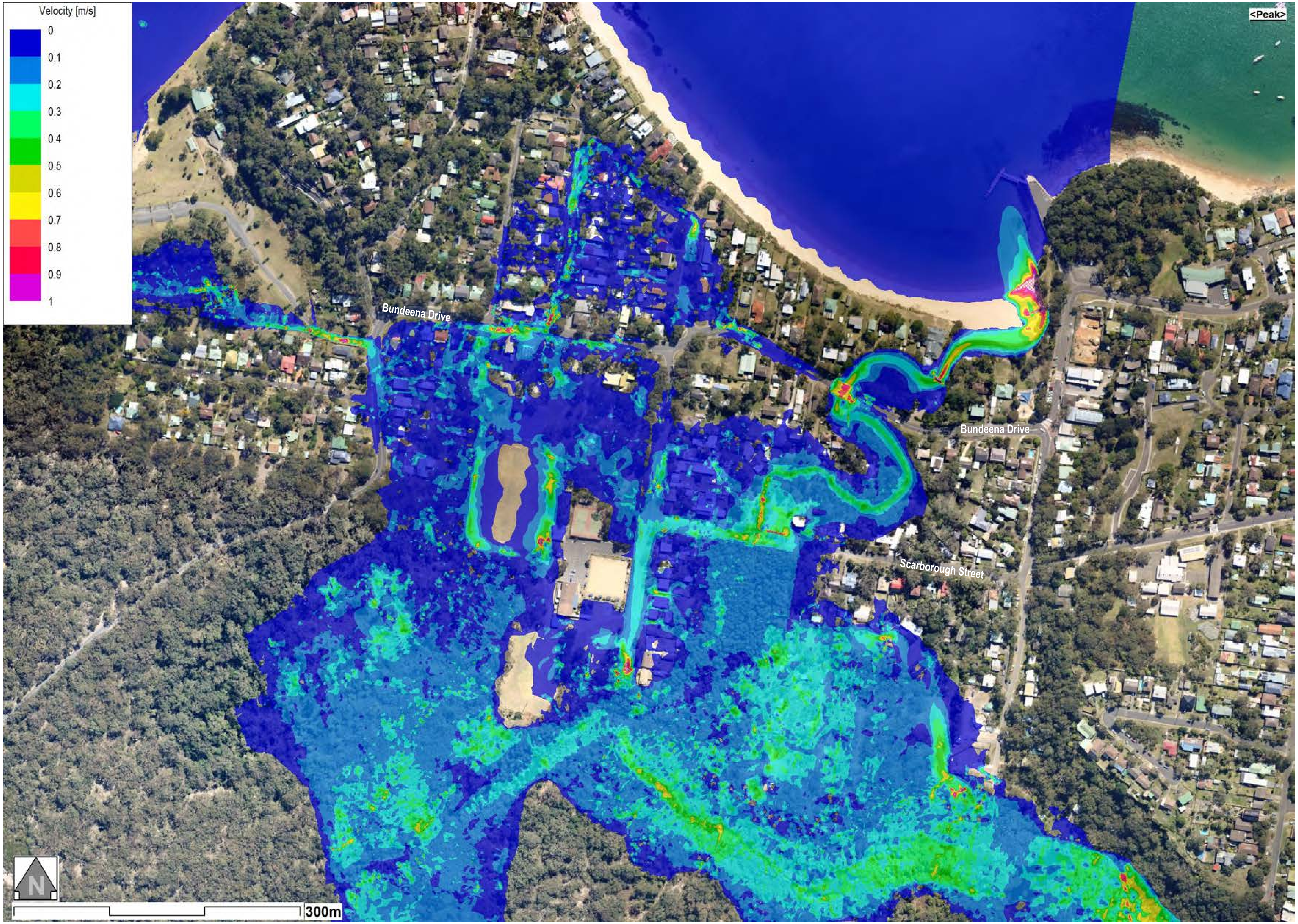
301015-03182 – Bundeena Creek Flood Study
G.6_fg301015-03182_EH131111-1%AEP_Velocity.doc

PEAK FLOW VELOCITIES DURING THE 1% AEP EVENT

FIGURE G.7



NOTES:

Hatching indicates flood velocities greater than 1 m/s

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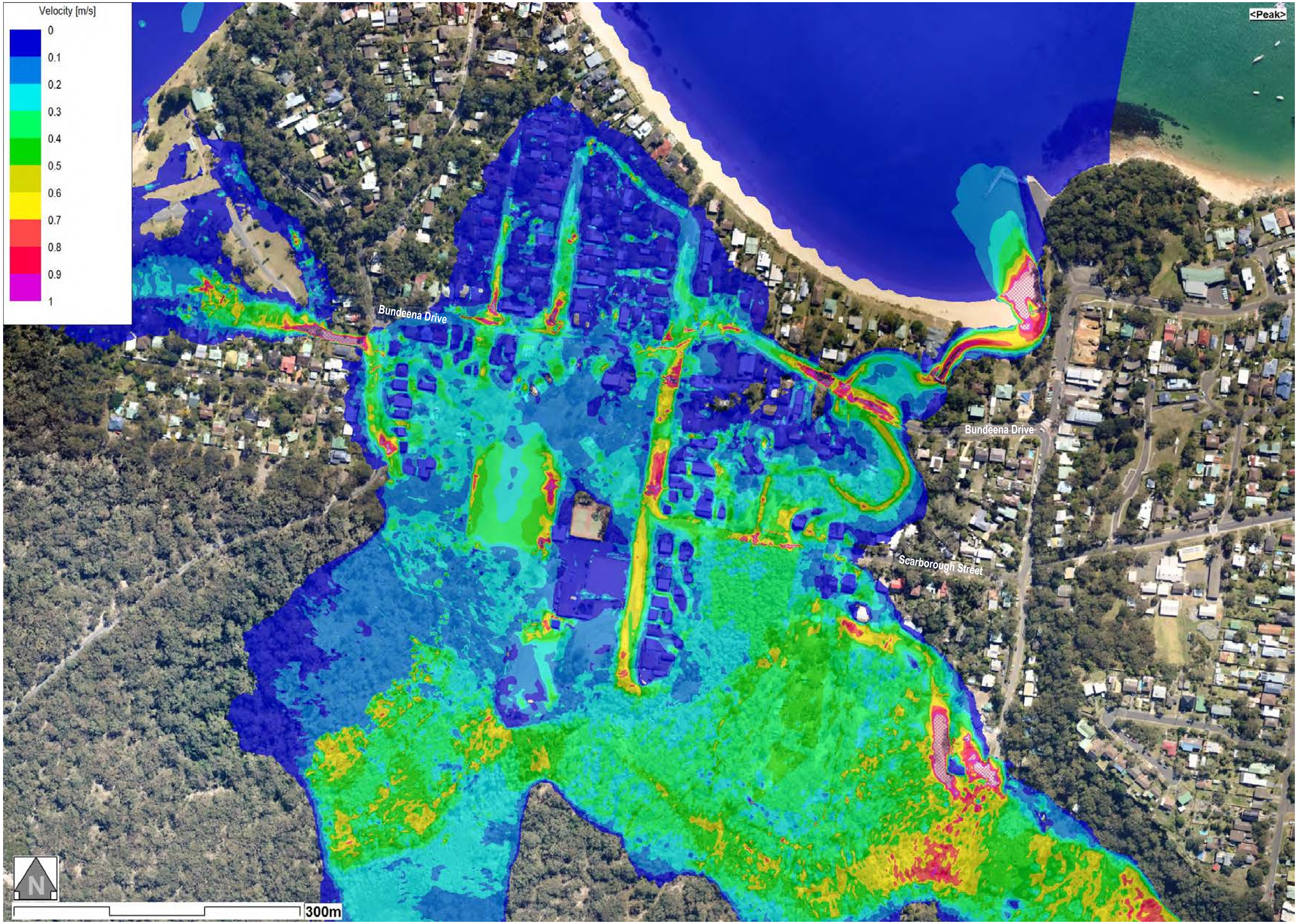
301015-03182 – Bundeena Creek Flood Study
G.7_fg301015-03182_EH131111-0.5%AEP_Velocity.doc

PEAK FLOW VELOCITIES DURING THE 0.5% AEP EVENT

FIGURE G.8



NOTES:

Hatching indicates flood velocities greater than 1 m/s

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resources & energy

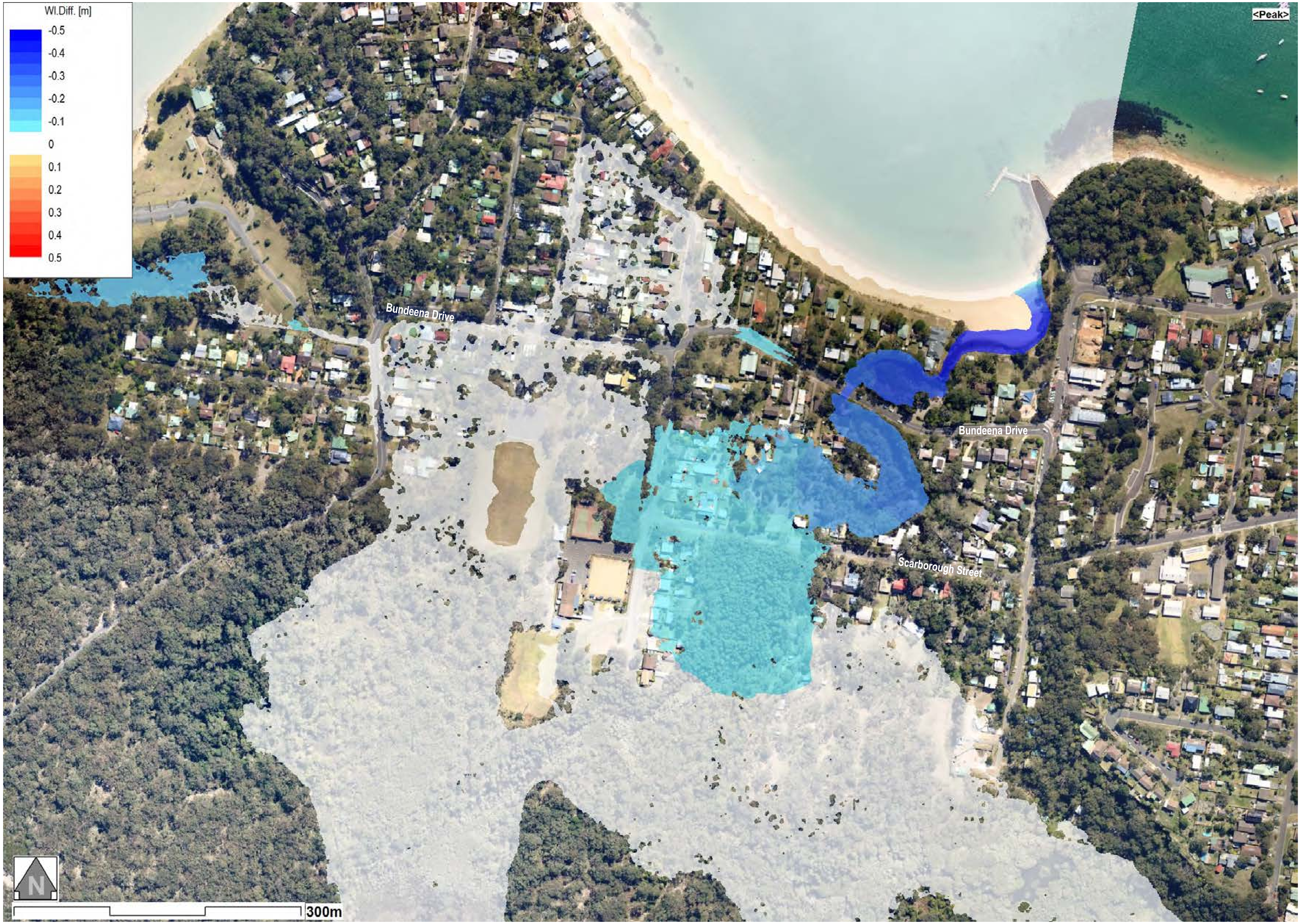
301015-03182 – Bundeena Creek Flood Study
G.8_fg301015-03182_EH131111-PMP_Velocity.doc

PEAK FLOW VELOCITIES DURING THE PROBABLE MAXIMUM FLOOD

APPENDIX H

SENSITIVITY TESTING OF CREEK MOUTH GEOMETRY

FIGURE H.1



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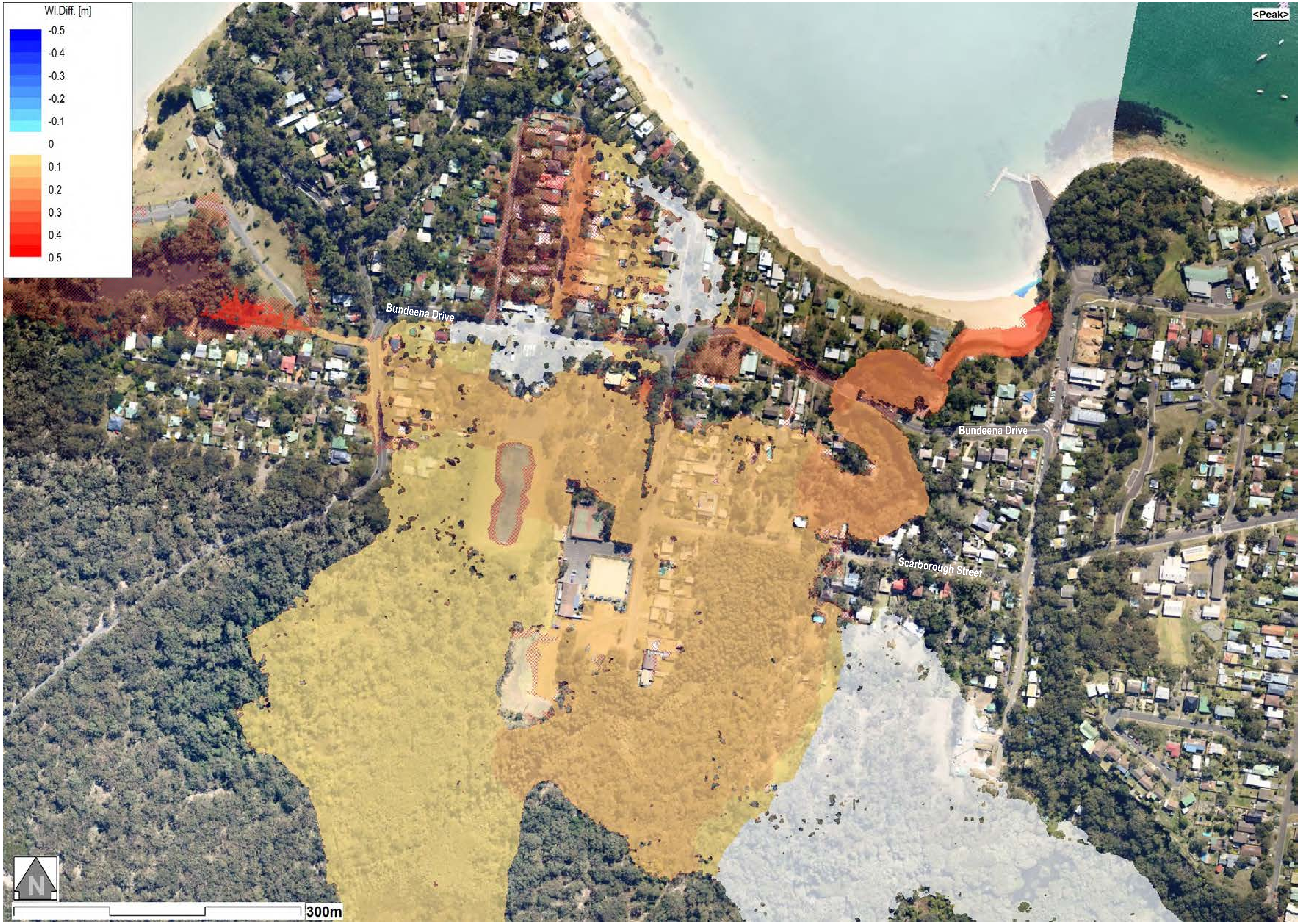
301015-03182 – Bundeena Creek Flood Study
H.1_fg301015-03182_EH131125-1%AEP_Scoured-PD_Diff.doc

CHANGE IN 1% AEP FLOOD LEVELS RESULTING FROM REVISED CREEK MOUTH GEOMETRY [COMPLETELY SCOURED OUTLET SCENARIO]

FIGURE H.2



NOTES:
Hatching indicates additional extent of flooding.

WorleyParsons
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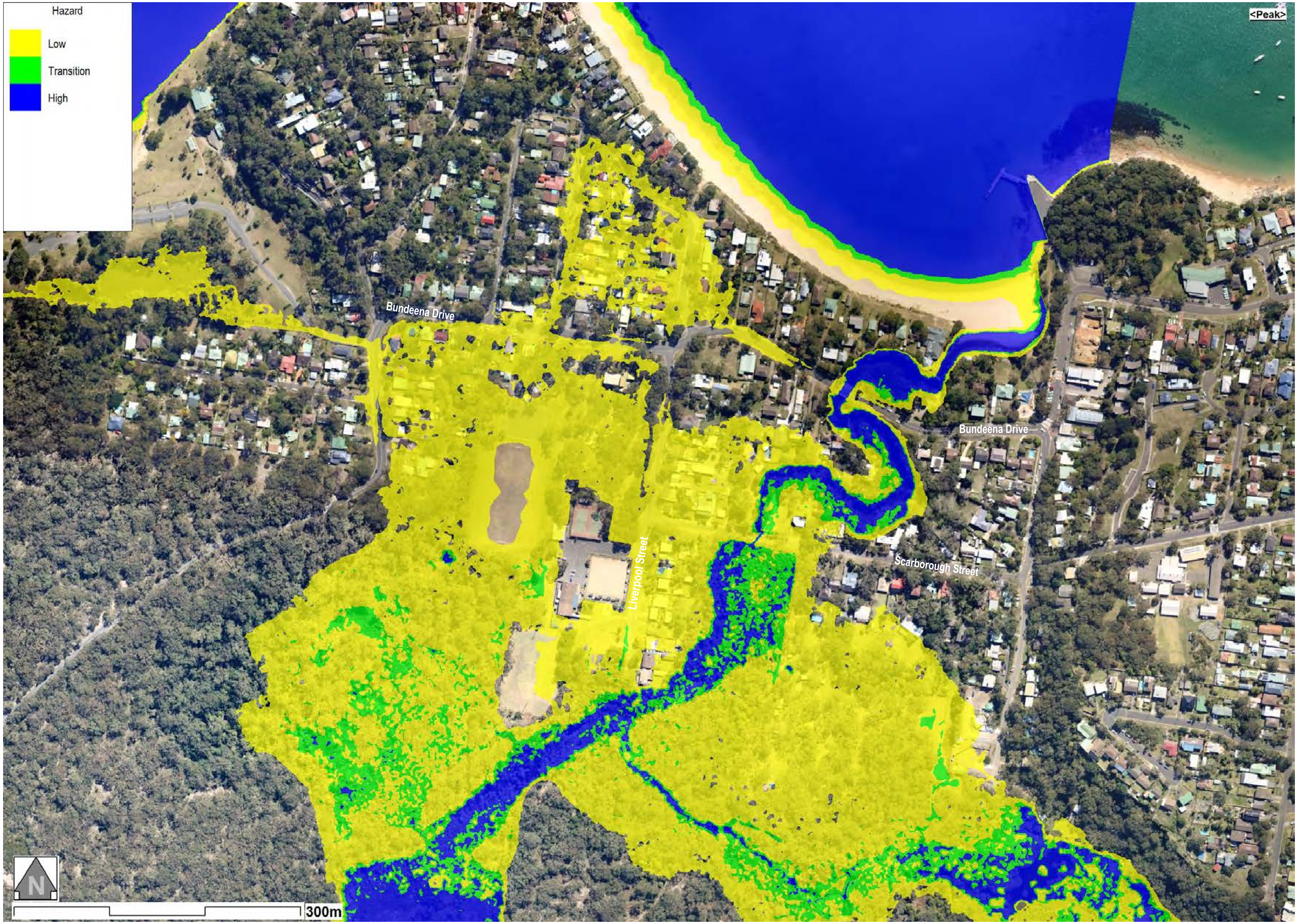
301015-03182 – Bundeena Creek Flood Study
H.2_fg301015-03182_EH131125-1%AEP_Blocked-PD_Diff.doc

CHANGE IN 1% AEP FLOOD LEVELS RESULTING FROM REVISED CREEK MOUTH GEOMETRY [COMPLETELY BLOCKED OUTLET SCENARIO]

APPENDIX I

PROVISIONAL FLOOD HAZARD MAPPING

FIGURE I.1



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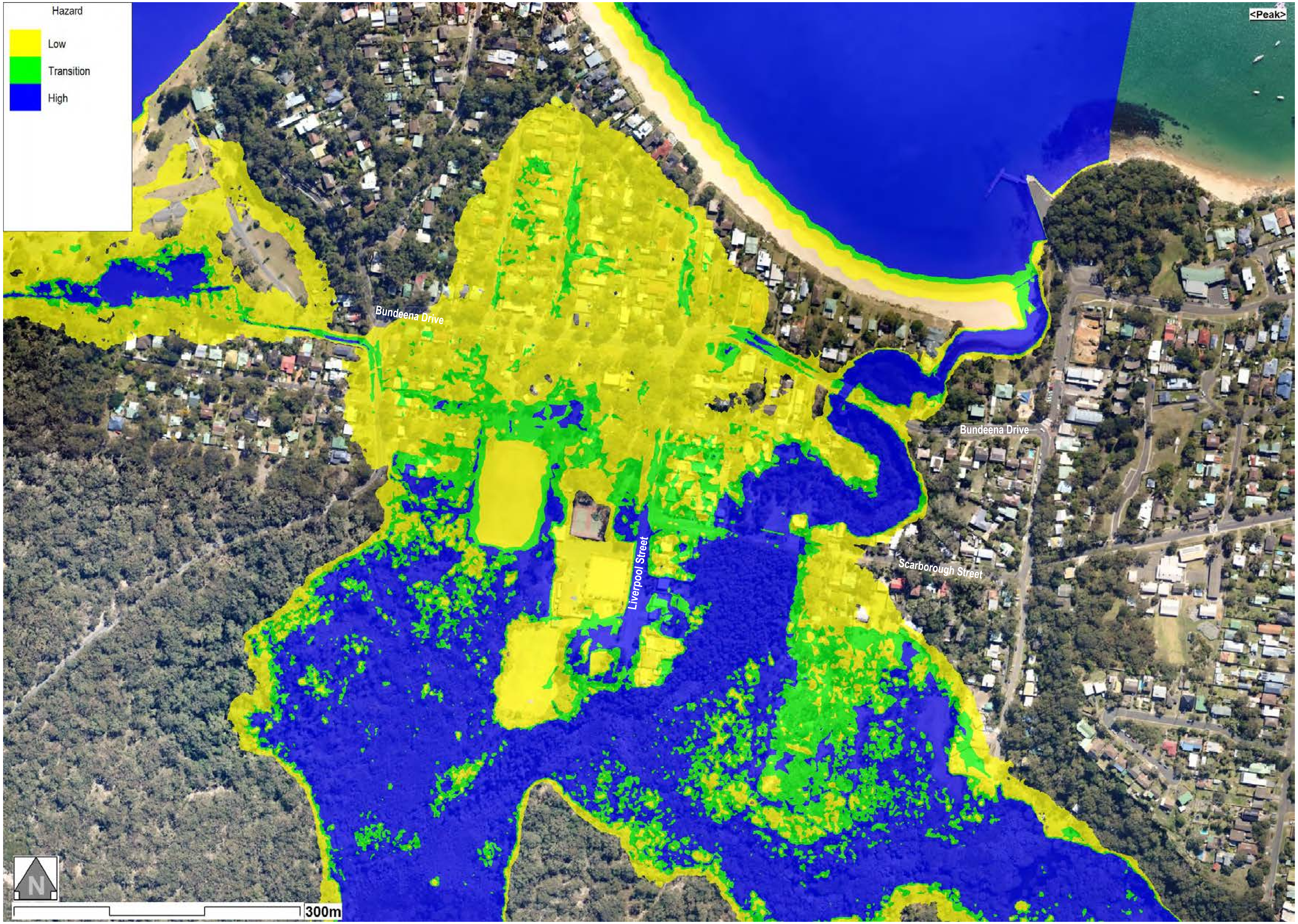
301015-03182 – Bundeena Creek Flood Study
I.1_fg301015-03182_EH131111-1%AEP_ProvHazard.doc

PROVISIONAL FLOOD HAZARD MAPPING FOR THE 1% AEP EVENT

FIGURE I.2



WorleyParsons
resources & energy

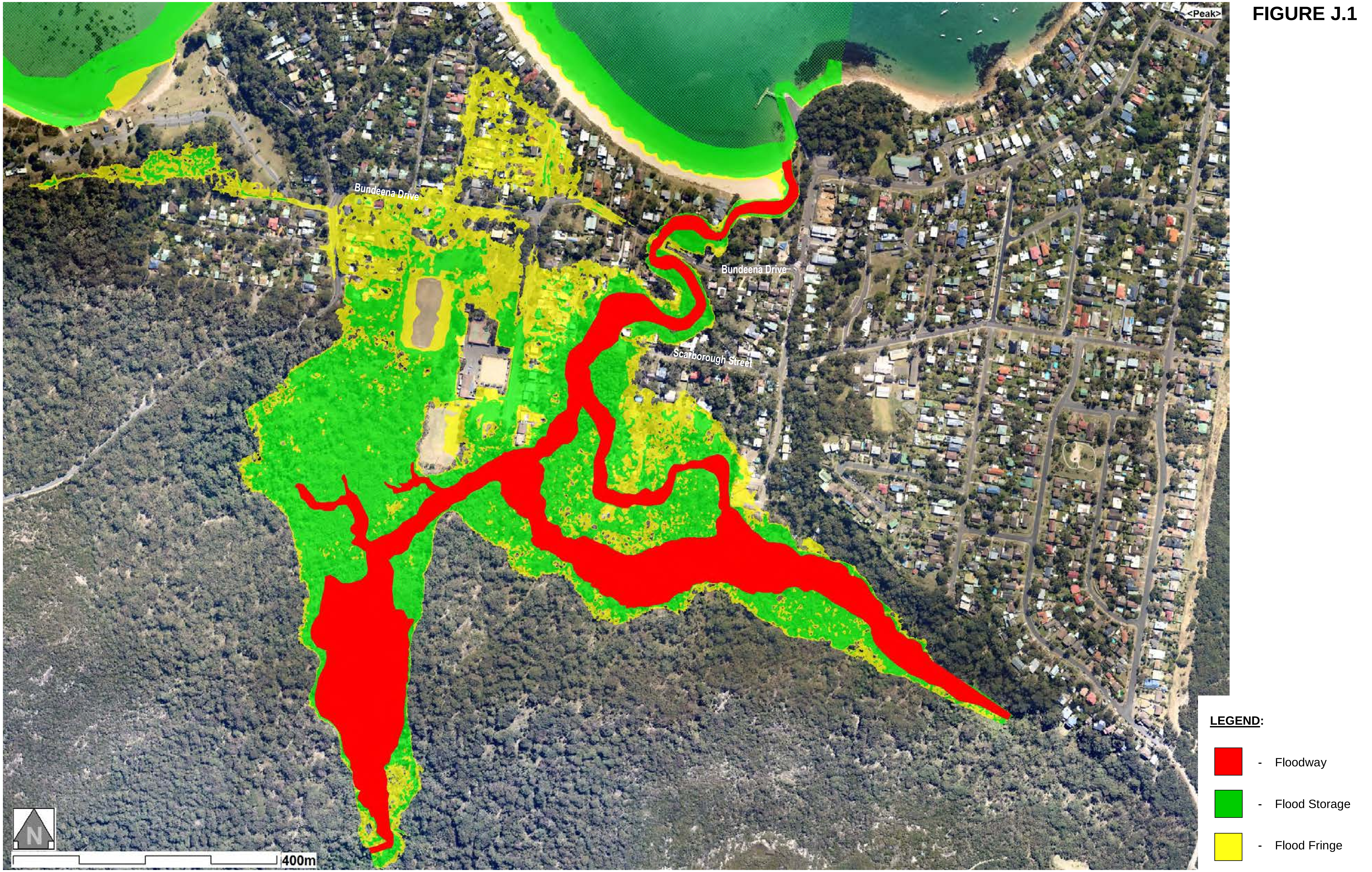
301015-03182 – Bundeena Creek Flood Study
I.2_fg301015-03182_EH131111-PMP_ProvHazard.doc

PROVISIONAL FLOOD HAZARD MAPPING FOR THE PROBABLE MAXIMUM FLOOD

APPENDIX J

PROVISIONAL HYDRAULIC CATEGORY MAPPING

FIGURE J.1



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301015-03182 – Bundeena Creek Flood Study
J.1_fg301015-03182_EH140117-1%AEP_Hydraulic Cat.doc

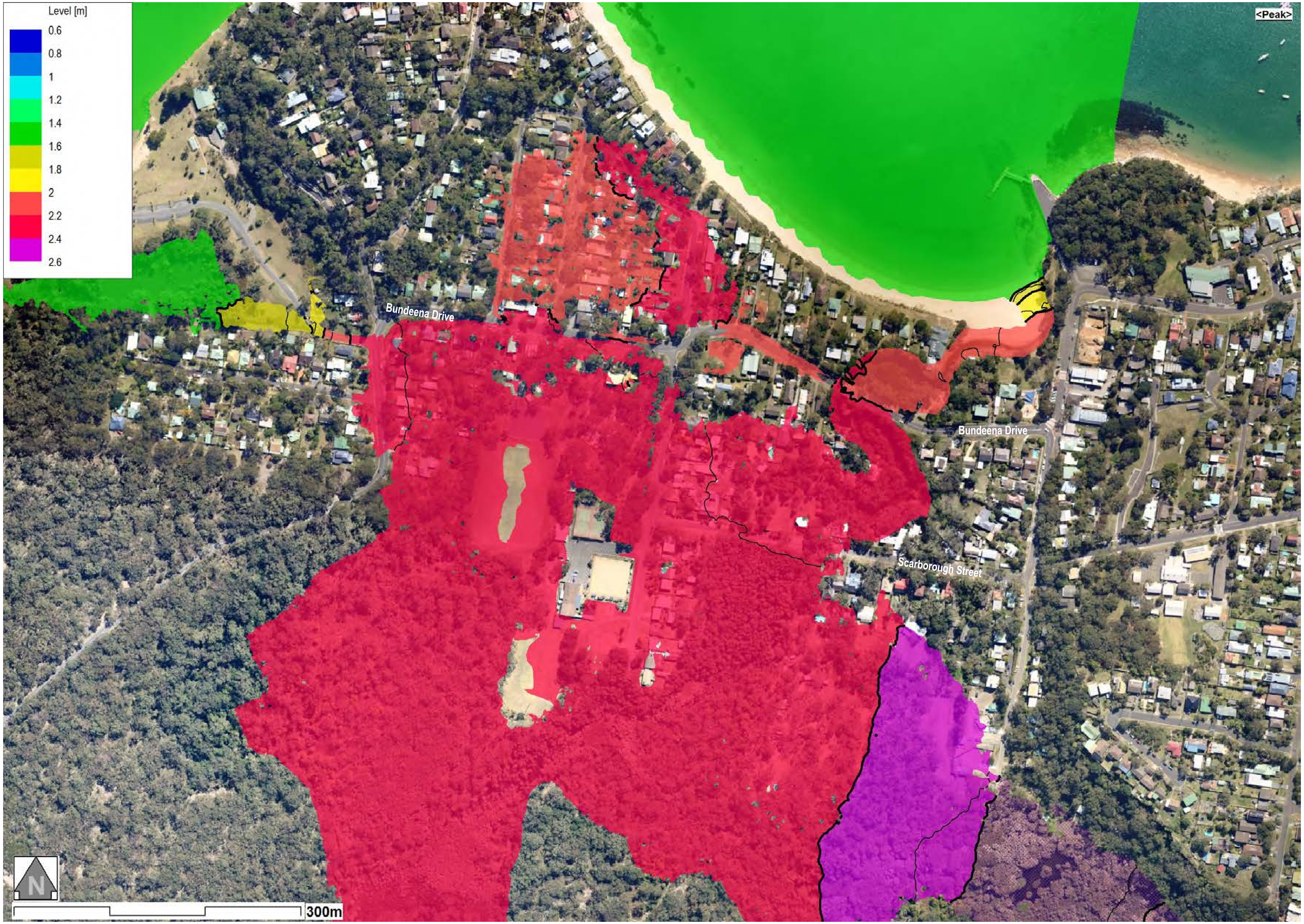
PROVISIONAL HYDRAULIC CATERGORY MAPPING

APPENDIX K

CLIMATE CHANGE SCENARIOS –

FLOOD LEVEL & DIFFERENCE MAPPING

FIGURE K.1



LEGEND:

0.1 metre contour line

0.2 metre contour line

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301015-03182 – Bundeena Creek Flood Study
K.1_fg301015-03182_EH131125-CC_1%AEP_+20%rf_Level.doc

PEAK 1% AEP FLOOD LEVELS
[20% INCREASE IN RAINFALL INTENSITY]

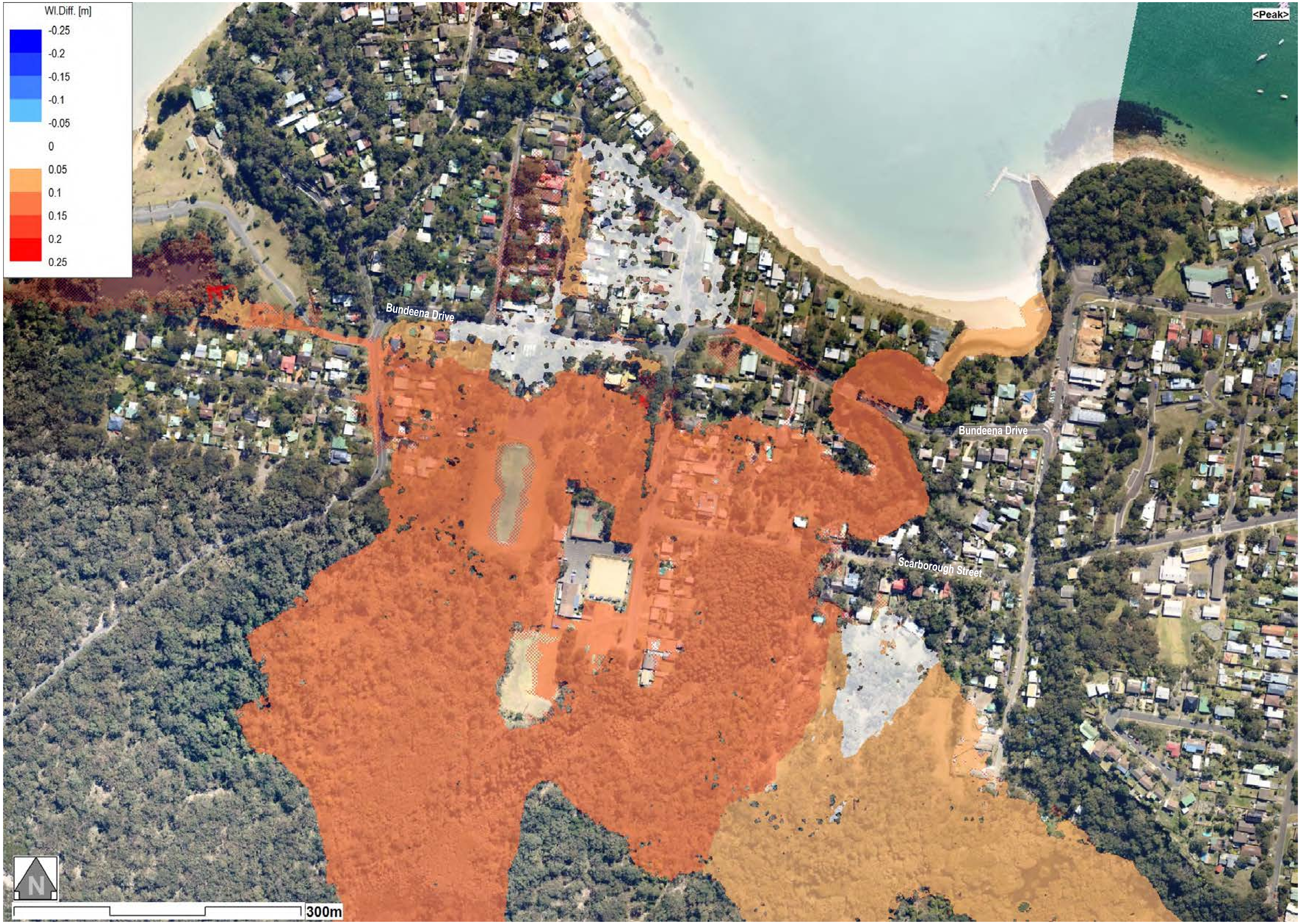

FIGURE K.2

NOTES:
Hatching indicates additional extent of flooding.

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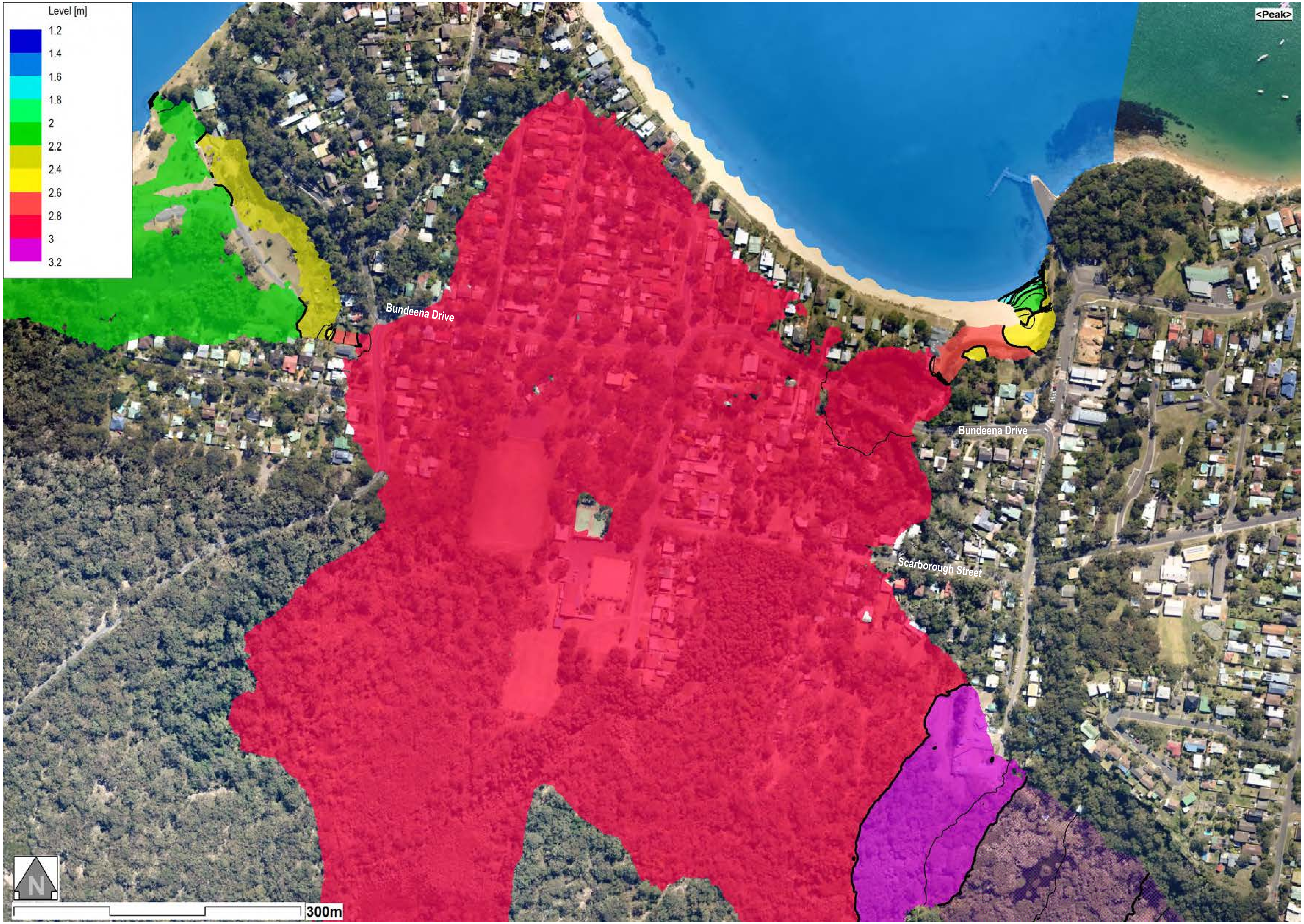
301015-03182 – Bundeena Creek Flood Study
K.2_fg301015-03182_EH131125-CC_1%AEP_+20%rf-PD_Diff.doc

CHANGE IN 1% AEP FLOOD LEVELS [20% INCREASE IN RAINFALL INTENSITY]

FIGURE K.3



LEGEND:

0.1 metre contour line

0.2 metre contour line

WorleyParsons
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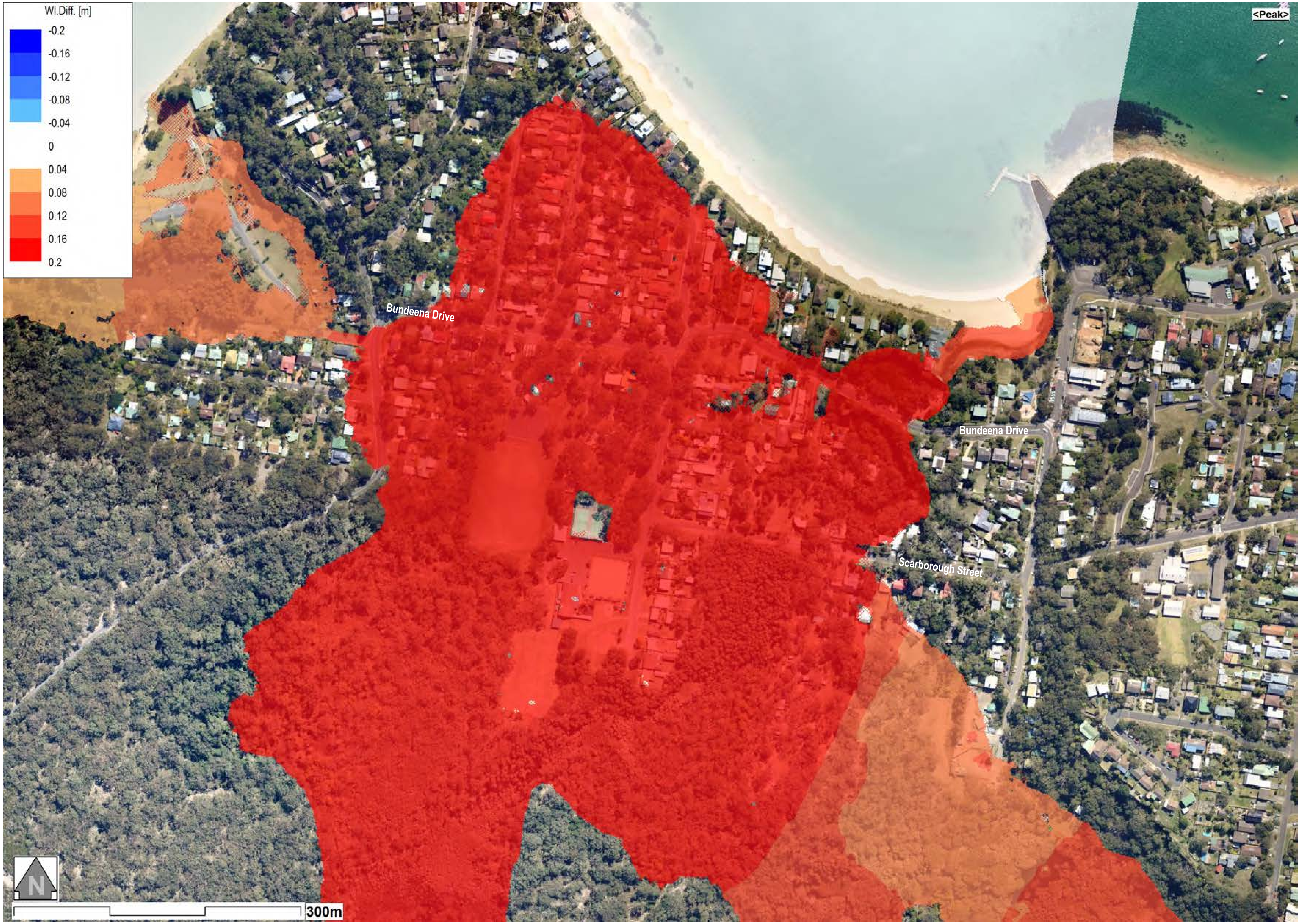
301015-03182 – Bundeena Creek Flood Study
K.3_fg301015-03182_EH131125-CC_PMP_+20%rf_Level.doc

PROBABLE MAXIMUM FLOOD LEVELS
[20% INCREASE IN RAINFALL INTENSITY]

FIGURE K.4



NOTES:
Hatching indicates additional extent of flooding.

WorleyParsons
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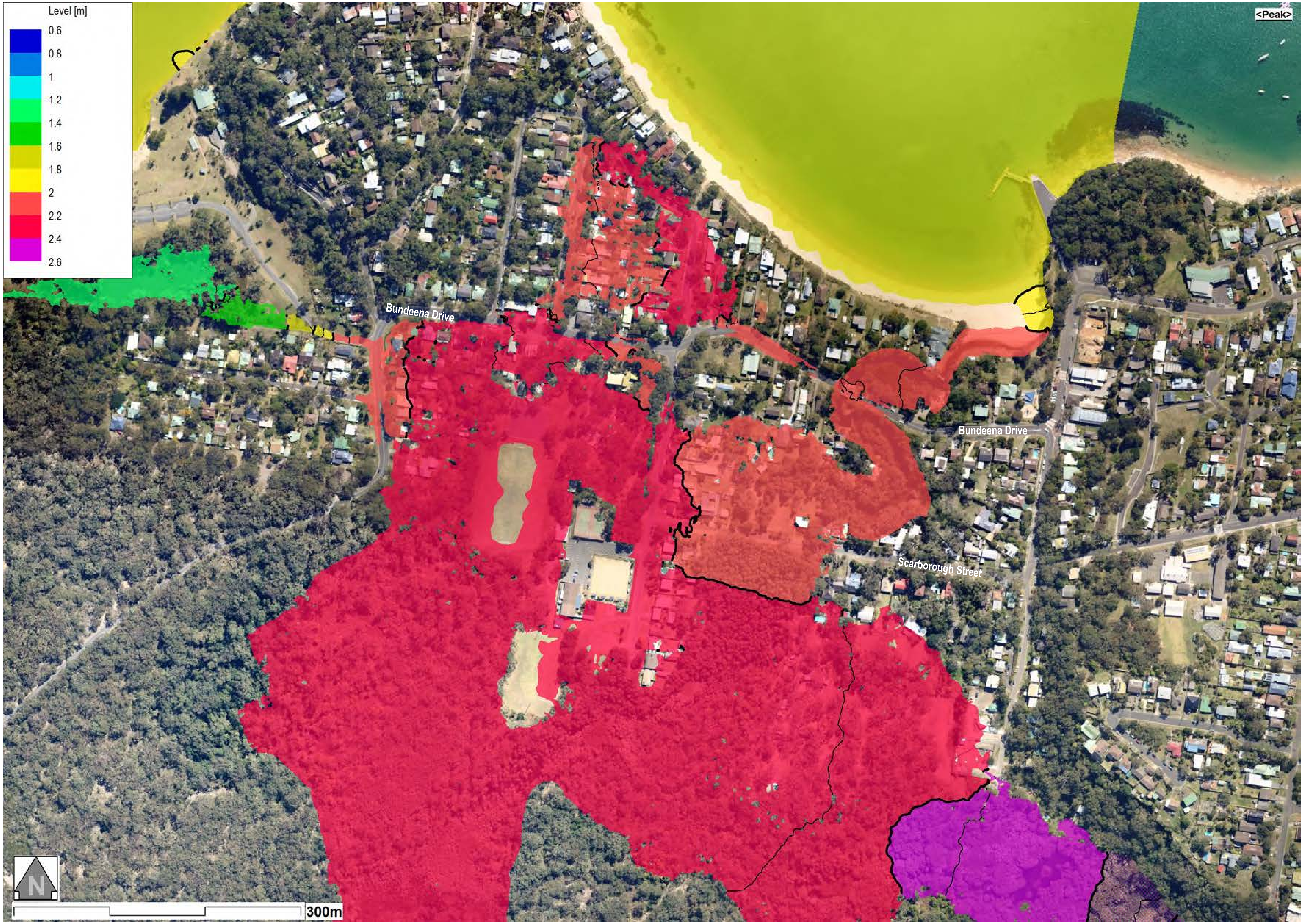
301015-03182 – Bundeena Creek Flood Study
K.4_fg301015-03182_EH131125-CC_PMP_+20%rf-PD_Diff.doc

CHANGE IN PROBABLE MAXIMUM FLOOD LEVELS
[20% INCREASE IN RAINFALL INTENSITY]

FIGURE K.5



LEGEND:

0.1 metre contour line

0.2 metre contour line

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301015-03182 – Bundeena Creek Flood Study
K.5_fg301015-03182_EH131125-CC_1%AEP_2050_Level.doc

PEAK 1% AEP FLOOD LEVELS
[2050 SEA LEVEL RISE SCENARIO]

FIGURE K.6

NOTES:
Hatching (excluding ocean) indicates additional extent of flooding.

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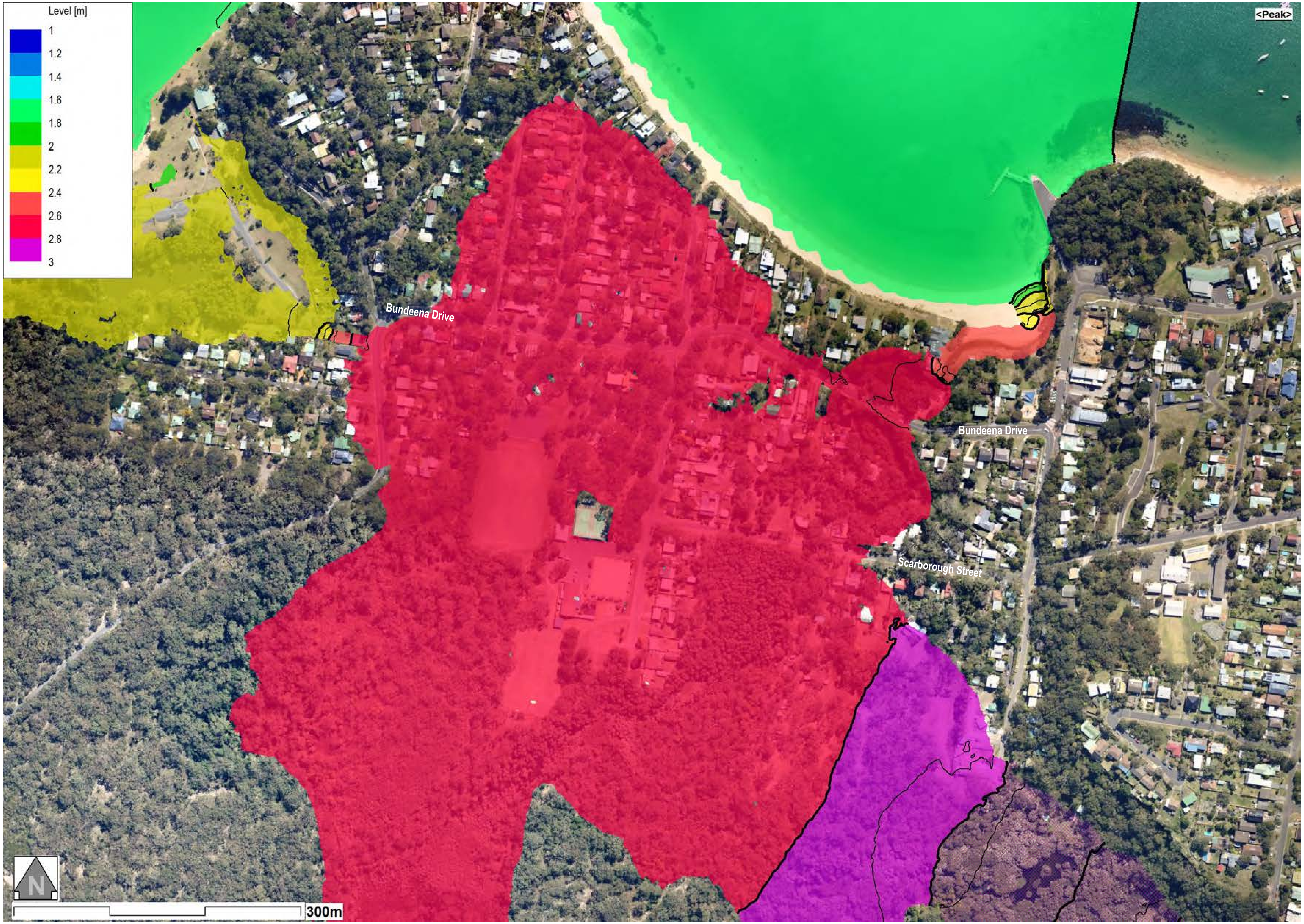
301015-03182 – Bundeena Creek Flood Study
K.6_fg301015-03182_EH131125-CC_1%AEP_2050-PD_Diff.doc

CHANGE IN 1% AEP PEAK FLOOD LEVELS RESULTING FROM SEA LEVEL RISE [2050 SEA LEVEL RISE SCENARIO]

FIGURE K.7



LEGEND:

0.1 metre contour line

0.2 metre contour line

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PROBABLE MAXIMUM FLOOD LEVELS
[2050 SEA LEVEL RISE SCENARIO]

FIGURE K.8

NOTES:
Hatching (excluding ocean) indicates additional extent of flooding.

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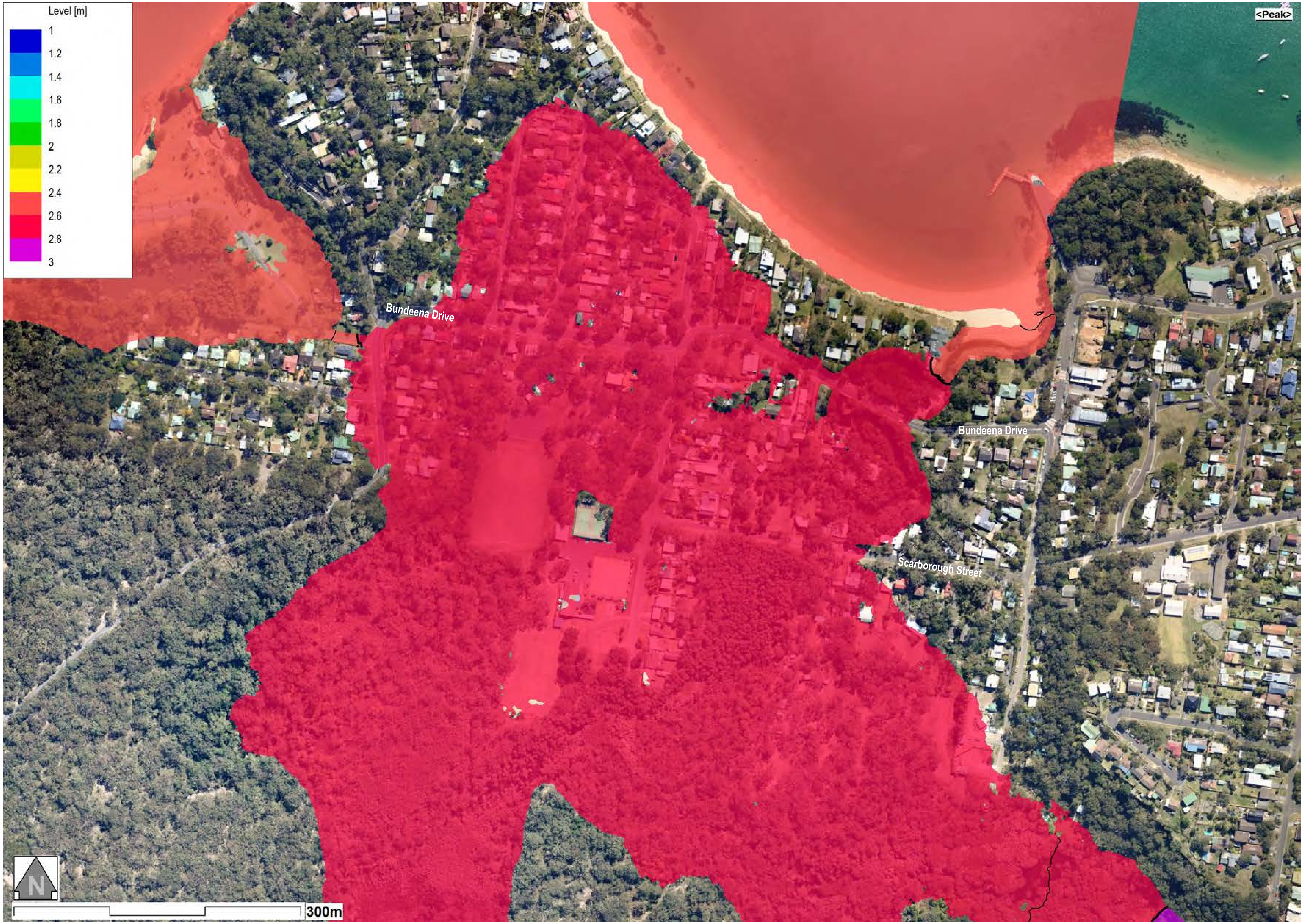
301015-03182 – Bundeena Creek Flood Study
K.8_fg301015-03182_EH131125-CC_PMP_2050-PD_Diff.doc

CHANGE IN PROBABLE MAXIMUM FLOOD LEVELS RESULTING FROM SEA LEVEL RISE [2050 SEA LEVEL RISE SCENARIO]

FIGURE K.9



LEGEND:

0.1 metre contour line

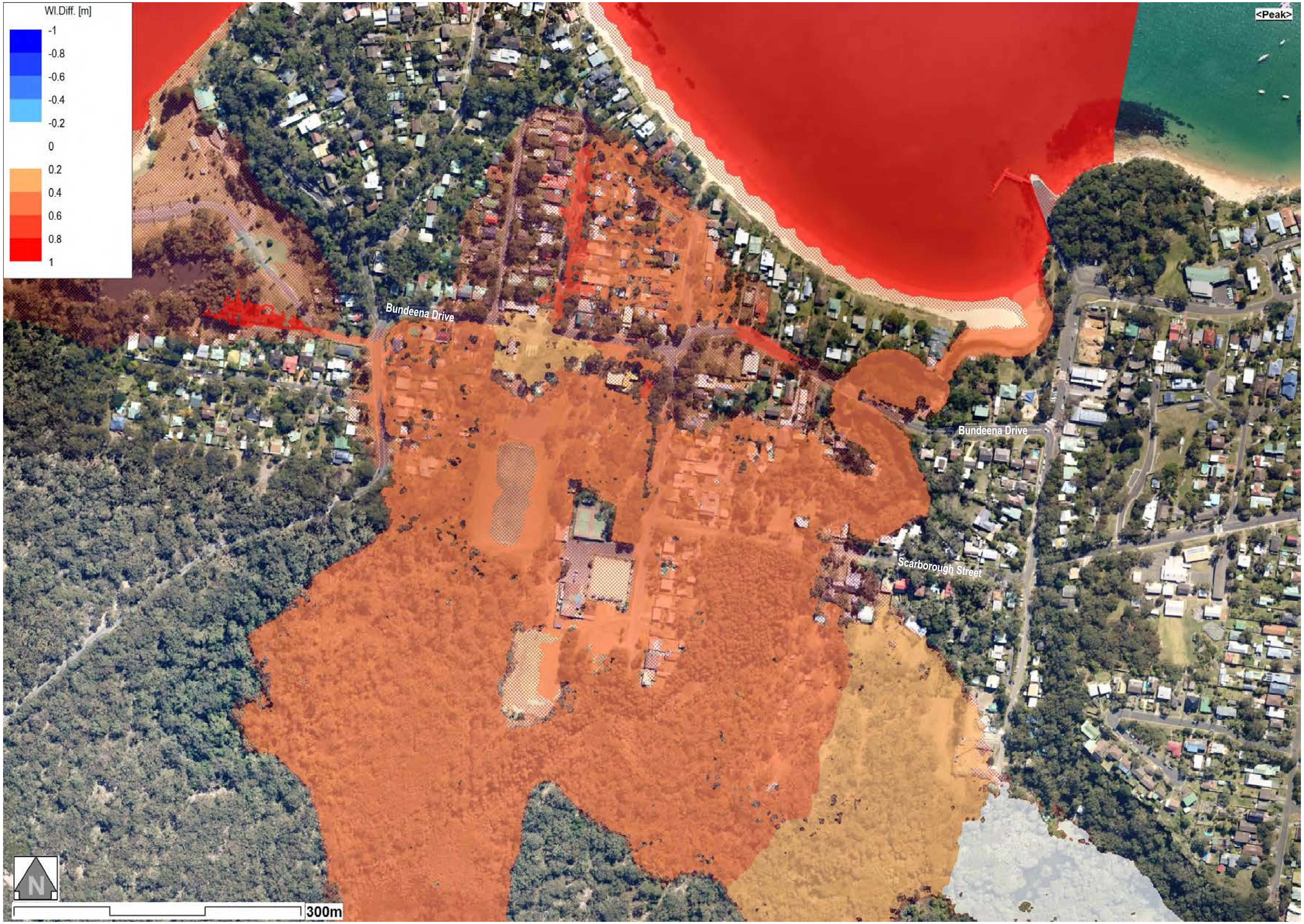
0.2 metre contour line

WorleyParsons
resources & energy

301015-03182 – Bundeena Creek Flood Study
K.9_fg301015-03182_EH131125-CC_1%AEP_2100_Level.doc

PEAK 1% AEP FLOOD LEVELS
[2100 SEA LEVEL RISE SCENARIO]

FIGURE K.10



NOTES:
Hatching (excluding ocean) indicates additional extent of flooding.

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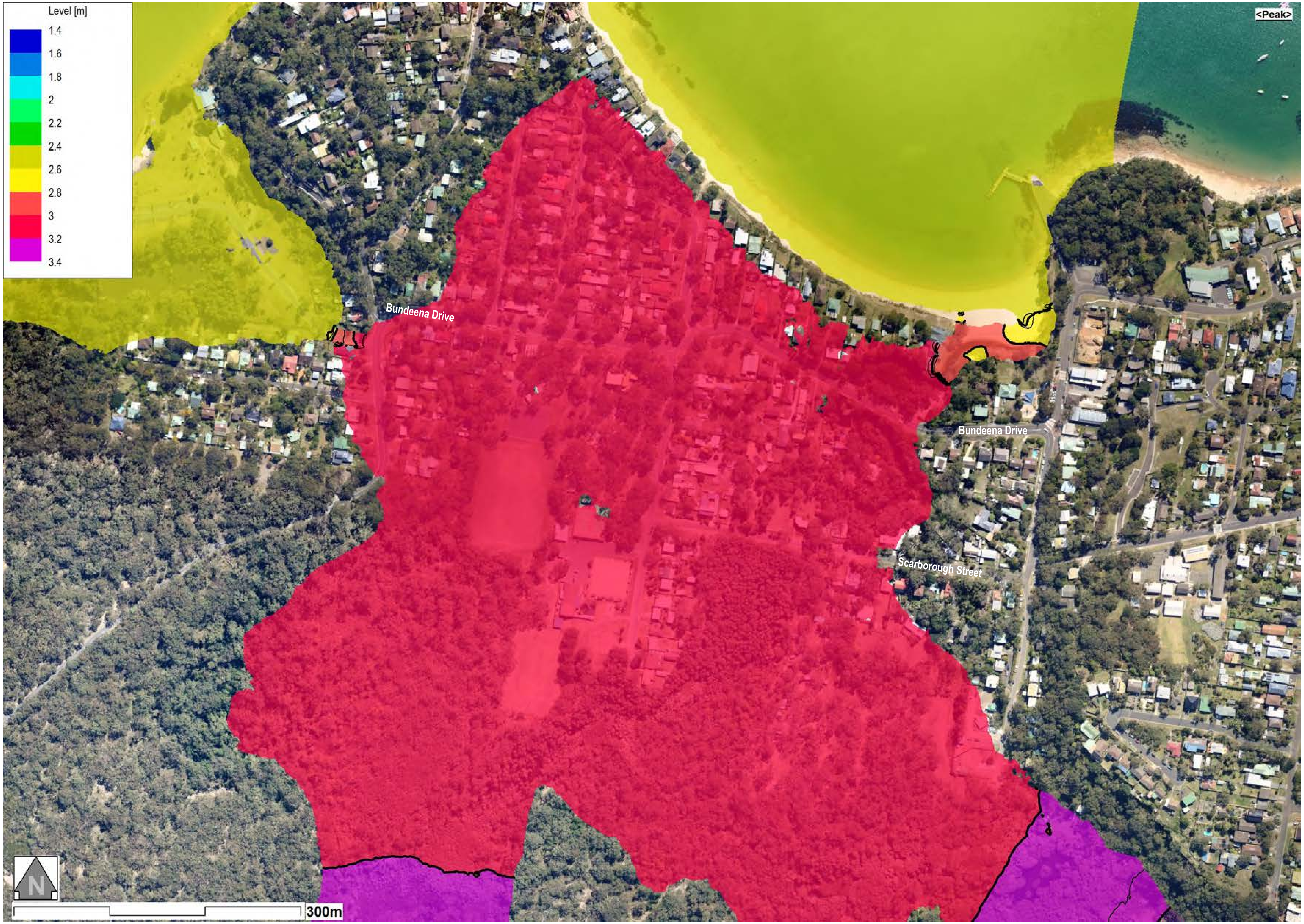
301015-03182 – Bundeena Creek Flood Study
K.10_fg301015-03182_EH131125-CC_1%AEP_2100-PD_Diff.doc

CHANGE IN 1% AEP PEAK FLOOD LEVELS RESULTING FROM SEA LEVEL RISE [2100 SEA LEVEL RISE SCENARIO]

FIGURE K.11



LEGEND:

0.1 metre contour line

0.2 metre contour line

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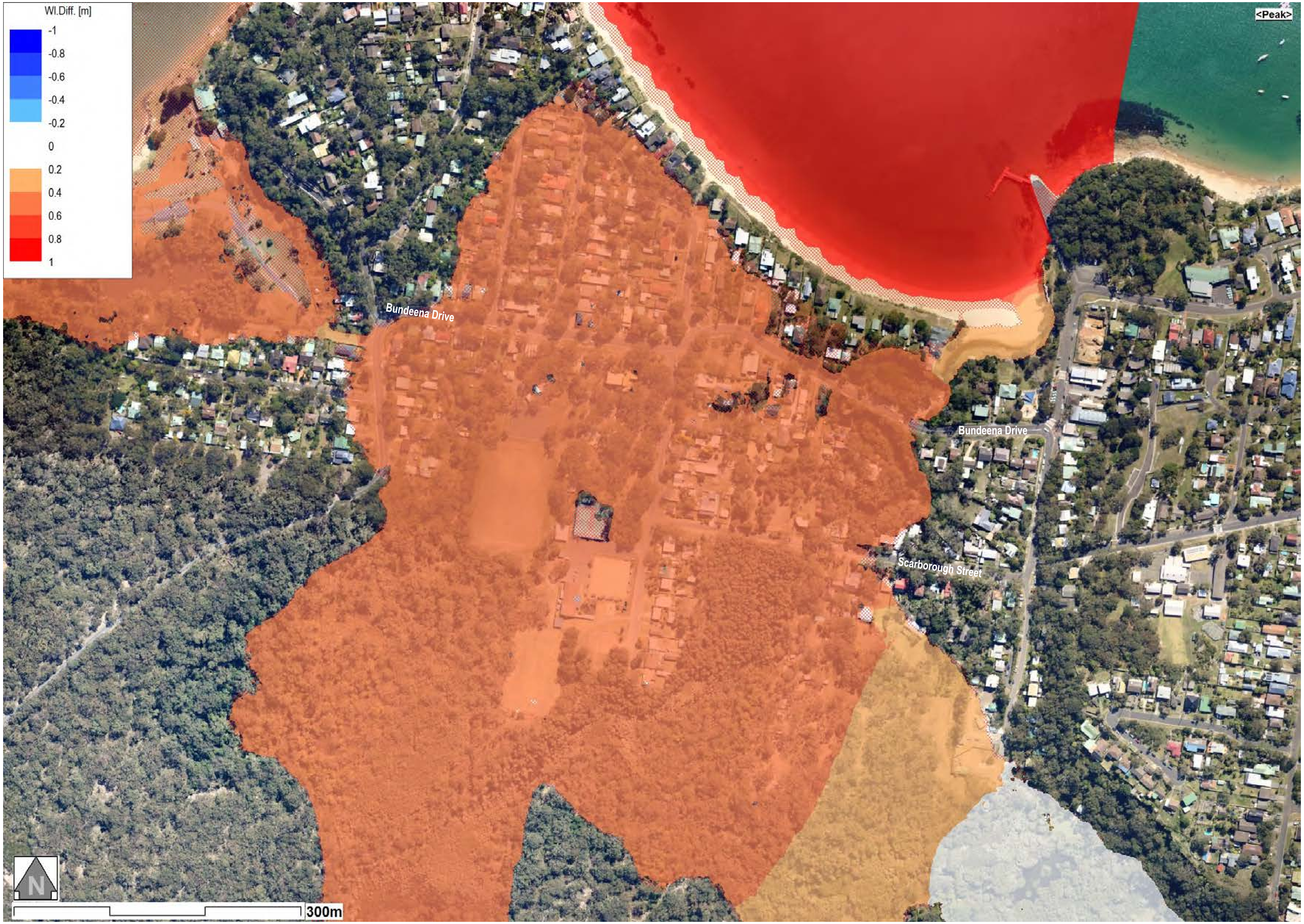
PROBABLE MAXIMUM FLOOD LEVELS
[2100 SEA LEVEL RISE SCENARIO]

FIGURE K.12



NOTES:
Hatching indicates Hatching (excluding ocean) indicates additional extent of flooding.

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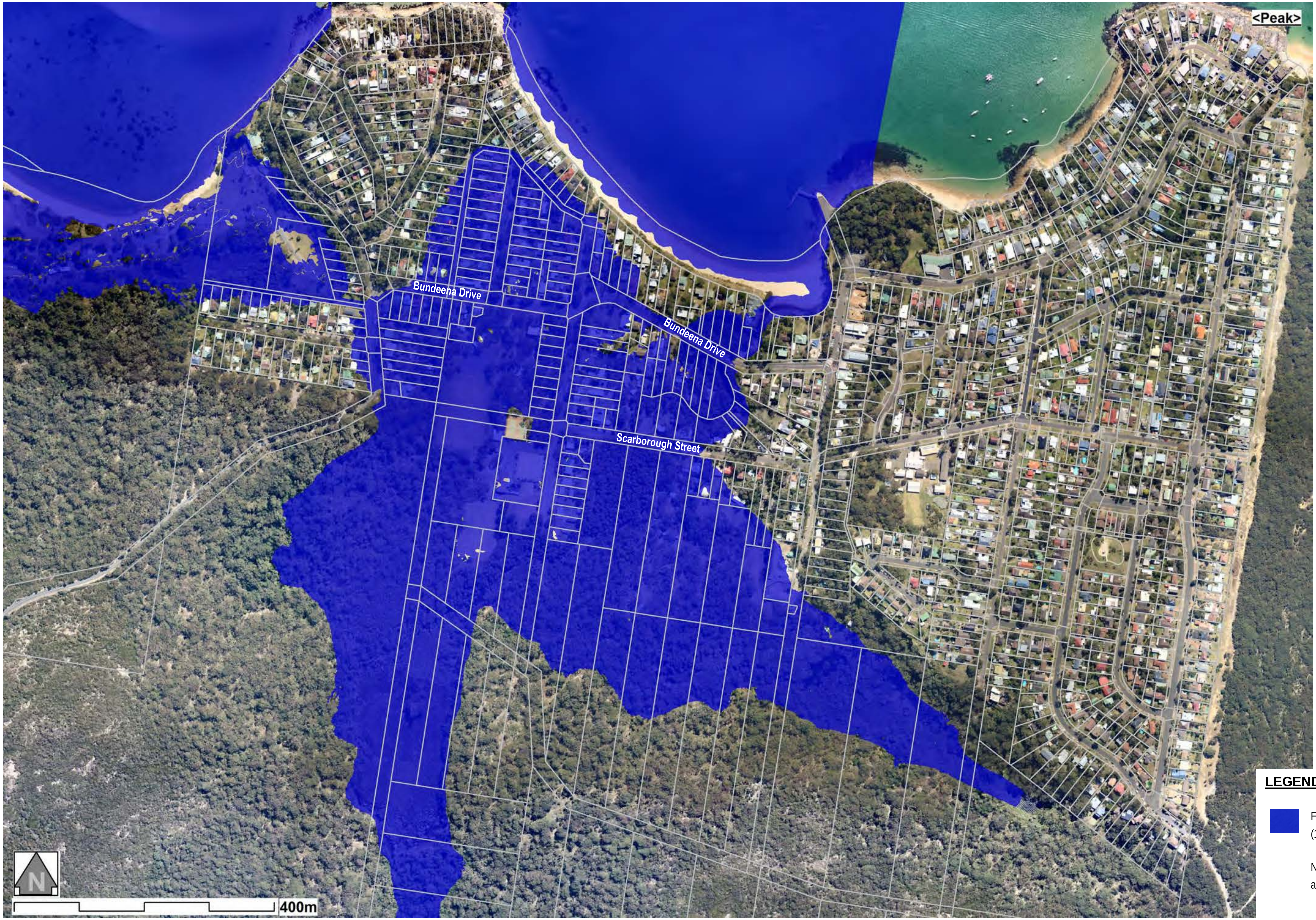
301015-03182 – Bundeena Creek Flood Study
K.12_fg301015-03182_EH131125-CC_PMP_2100-PD_Diff.doc

CHANGE IN PROBABLE MAXIMUM FLOOD LEVELS RESULTING FROM SEA LEVEL RISE [2100 SEA LEVEL RISE SCENARIO]

APPENDIX L

FLOOD PLANNING AREA MAPPING

FIGURE L.1



LEGEND:

Flood Planning Area
(1% AEP + 0.5 m freeboard)

Note: 1.51 mAHD Ocean Level assumed

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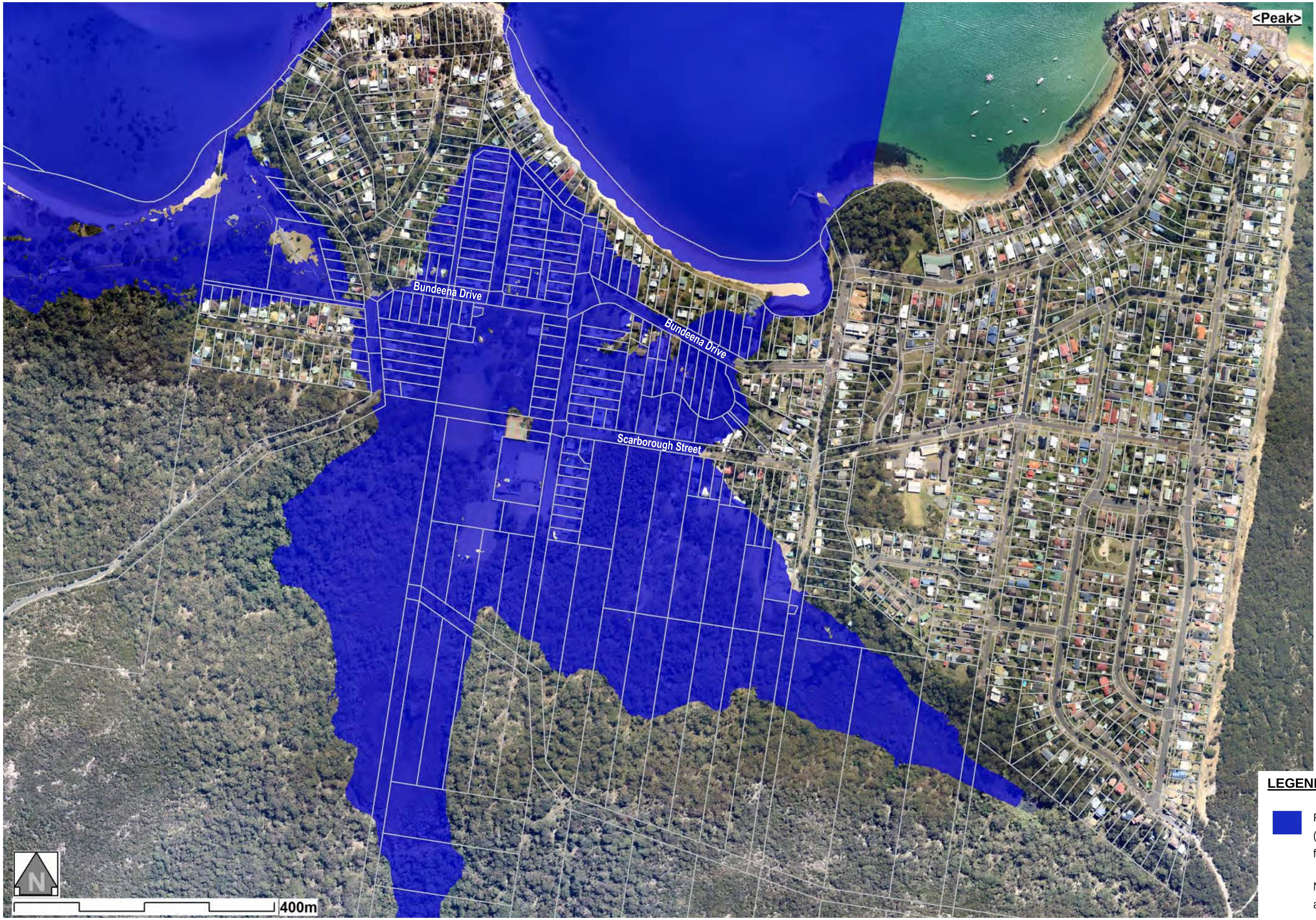
FLOOD PLANNING AREA

FIGURE L.2



LEGEND:

Flood Planning Area (1% AEP Yr 2050 + 0.5 m freeboard)

Note: 1.79 mAHD Ocean Level assumed

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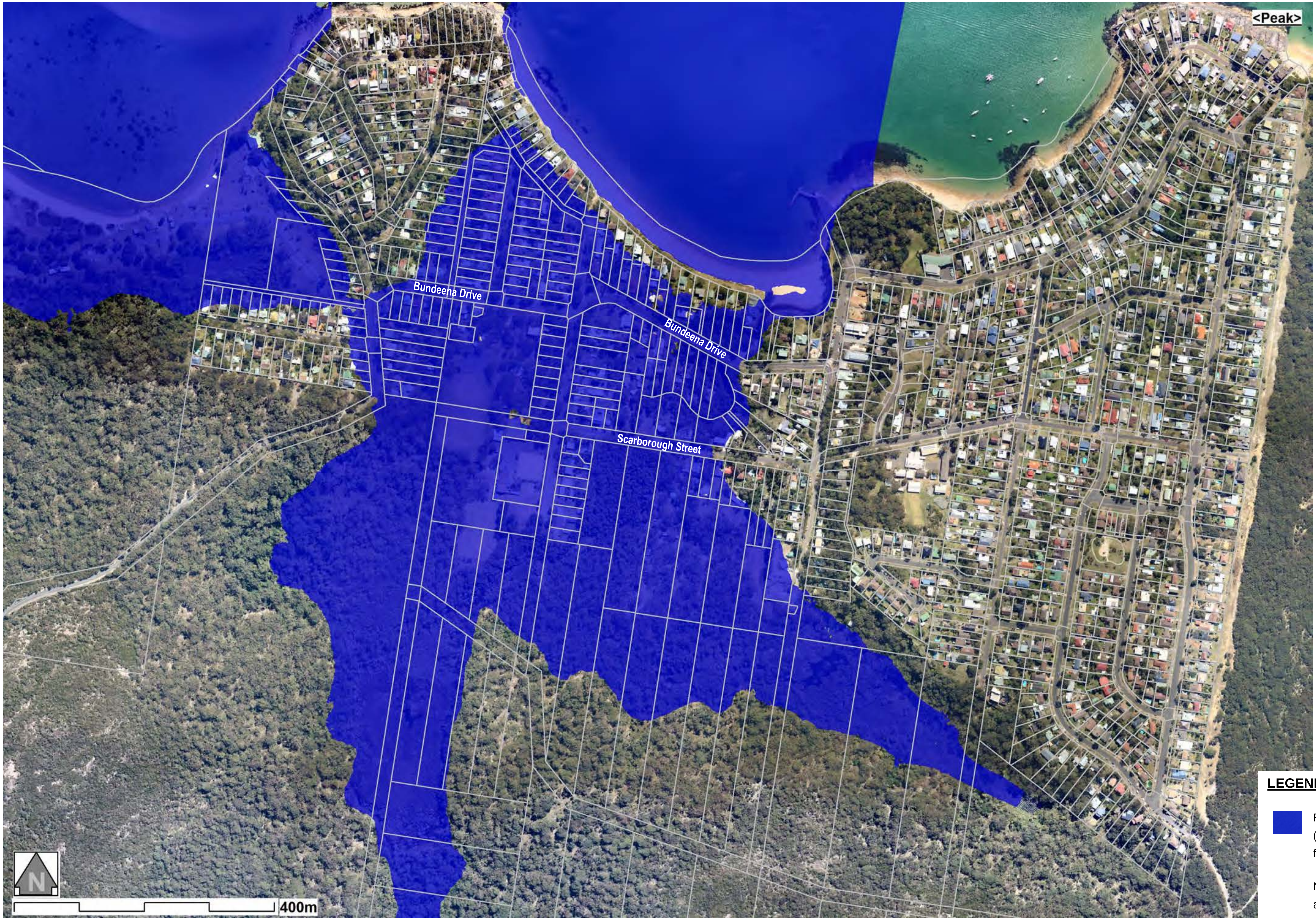
301015-03182 – Bundeena Creek Flood Study
L.2_fg301015-03182_EH140117-FPA_CC_1%AEP_2050+0.5m.doc

FLOOD PLANNING AREA
[YEAR 2050 SEA LEVEL RISE]

FIGURE L.3



LEGEND:

Flood Planning Area (1% AEP Yr 2100 + 0.5 m freeboard)

Note: 2.41 mAHD Ocean Level assumed

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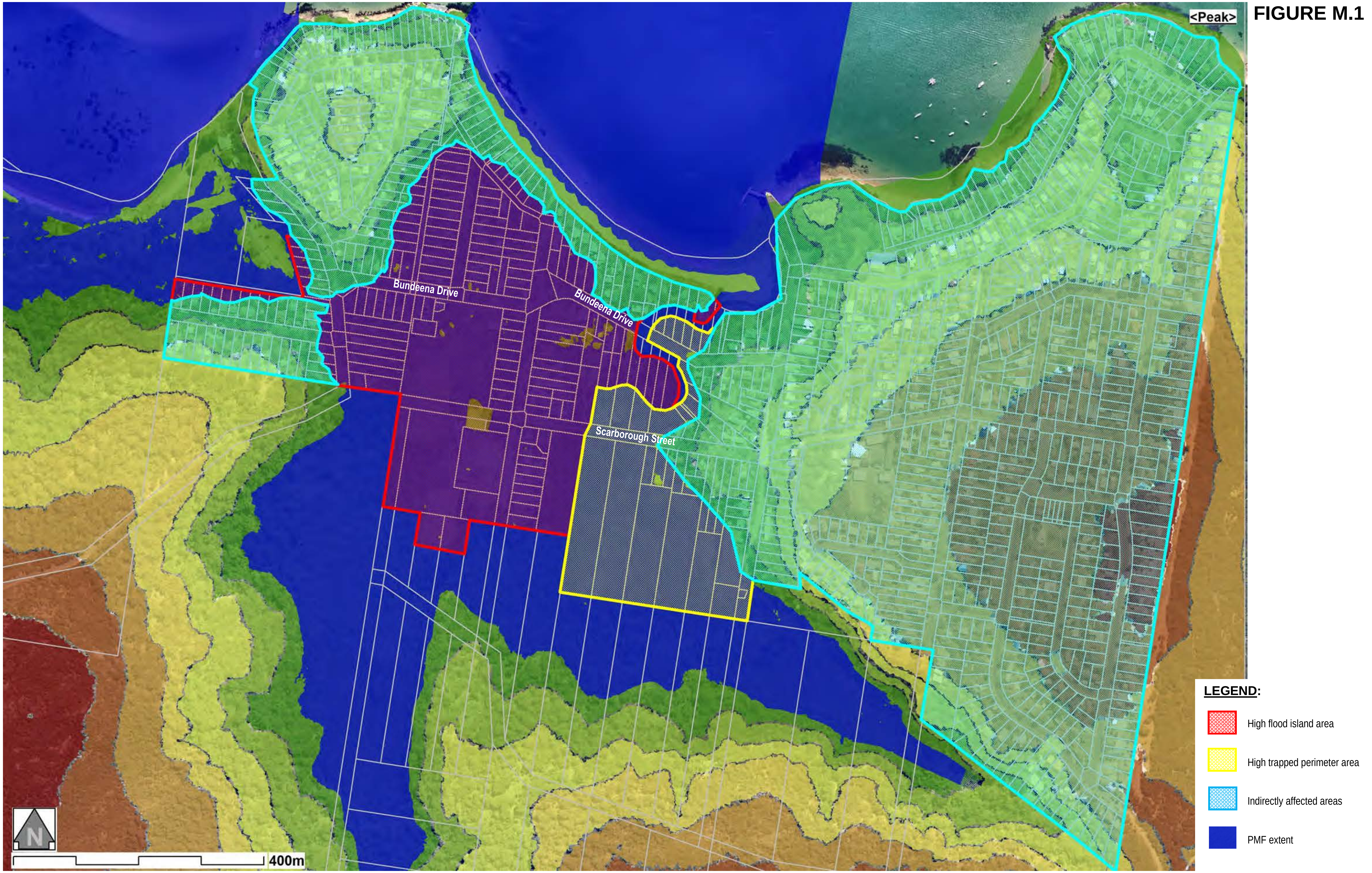
301015-03182 – Bundeena Creek Flood Study
L.3_fg301015-03182_EH140117-FPA_CC_1%AEP_2100+0.5m.doc

FLOOD PLANNING AREA
[YEAR 2100 SEA LEVEL RISE]]

APPENDIX M

PRELIMINARY EMERGENCY RESPONSE COMMUNITIES

FIGURE M.1



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301015-03182 – Bundeena Creek Flood Study
M.1_fg301015-03182_EH140117-Emergency_Communities.doc

PRELIMINARY ASSESSMENT OF FLOOD MANAGEMENT COMMUNITIES