Otago Regional Council Storm Surge Modelling Study

NIWA Client Report: CHC2008-047
June 2008

NIWA Project: ORC07503

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Executive Summary

Otago Regional Council (ORC) contracted the National Institute of Water and Atmospheric Research (NIWA) to undertake a study of potential inundation of the Otago coast due to extreme sea level events with return periods of 20, 50, 100 and 500 years. The focus is on seventeen locations along the Otago coastline.

Extreme sea levels occur as a consequence of a combination of tides, storm surge and wave set-up and run-up. Storm surges result from low atmospheric pressure and wind stress. Long data time series of atmospheric pressure and wind speed and direction were available from locations in Otago, and were used here to derive long time series of storm surge events. An 18-year time series of tidal height for each location was derived using an established tidal model of New Zealand coastal waters. Finally, time series of wave set-up and run-up were calculated from a 30-year hindcast of wave conditions (Gorman et al., 2003).

From the above time series, cumulative distribution functions (cdf) and probability density functions (pdf) were calculated for each independent variable. In order to investigate extreme events from finite time series, the tails of the pdf's were extended using established statistical techniques (the r-largest method, Smith [1986]). The resulting pdf's for tides, storm surge and wave set-up were then convolved to provide a pdf of extreme sea level.

Predicted sea level heights are presented relative to both present mean level of the sea (MLOS) and Dunedin Vertical Datum 1958 (DVD-58), which is 0.109 m below MLOS.

Results show that the maximum predicted sea level in the studied areas is 2.63 m above MLOS at Toko Mouth, having a return period of 500 years. The maximum level with a return period of 20 years is 2.36 m above MSOL, also at Toko Mouth. In contrast, minimum levels are predicted for Warrington, with 20- and 500-year return sea levels of 1.55 m and 1.78 m above MSOL respectively. Predicted levels vary between locations by up to 85 cm. Wave set-up makes a significant contribution to the sea level values, and is strongly dependent on local beach slope. Tidal heights and storm surge conditions vary relatively little spatially, and so wave set-up dominates the spatial variability in the predictions.

Maps of land areas at risk from inundation by extreme sea level events were produced for 17 settlements in Otago for each return period. Inundation varied greatly between locations, depending on the local topography. A number of low-lying areas are at risk of extensive inundation from storm events. In particular, areas around Papatowai, the Catlins River, Taranui, Taieri Mouth, Long Beach, Purakanui, Karitane, Clutha delta and Toko Mouth appear to be susceptible to inundation. Anticipated future rises in sea level increase the depth and extent of inundation in several localities.

The main limitations of the study concern the relatively short length of data time series, the necessary approximations of seabed and beach slope required for each calculation and the neglect of complicated ocean dynamics in the surge and set-up calculations. These simplifications introduce inherent uncertainty into the calculations. However, the results are based on best available data, compare well with previous studies, and are considered essentially robust. The maps of potential inundation, while highly detailed due to the high resolution of the LiDAR data, are entirely dependent on the accuracy of the sea level predictions; the limitations of these predictions must therefore be kept in mind when inspecting and interpreting the maps.

1. Introduction

The Otago Regional Council contracted NIWA to undertake a hazards management investigation into the risk to coastal and estuarine communities along the Otago coast from storm surge and tsunami events. As storm surge and tsunamis represent independent threats to the Otago coast, this investigation has been separated into two parts with this second report covering the storm surge component including:

1. The determination of extreme sea levels for return periods of 20, 50, 100 and 500 years, due to combinations of tides, wind-stress, atmospheric pressure and waves.

2. Inundation modelling to determine extent of land flooded by extreme sea levels.

The Otago coastline investigated in this study extends from the Waitaki Fan in the north, to Wallace Beach in the south (Figure 1.1). The places of interest, where sea level elevation will be specified and inundation mapping will be undertaken include the settlements of:

- Tautuku Peninsula,
- Papatowai,
- Catlins Lake/Catlins River settlements (including Jacks Bay and Surat Bay),
- Kaka Point,
- Clutha delta,
- Toko Mouth and estuary,
- Taieri Mouth and estuary,
- Brighton,
- Kaikorai Mouth and estuary,
- Dunedin Harbour and South Dunedin (including St. Clair, St Kilda, and Tomahawk beaches),
- Long Beach,
- Purakanui and estuary,
- Blueskin Bay
- Karitane
- Moeraki,
- Hampden,
- Kakanui/Taranui and,

- Oamaru.

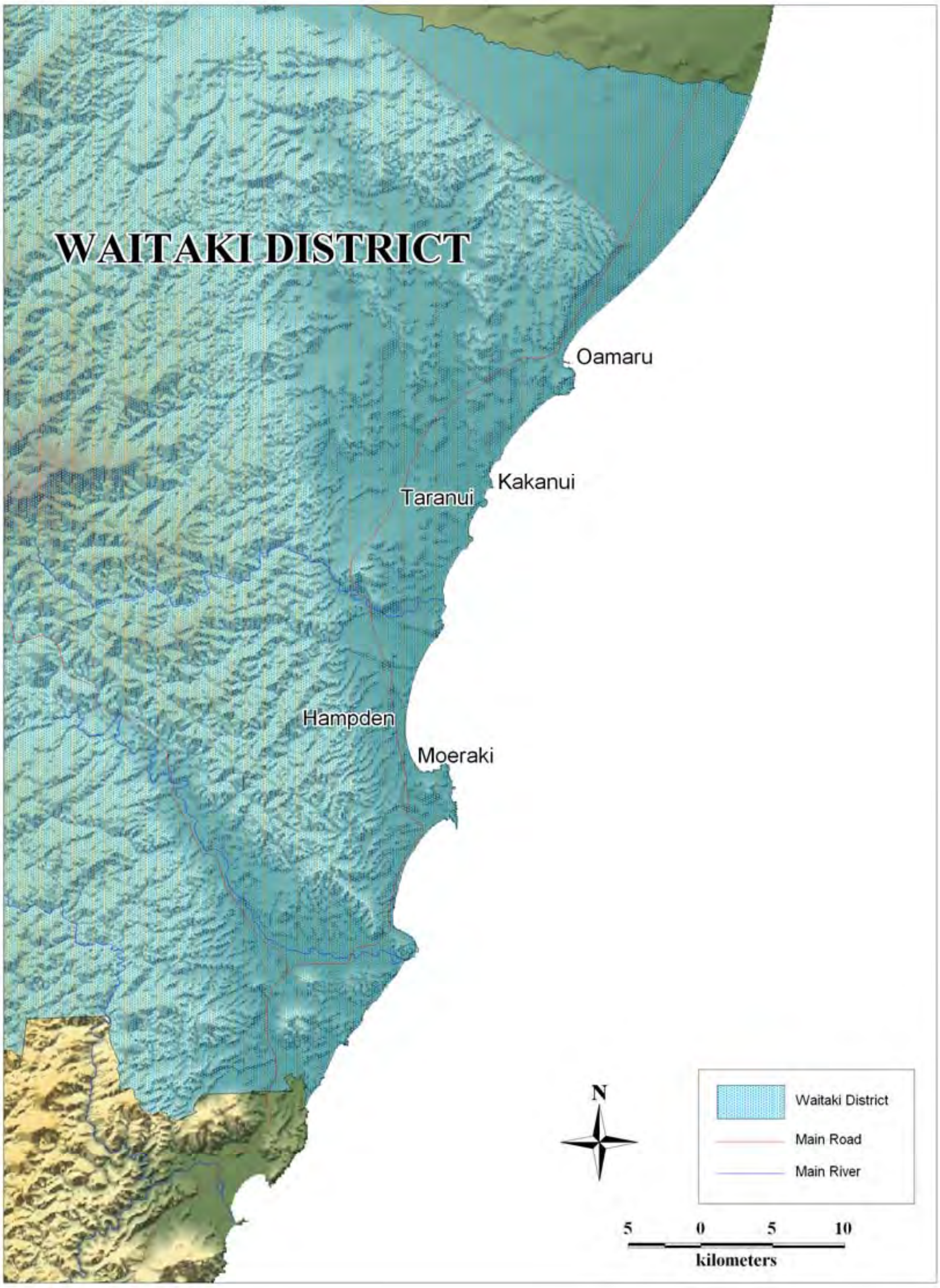

Figure 1.1: Maps of Waitaki District, Dunedin City and Clutha District including study areas. (provided by ORC)

Figure 1.1 (cont'd). Maps of Waitaki District, Dunedin City and Clutha District including study areas. (provided by ORC)

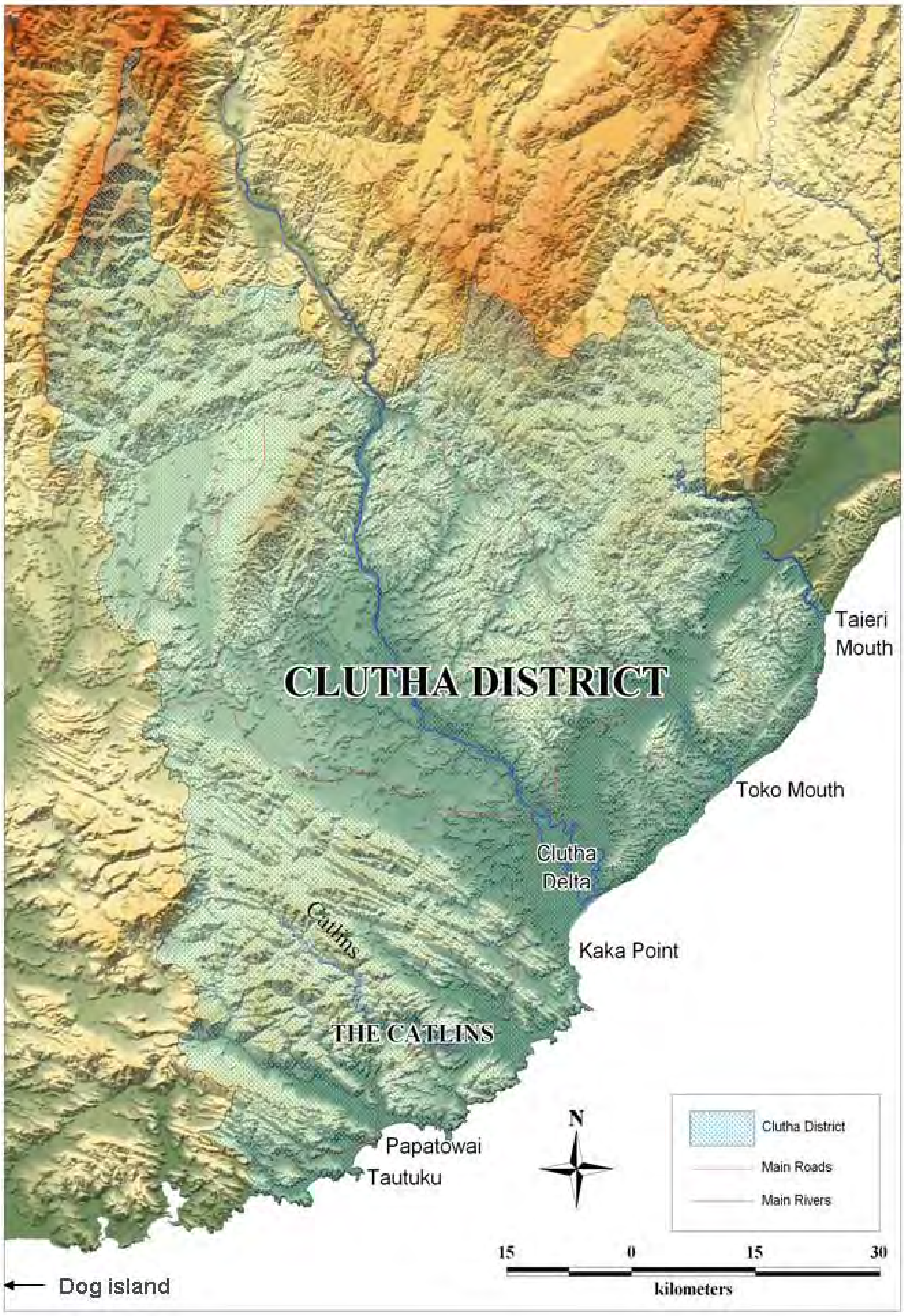

Figure 1.1. (cont'd). Maps of Waitaki District, Dunedin City and Clutha District including study areas. (provided by ORC)

An earlier study conducted on behalf of Otago Regional Council (Wild et al., 2005) investigated extreme sea levels with return periods of 2, 5, 10, 20, 50 and 100 years for eight locations along the Otago coastline. That earlier study investigated tide and storm surge effects on sea level only. Here we consider also the effects of wave set-up and wave run-up.

2. Sea-Level Prediction: Data and Methodology

2.1. Introduction

A number of meteorological and astronomical phenomena are involved in the development of extreme sea level events and could combine in a number of ways to produce an event of a given probability. The processes involved are:

- Inverse Barometer Effect
- Wind Set-up
- Tides
- Wave Set-up
- Wave Run-up

The inverse barometer effect describes the response of the sea to atmospheric pressure: specifically, as atmospheric pressure drops, sea level rises in response and when atmospheric pressure increases, sea level is lowered. Wind set-up describes the "piling up" of water against the coast by prevailing winds acting on the water surface and driving water currents landwards. The combined effect of these two effects, which often occur together since strong winds are generally associated with atmospheric lows, produce "storm surge" events. In shelf sea regions, tides usually have a critical influence on sea level. Storm surges usually only have significant effects if they coincide with high tides. The combination of tide and storm surge is sometimes called a "storm-tide".

Waves also raise the effective sea level by two mechanisms. Wave set-up is the increase in mean sea level through the effect of breaking waves. This is thus a persistent elevation of sea level when breaking waves are present. Wave run-up is the maximum vertical extent of wave uprush on a beach or structure above the still water level, and thus constitutes only a short-term flux of water (relative to set-up and storm surge time scales).

All of the above processes have different driving mechanisms and thus different response time scales and return periods. There is no single definitive scenario that would cause an extreme sea level event of a given probability, and any attempt to attribute this could be misleading. To work around this, we propose calculating sea levels for different return periods and modelling inundation resulting from these. We chose this method over the replication of specific historical storm events because there are few useful records available of past events that caused significant storm surge and inundation. The available number of events is not large enough to reliably separate the effects of the four factors above or understand how they might combine in the future.

The method will start by the derivation of historical records for each component above. These records will be used to create probability density functions (pdf's) for each component, i.e. histograms describing the frequency of each sea level height occurring due to that particular component. Where necessary, possible extreme values of sea level beyond those occurring in the historical records will be modelled using statistical methods. This method is described more fully in Sections 2.3 – 2.5 below. The pdf's for each component are then combined to create a pdf for total sea level elevation, and hence sea level predictions for each return period of interest can be made. This method is described in Section 2.6.

2.2. Derivation of historical storm surge record

2.2.1. Inverse barometric effect

Sea level usually responds to changes in atmospheric pressure over several hours, with the effects observed over a large area of ocean. When atmospheric pressure falls, the mean level of the sea (MLOS) rises, with the amount that sea level increases varying according to location.

In isostatic conditions (e.g., without winds), sea level variation is related to barometric pressure changes by the inverted barometer (IB) response. The theoretical IB response is an increase of 10 mm in sea level for every drop of 1 hPa below the annual-average barometric pressure. However, in reality, sites exposed to prevailing westerly winds generally respond to changes in barometric pressure at greater than the conventional inverted barometer response (0.01 $m.hPa^{-1}$), and eastern sites sheltered from the west respond at less than this factor (Goring, 1995).

An equation for calculating the inverse barometer effect is:

$$\eta_{\Delta p} = F\,(a - p) \tag{2.1}$$

where $\eta_{\Delta p}$ = inverted barometer effect (m)

F	=	barometric response factor (m.hPa^{-1})
a	=	region's average barometric pressure (hPa)
p	=	recorded barometric pressure (hPa)

The values of F = 0.008 m.hPa^{-1} and a = 1011.4 hPa for the Otago coastline were calculated in the NIWA study 'Otago extreme sea level analysis' (Wild et al., 2005), using an analysis of recorded barometric pressure at Taiaroa Head, Green Island and Dog Island, and storm surge recorded at Green Island, Otago Harbour at Port Chalmers and Otago Harbour at the Spit jetty (i.e., Otago Heads). These values of F and a are used throughout this study.

A record of barometric pressure is also available from the Wild et al. (2005) study, covering the period 1961 – 2005. This record is derived from a combination of data from Taiaroa Heads and Dog Island, as barometric pressures were not found to vary significantly between the regions of interest. For this study, that record was extended to 2007 using additional data from Taiaora Heads. From this series, the inverse barometric effect is calculated and is used uniformly along the whole coastline.

2.2.2. Wind stress

Data availability

Data on wind speed and direction are available for several sites along the Otago coastline. These data were extracted from the NIWA Climate Database and a comparison made between the sites: a typical sample is shown in Figure 2.1. The wind speed at Taiaroa Heads is consistently higher than at other sites due to the exposed position of the site. It was therefore decided to use the Taiaroa Heads data for derivation of wind set-up for the Otago coast, both in order to adopt a precautionary approach (stronger winds mean larger set-up and consequently higher sea levels) and because this site is considered most representative of winds blowing over the continental shelf waters (winds are generally stronger over water than over land).

Wind set-up calculation

The wind set-up calculation methodology used here is that of Wild et al. (2005). The details are repeated here for clarity.

Onshore winds (at right angles to the coast) push water across the continental shelf, setting up sea levels at the coast. A similar outcome occurs for winds travelling over the sea with the coast on their left "wing", which for Otago are winds from the south-west quarter. This latter response occurs due to Ekman flow to the left in the southern hemisphere, arising from the Coriolis force on a spinning Earth.

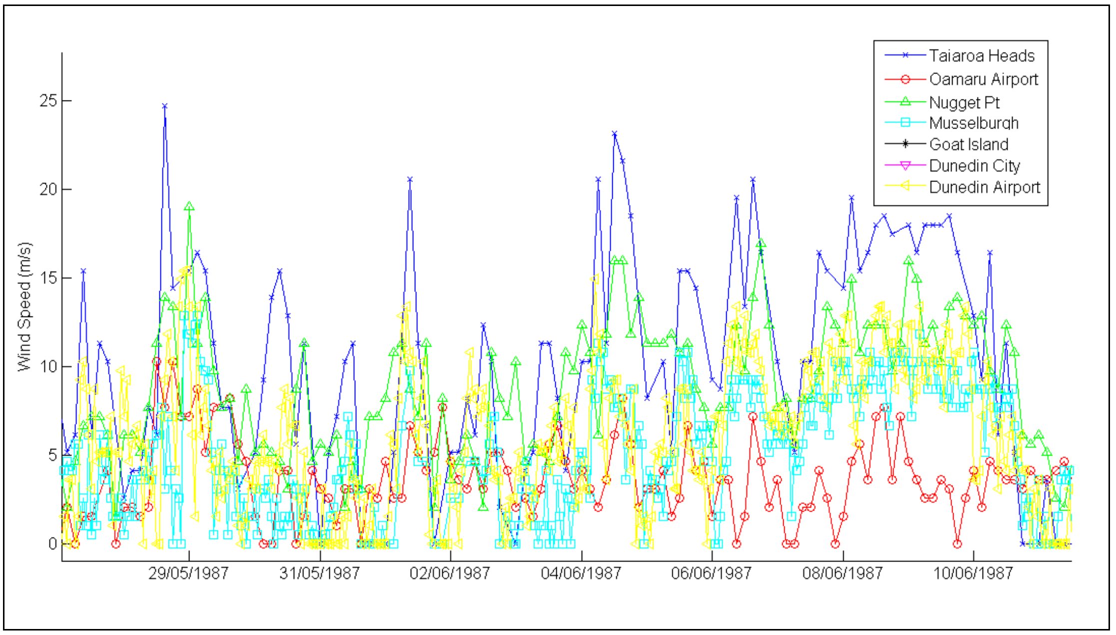

Figure 2.1: Sample Comparison of Wind Speeds at Sites along the Otago Coast.

The prediction of wind stress set-up along the coast is more complex than the prediction of inverse barometric effect due to the greater variability in wind velocities over time, their degree of persistence (needs several hours to build up the set-up in sea level), as well as the varying wind directions, passage of fronts and non-uniform water depth and continental shelf width along the Otago coast. Wind data may also be affected by sheltering caused by local topography, while features like Otago Harbour can funnel winds preferentially along the main axis of the harbour.

Silvester (1974) estimated the set-up in sea level caused by wind stress using Equation 2.2:

$$\eta_w = 6.915 \frac{K U_{10}^2 W}{g h_1} \tag{2.2}$$

where η_w = vertical water level set-up due to onshore wind stress (m)

K = 3×10^{-6}

U_{10} = equivalent steady wind speed 10 m above MSL ($m.s^{-1}$)

W = width of continental shelf (m)

h_1	=	depth at shelf edge (m)
g	=	gravitational acceleration = 9.81 m s^{-2}

The ratio W/h_1 is a measure of the slope of the seabed across the continental shelf. For this study, we took the edge of the inner continental shelf to be at the 100 m depth contour (Table 2.1). Others (e.g. Tonkin and Taylor, 1997) have used other depth contours to mark the shelf edge. It is not a critical choice, provided that the value of *W* is chosen appropriately for the value of h_1.

For the Otago coast, the wind record from Taiaroa Head has been used to determine wind stress as it is the most representative of winds blowing over the shelf waters. The Taiaroa Head climate station is located at the entrance to Otago Harbour at 72 m above MSL. An equivalent 10 m wind velocity reading (U_{10}) has been calculated assuming the empirical altitude relationship from (Beer, 1997):

$$\frac{U}{U_{10}} = \left(\frac{z}{10}\right)^k \tag{2.3}$$

where	U_{10}	=	equivalent steady wind speed 10 m above MSL (m.s^{-1})
	U	=	wind speed at Taiaroa Head (m.s^{-1})
	z	=	anemometer height (=72 m for Taiaroa Heads)
	k	=	varies with atmospheric stability with a typical value of 1/7

To provide a conservative estimate of the wind stress effect along the Otago coast, a range of wind directions from 15° to 250° have been assumed to be perpendicular to the coast for each site. This approach is likely to give a slightly higher sea level set-up than expected when the wind is not blowing onshore or alongshore from the SW quarter. Outside of this directional range, the wind stress was set to zero as the wind stress effect is likely to be negligible or produce a set-down at the coast (e.g., offshore winds).

For the waters within Dunedin Harbour, the storm surge is assumed to be the combined total of the wind set-up at Otago Heads, and an ***additional*** wind set-up for within the harbour when the wind is blowing from the north-east (i.e. directly down the harbour at an angle of 15° to 75° from north). The additional wind stress set-up within Dunedin Harbour is calculated using Equation 2.4 (Pugh, 1987).

$$\eta_w = \frac{C_D \rho_A U_{10}{}^2 w}{\rho g h} \tag{2.4}$$

where η_w = vertical water level set-up due to onshore wind stress (m)

C_D = $(0.63 + 0.066U_{10}) \times 10^{-3}$, $U_{10} \leq 21$ m.s^{-1}

= 2.02×10^{-3}, $U_{10} > 21$ m.s^{-1}

U_{10} = equivalent steady wind speed 10 m above MSL (m.s^{-1})

ρ_A = density of air = 1.29 kg.m^{-3}

ρ = density of seawater = 1025 kg.m^{-3}

w = width of shelf over which wind blows (m)

h = average depth (m)

Results produced using Equations 2.2 to 2.4 have been generated using Taiaroa Head wind velocity data. This record initially has a recording interval of 6 hours, but changes to hourly data in February 1975. A summary of the parameters used to generate wind stress effect for the Otago coastline and Dunedin is shown in Table 2.1.

Table 2.1: Parameters used to determine wind stress set-up for Otago coast sites

Location	Onshore wind direction range (degrees from north)	Shelf width (km)	Water depth, h (m)
Otago coastline	15-250	25	100
Dunedin[a]	15-75[a]	20[a]	10[a]

[a] Otago Heads wind stress effect plus wind stress effect calculated using Pugh (1987) with an average width of shelf over which wind blows of 20km, and an average depth of 10m.

The wind set-up component of storm surge for the Otago coastline used parameters initially derived for Otago Heads (Table 2.1). This wind set-up was then applied uniformly at all the other open coast sites. This can be revised in the future if any long-term sea level measurements at other sites, or 3-dimensional storm surge modelling, suggests otherwise.

2.3. Estimation of complete storm surge distribution

2.3.1. Empirical PDF

By combining the historical series of wind stress set-up and inverse barometric effect, time series of storm surge spanning the years 1961-2007 were derived. Two such series were created: one for open coast sites, and a second for Otago Harbour, as specified by the additional wind-stress set-up in Section 2.2.2 above. To account for other residual meteorological effects, including coastally trapped wave propagation along the coast, and the effects of a moving-storm system, an additional 20% factor has been added to the derived total storm surge for the open coast sites (Wild et al., 2005). (Note that, although it is not unusual for a storm surge to be twice the inverse barometer set-up, the calculated wind stress component is generally less than the magnitude of the pressure-related set-up). The open-coast storm surge distribution is assumed to hold for all the sites in the study because both inverse barometer and wind stress are large-scale phenomenon in relation to the study area.

From the derived storm surge sequence, an empirical probability density function (pdf) is constructed. This empirical distribution will give a good representation of the true surge pdf for non-extreme values, due to the long storm surge data series. However, for extreme surge values, with return periods much larger than the 46-year length of record, there may be insufficient information in the record to properly construct the pdf; in particular, it is possible that more extreme surges than have been recorded could occur in the future. In order to properly account for this probability, a tail is fitted to the empirical pdf above a threshold Z which is set such that on average 5 storm surge events per year exceed Z.

2.3.2. Fitted tail

R-Largest method overview

The shape of the pdf tail is calculated using the r-largest method (Smith, 1986). This method is based on the idea of using a fixed number, r, of independent extreme values from each year to provide robust estimates of the parameters of the extreme value distribution from a short period of record. Practically, the method involves 3 steps:

1. Identification of independent extreme events. Observations are classified as independent if they are separated in time by at least a standard storm length, here defined as 30 hours.

2. Selection of a suitable number of independent events from each year of data. The number of events has to be large enough to ensure sufficient data are available to obtain reasonable parameter estimates, but also small enough that the lowest level used still belongs to the extreme tail of the distribution. Typically, the number of events is taken as five.

3. Fitting an extreme value distribution to the selected event maxima.

Clustering of extreme events

In order to complete the fitting of the extreme value distribution, we must investigate the dependency between hourly observations of storm surge, which are not independent but tend to cluster as storms. We apply ideas arising from Leadbetter (1983) which are implemented in the form of the Extremal Index, $\theta(x)$, a multiplicative factor that varies with level and when multiplied by the number of hourly observations, N, (storm surge or sea level), gives the number of independent observations above a given level, x:

i.e. *Number.of independent observations (storm surge or sea level) above level x is* $N\theta(x)$

A physical interpretation of the Extremal Index can be given in terms of its reciprocal, $\theta^{-1}(x)$, as representing the average number of data intervals that water levels exceed the threshold value, Z, during a storm event (Tawn and Vassie, 1989). In terms of clustering of exceedances, $\theta^{-1}(x)$ represents the average number of exceedances in a cluster for a specified threshold. One difficulty is that the Extremal Index is required for levels beyond the range of the data, and must therefore be extrapolated. For any given distribution function, F(x), if x is sufficiently large, it can be shown from extreme value theory (Leadbetter, 1983) that $\theta^{-1}(x)$ is invariant to x. Hence the correct function to extrapolate at the extremes is a constant θ^{-1}. This constant is estimated using a weighted least-squares approach on the $\theta^{-1}(x)$ estimates for the data above a minimum threshold level at the extreme.

Statistical methodology

The form of the fitted distribution is based on statistical extreme value theory. We assume that the storm surge data are such that the annual maxima would follow a Gumbel (GEV Type 1) distribution (a test is performed to check that this assumption is correct). The pdf of the Gumbel distribution is as follows (Gumbel, 1958):

$$f(x;\mu,\sigma) = \frac{1}{\sigma}\cdot\exp\left(-\frac{x-\mu}{\sigma}\right)\cdot\exp\left\{-\exp\left(-\frac{x-\mu}{\sigma}\right)\right\}$$

It can then be shown that if the r largest independent events are selected from the data, these will have the following joint probability density (Smith, 1986):

$$f\left(x_{11}\ldots x_{Nr};\mu,\sigma\right)=\sigma^{-Nr}\exp\left\{-\sum_{n=1}^{N}\left[\exp\left(-\frac{x_{nr}-\mu}{\sigma}\right)+\sum_{j=1}^{r}\frac{x_{nj}-\mu}{\sigma}\right]\right\}$$

Here, N = the number of years, with r values being selected each year. This function can be treated as a likelihood and maximised with respect to μ and σ to find the Maximum Likelihood Estimates of these parameters. Although there is no analytical expression for the estimators, the optimisation can be done numerically.

Because μ and σ are the same two parameters which characterise the gumbel distribution, and using our calculated value for the extremal index θ, we can now use the result that for the recorded surge values $Y_1 \ldots Y_N$:

$$\Pr[\max(Y_1 \,..\, Y_N)<= y)] = [\Pr(Y<= y)]^{N\theta} = F_Y(y)^{N\theta}$$

Here, N is the number of data samples from a single year. Hence

$$F_Y(y) = \Pr[\max(Y_1 \,..\, Y_N)<= y)]^{1/N\theta}$$

$$= \exp\left(-\frac{1}{N\theta}\exp\left\{-\frac{y-\mu}{\sigma}\right\}\right) \text{ for } y > Z \text{ (the threshold)}$$

Hence we now have a complete pdf for the storm surge, with the empirical distribution below the threshold and the fitted tail above it.

2.4. Derivation of tidal distributions

Given a set of tidal constituents for any location (i.e., a set of different sine curves of different periods that combine to describe the tide locally), a local 'predicted' tide record can be generated for any time period. The tidal constituents are generated using a tidal model of the New Zealand EEZ developed by NIWA (Walters, et al., 2001). A tide record of 18.61 years (a complete nodal tidal cycle) is then created for each location. The complete pdf of tide heights is given by plotting this tide record as a histogram, and no fitted tail for extreme values (as per the storm surge) is required as the record contains a complete tidal cycle.

The tide pdf must be calculated separately for each region of interest as the tidal range varies along the Otago coast, as exemplified by the Mean High Water Spring (MHWS) level in Figure 2.2. These values are presented as metres above the mean level of the sea (MLOS).

2.5. Derivation of wave height, set-up and run-up distributions

2.5.1. Wave height distributions

Hindcasts of wave height, frequency and direction just outside the surf zone for the Otago coast over the period 1979 to present are available from NIWA wave hindcasting studies (Gorman *et al.* 2003). The wave hindcast was prepared using the WAM wave generation model forced by wind fields from the United States National Center for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF). The hindcasts provide wave parameters (period, height, direction) at 3-hour intervals on a model grid with a spatial resolution of 1.25° x 1° covering the South Pacific and Southern Ocean. Hindcast data from cells adjacent to the Otago coast have been used for this study.

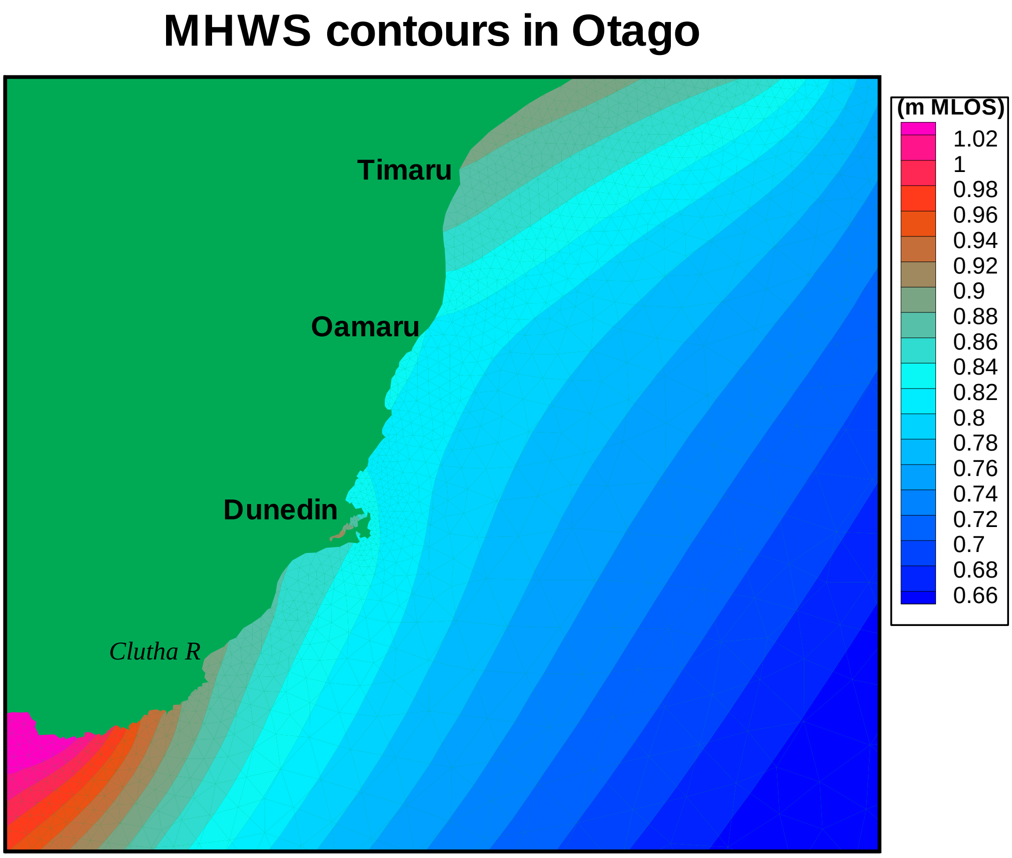

Figure 2.2: Distribution of MHWS level in Otago waters in terms of the mean level of the sea based on a tidal model of New Zealand (Walters et al., 2001).

2.5.2. Wave set-up and run-up

The wave height distribution describes the sea state just outside the surf zone. In order to predict how the waves will impact on the coastline, the wave height must be converted into wave set-up and wave run-up. Wave set-up is the elevation of the mean level of the sea due to the waves. Wave run-up is the additional height gained by breaking waves which may wash against land at higher elevations but will not permanently inundate this land. Since breaking waves are attenuated in sheltered areas such as inlets, wave run-up is restricted to open coast sites. These two variables will be calculated from the wave height distributions using empirical formulae given by Stockdon *et al* (2006):

Wave set-up = $0.35 \cdot \beta_f \cdot (H_0 L_0)^{1/2}$

Wave run-up = $1.1 \cdot \left(0.35 \cdot \beta_f \cdot (H_0 L_0)^{1/2} + \frac{\left[H_0 L_0 \cdot \left(0.563 \cdot \beta_f^{\ 2} + 0.004\right)\right]^{1/2}}{2} \right)$

where β_f is the beach slope, H_0 the wave height, and L_0 the wave length.

These formulae require knowledge of beach slope at each site of interest. As detailed shallow water bathymetry is not available for the Otago coastline, this slope will be estimated from the beachfront LIDAR data together with the 10m-spaced bathymetric contours and information from the NIWA coastal classification study. Various methods were tested for calculating the beach slope. The optimal method that was used involved finding the least squares best fit plane through all the points that lay within a given distance from start points and had elevation +/- 3m above MSL. This was calculated for a range of points along the coast of interest. From these slopes the mean and standard deviation were calculated and the slope was taken to be 1 standard deviation above the mean. Using these values the run-up and set-up pdf's were calculated for each of the 19 regions of interest.

2.6. Combining the Storm Surge, Tide and Wave Series

2.6.1. Dependency of Variables

Before combining the extreme value series for wind set-up and wave set-up, it is important to determine whether these variables are independent. It is possible that there would be some dependency due to a tendency for both wind and wave set-up to be elevated during storm events. However this is not expected to be the case for the Otago coast because wind set-up is typically a local phenomenon associated with wind speeds close to shore, while wave set-up is typically associated with swell generated by conditions far off shore. To check that this is the case, a graph of significant wave height against wind speed for Taiaroa Heads is shown in Figure 2.3. The graph shows no correlation between the two variables, we therefore make the assumption that they behave independently.

2.6.2. Convolution and sea level prediction

Once three separate pdf's are available - one for each independent component, storm surge, tide and waves - these are convolved (first convolve tide and storm surge, then convolve the result with the waves) to give the pdf for the total sea level. The level for any percentile can now be read off, and converted to a return period.

The method for finding extreme sea level for any given return period is as follows:

First the value of θ the extremal index for the combined sea level (tide+surge+waves) series should be found. The value will be found empirically using a long hourly record of total sea level available for Dunedin harbour, using the same methods as described in Section 2.3.2 for finding θ for other series.

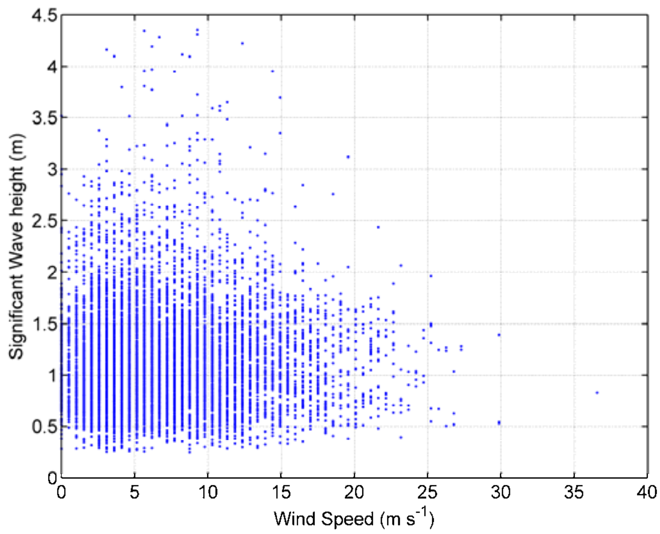

Figure 2.3: A comparison of wave height and wind speed for Taiaroa Heads.

The convolved pdf of 3-hourly values can be transformed into the pdf of annual maximum sea level using the following formula:

$$G(y) = \Pr[\max(Y_1 .. Y_N) <= y)] = [\Pr(Y <= y)]^{N\theta} = F_Y(y)^{N\theta}$$

where G(y) is the cumulative distribution function (CDF) of the annual maximum series, $F_Y(y)$ is the CDF of the 3-hourly series, N = 365*(24/3) is the number of 3-

hourly observations to be combined into the single annual maximum, θ is the extremal index.

A T-year return period storm has probability of occurring p = 1/T in one year. So set

$$G(y) = 1\text{-}p = 1 - 1/T$$

Therefore

$$F_Y(y) = (1 - 1/T)^{1/N\theta}$$

And the sea level height can be read direct from convolved distribution at this quantile for any return period T.

3. Sea-Level Prediction: Results

In this section, we will first discuss the probability density functions for the individual components contributing to extreme sea levels, before presenting the results of the combined effects (i.e. the pdf for extreme sea level events) in section 3.4.

3.1. The storm surge PDF

The plots below (Figures 3.1 and 3.2) show the fitted distributions for the tail of the storm surge cumulative distribution function (cdf). The plots show the empirical cdf derived from annual maxima of the storm surge time series together with the fitted extreme cdf. Note that there may be some discrepancies between the empirical and fitted distribution because the r-largest values, rather than just the single annual maximum value, were used to fit the distributions.

The amount of clustering present in extreme values of storm surge was calculated using the extremal index θ, which is dependent on the threshold height of the storm surge. Where a value for θ is required within the available data range, the empirical value can be used. For surge height we find $\theta(x)$ using a least-squares fit for thresholds greater than 0.45m. The values found are $\theta = 0.5342$ for the Taiaroa Heads series, and $\theta = 0.5371$ for the Dunedin Harbour Series. The least squares fit for the Taiaroa Heads series is shown in Figure 3.3 below.

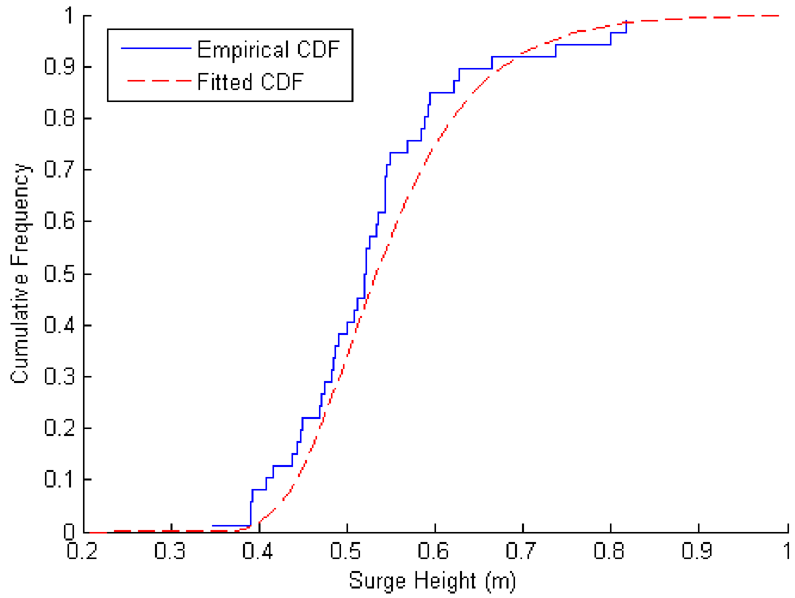

Figure 3.1: Plot of fitted extreme value cdf overlaid on empirical cdf of recorded annual maximum values for open coast sites.

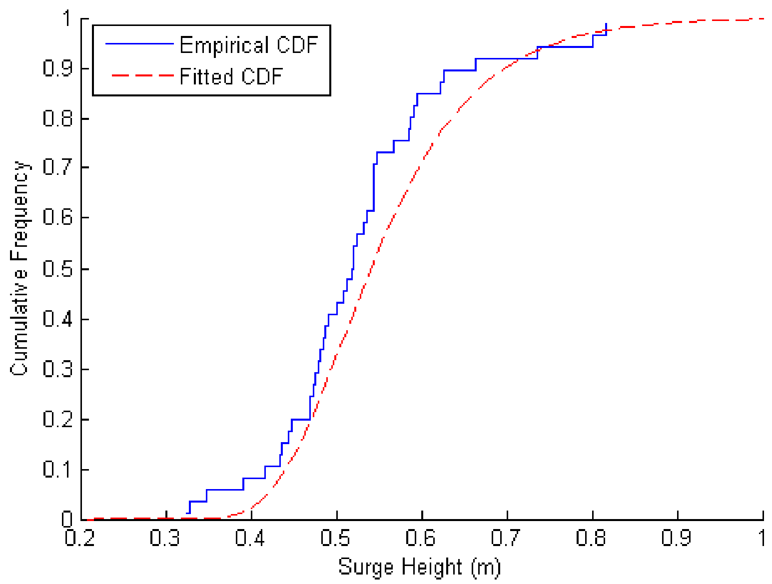

Figure 3.2: Plot of fitted extreme value cdf overlaid on empirical cdf of recorded annual maximum values for Dunedin harbour.

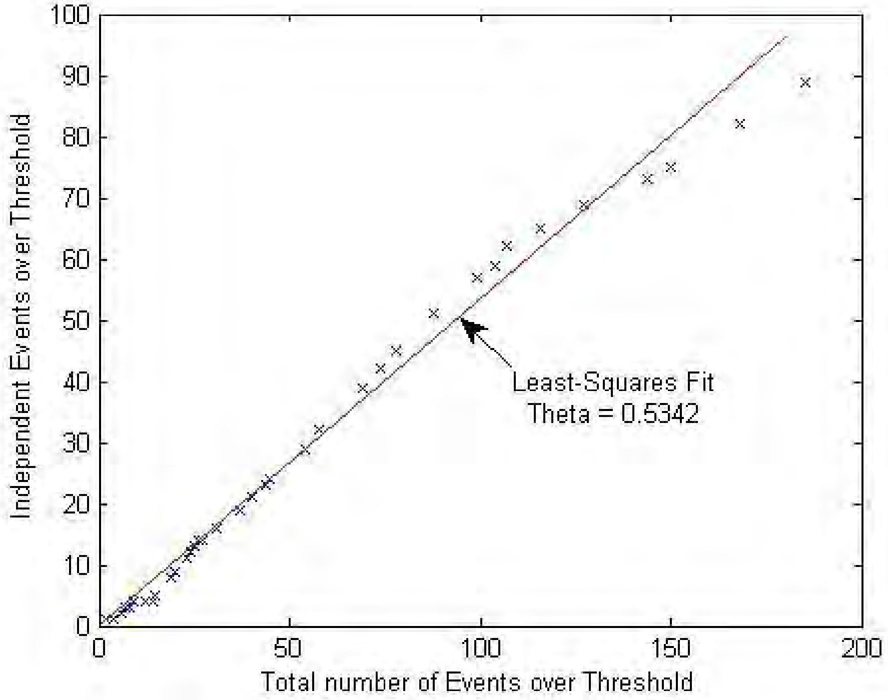

Figure 3.3: Finding θ for extreme values for the Taiaroa Heads series using a least squares fit.

The pdf for the tail was created using the results in the statistical methodology section

$$F_Y(y) = \Pr[\max(Y_1 .. Y_N) <= y)]^{1/N\theta}$$

$$= \exp\left(-\frac{1}{N\theta}\exp\left\{-\frac{y-\mu}{\sigma}\right\}\right) \text{ for } y > Z \text{ (the threshold)}$$

The maximum surge which could occur in New Zealand coastal waters is between 0.8 and 1 m (Heath, 1979), this height being consistent over the whole New Zealand coast (Goring, 1995). The pdf is therefore truncated at a surge height of 1 m to avoid unrealistically large values from the extreme tail of the distribution (see Tawn and Vassie, 1989).

The complete storm surge pdf was created by combining the observed distribution for low storm surges with the derived extreme value distribution for the surge tail. The complete pdf is recorded as a probability density at intervals of 0.01 m. The two functions are shown below (Figures 3.4 and 3.5).

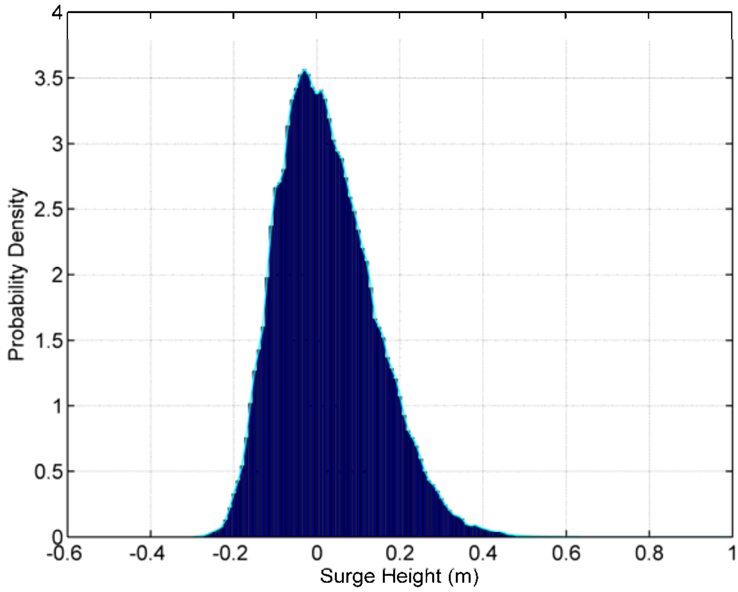

Figure 3.4: The complete pdf for storm surge height at Taiaroa Heads.

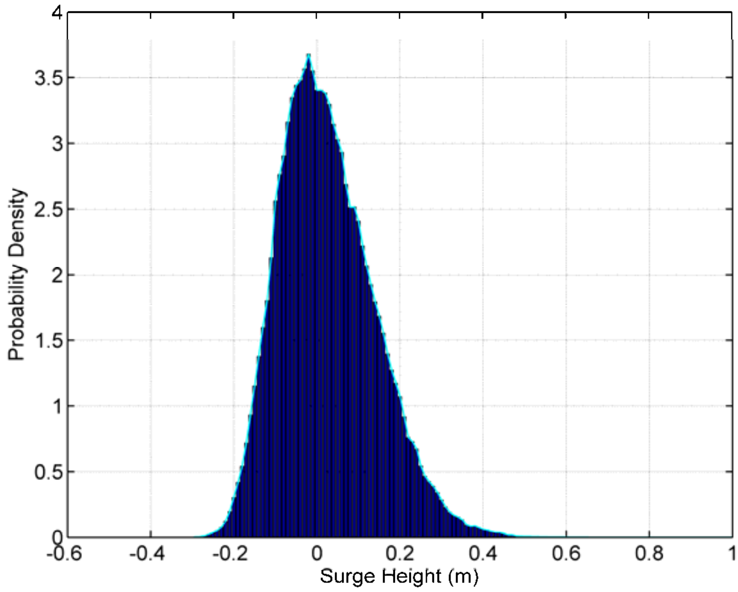

Figure 3.5: The complete pdf for storm surge height at Dunedin Harbour

3.2. The Tide PDF

Nineteen tidal records were created, one for each site of interest. The frequency distribution of tide levels was then plotted as a histogram to form the tidal pdf.

Examples of the tide pdf for Brighton and Dunedin Harbour are shown in Figures 3.6 and 3.7.

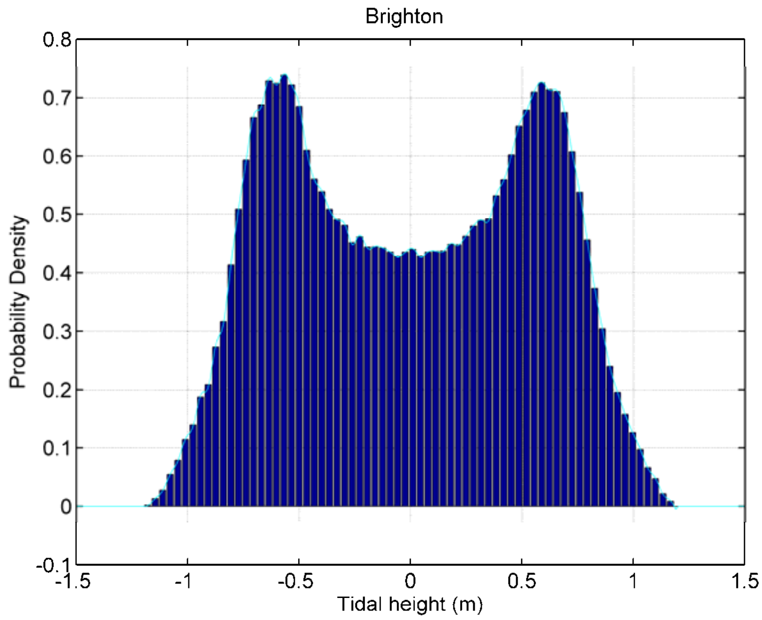

Figure 3.6. The tide pdf for Brighton.

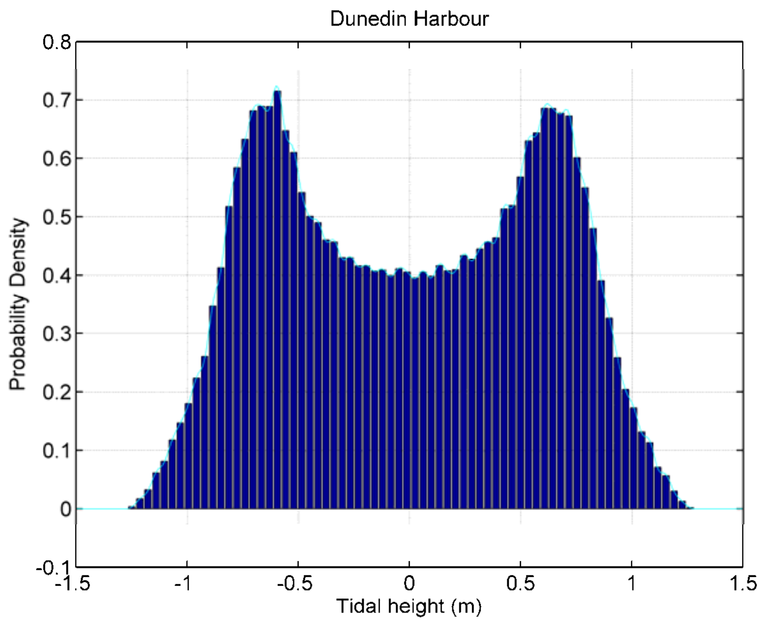

Figure 3.7. The tide pdf for Dunedin Harbour**.**

3.3. The Wave PDF

The wave set-up and run-up pdf's were derived in exactly the same way as the storm surge pdf, and were individually determined for each site of interest to capture the varied wave conditions and shore topography along the coast line. Two examples of wave set-up pdf's for South Dunedin and Oamaru are shown in Figures 3.8 and 3.9.

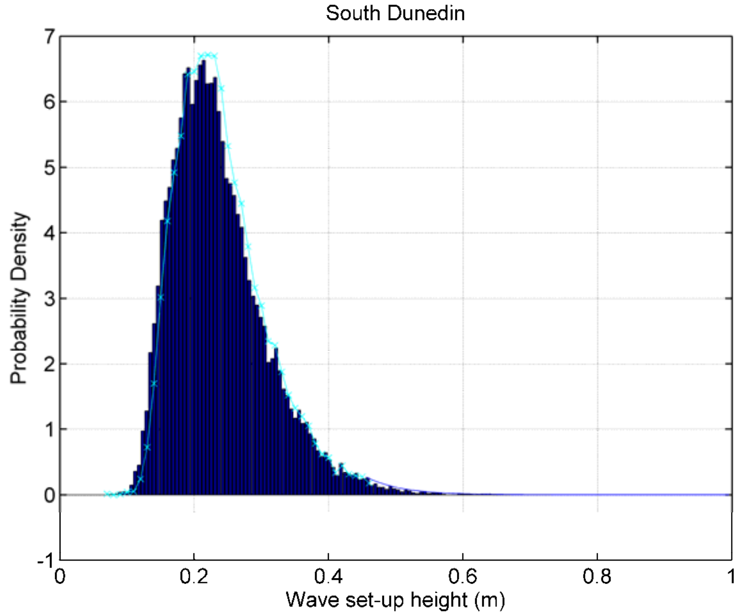

Figure 3.8. Probability density function for wave set-up height at South Dunedin**.**

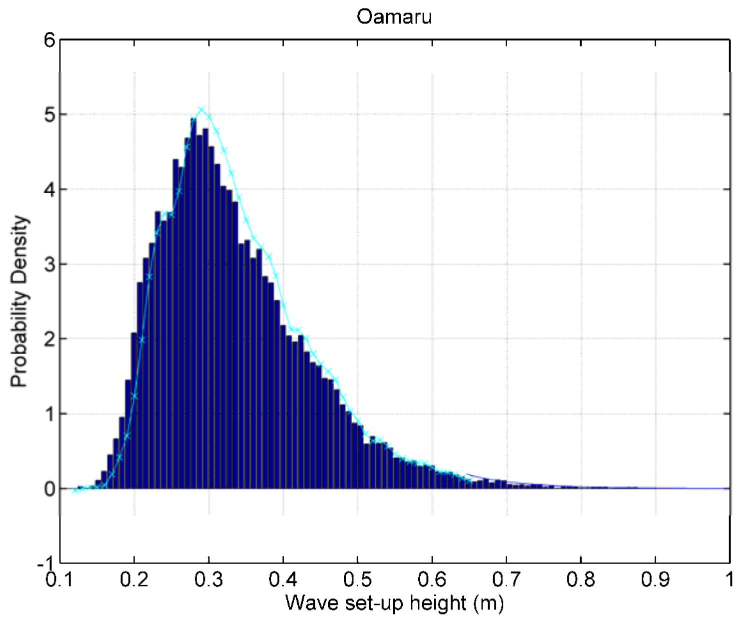

Figure 3.9. Probability density function for wave set-up height at Oamaru.

3.4. Sea level predictions

The extremal index θ for the combined series was found from the sea level record for Dunedin Harbour. As θ should be calculated from a series recorded at the same interval as the combined series, the Dunedin series was sampled at 3-hourly intervals. For high thresholds, θ was found to have a constant value of 1, and hence this value will be used for calculation of extreme sea levels. The reason for this is that clusters of high values are not found as the tide would have receded between 3-hour observations.

The combined sea-level pdf, determined by convolving the tide, storm surge and wave set-up pdf's, was integrated to form a cdf and then converted to a cdf of annual maximum sea level using the formula given in Section 2.6.2. The extreme sea levels calculated for each return period and location are given in Table 3.1. These values are given relative to the mean level of the sea (MLOS), and can be referenced to Dunedin Vertical Datum 1958 by increasing the given values by 0.11 m.

Table 3.1: Predicted extreme sea levels (m above MLOS) for four return periods.

	Return Period			
Location	**20 Years**	**50 Years**	**100 Years**	**500 Years**
Tautuku	1.85	1.91	1.95	2.06
Papatowai	1.78	1.84	1.89	2.00
Catlins	1.77	1.83	1.87	1.99
Kaka Point	1.75	1.81	1.86	1.97
Clutha	2.01	2.08	2.14	2.25
Toko Mouth	2.36	2.45	2.50	2.63
Taieri Mouth	1.79	1.86	1.90	2.01
Brighton	1.87	1.94	1.98	2.09
Kaikorai	1.82	1.88	1.93	2.04
South Dunedin	1.83	1.90	1.94	2.05
Dunedin Harbour	1.66	1.73	1.79	1.91
Long Beach	1.57	1.63	1.68	1.80
Purakanui	1.58	1.64	1.69	1.80
Warrington	1.55	1.61	1.66	1.78
Karitane	1.64	1.71	1.75	1.86
Moeraki	1.60	1.67	1.71	1.83
Hampden	1.84	1.91	1.96	2.07
Kakanui	1.96	2.03	2.08	2.20
Oamaru	2.01	2.08	2.14	2.26

3.4.1. Wave run-up prediction

Heights for wave run-up are calculated separately from sea-level as these indicate a ‘splash zone’ as opposed to inundated area. For each location we use two run-up scenarios, ‘Average Wave Run-up Scenario’ which indicates the median point of the wave run-up pdf, and ‘Maximum Recorded Run-up Scenario’ which is designed to represent the worst-case scenario represented in the recorded series. The results are shown in Table 3.2.

Table 3.2: Wave Run-up Predictions for each Location

	Average Predicted Wave Run-up Scenario (m)	Maximum Predicted Wave Run-up Scenario (m)
Tautuku	0.51	1.38
Papatowai	0.49	1.34
Catlins	0.50	1.36
Kaka Point	0.43	1.30
Clutha	0.51	1.52
Toko Mouth	0.62	1.85
Taieri Mouth	0.45	1.35
Brighton	0.47	1.39
Kaikorai	0.46	1.35
South Dunedin	0.47	1.37
Dunedin Harbour	0.26	0.81
Long Beach	0.22	0.86
Purakanui	0.23	0.86
Warrington	0.24	0.83
Karitane	0.26	0.92
Moeraki	0.28	0.85
Hampden	0.36	1.09
Kakanui	0.44	1.33
Oamaru	0.46	1.38

Tables 3.1 and 3.2 contain the key results of this study, and the values presented form the basis of the inundation mapping presented in Sections 4 and 5. These results are discussed in more detail in Section 6.

4. Inundation Prediction: Data and Methodology

4.1. LiDAR data

Topography data from Light Detection and Ranging (LiDAR) surveys of the seventeen regions of interest in this study were provided by Otago Regional Council. These data provide detailed information of topography adjacent to the coast, and are used to derive digital elevation models (DEM) in GIS. The elevation data are referenced to Dunedin Vertical Datum 1958 (DVD-58).

4.2. Inundation prediction

In order to predict extent and depth of inundation for each region of interest, the predicted extreme sea levels for each return period are propagated inland. This is achieved by overlaying the required sea level onto the DEM surface created from the LiDAR data described above. The difference between the predicted sea level and the DEM provides an estimate of potential inundation extent and depth in the area, which has been mapped with colour coded shading for each individual settlements and regions of interest in Section 5 of this report. For each region, inundation is mapped for each return period, and for each sea level scenario: present-day sea level, sea-level rise of 0.3 m, sea-level rise of 0.5 m.

The high resolution of the LIDAR allows the correct representation of smaller features such as sand-dunes which contain rises in sea level and protect the land behind. However an important caveat to note is that due to the high resolution of the LIDAR data, very precise maps of inundation will be produced. The precision of these maps does not, however, imply an equivalent level of accuracy in the predictions, which may be affected by imprecise knowledge of sea-level phenomena. The simplifying assumptions involved in making the sea-level estimates, and the consequent limitations of the values produced, should be kept in mind when examining and interpreting the maps.

A further caveat is that erosion is not included in the modelling process, and the dynamic adaptation of coastal morphology to changing sea states is not considered. Locations susceptible to inundation following prolonged erosive impact have not been identified in this modelling exercise.

Finally, areas of potential inundation that lie beyond the coverage of the LiDAR data are also marked on the maps. The reliability of these marked areas are much less than inundation predictions in the LiDAR region, simply because the topographic data are less accurate and of much lower resolution. These areas must therefore be treated with considerable caution.

4.3. Wave run-up prediction

For each inundation map, we additionally show the area affected by wave run-up i.e. breaking waves. Locations within these limits are not predicted to be permanently inundated but may be susceptible to breaking surges. We will use a similar process to the inundation mapping to calculate the inland extent of the wave run-up, with one important difference. Wave run-up is solely due to breaking waves and, thus, will not occur in sheltered areas. To account for this we will define an open-coast or surf-zone boundary (e.g., outside bays or harbours) from which the wave run-up will occur. Note that the map legends refer to “Average Run-up Return” and “Maximum Run-up Return”, which indicate run-up extents on top of the return-period inundation.

5. Inundation Prediction: Results

For each settlement of interest, we present below maps of predicted inundation, mean wave run-up and maximum wave run-up for return periods of 20, 50, 100 and 500 years. The calculations are presented for three sea level scenarios: present mean level of the sea (MLOS), MLOS + 0.3 m, and MLOS + 0.5 m.

5.1. Tautuku

Predicted inundation and wave run-up extent for present mean sea level are shown in Figures 5.1 – 5.4, for mean sea level + 0.3 m in Figure 5.5 – 5.8, and for mean sea level + 0.5 m in Figure 5.9 – 5.12.

- Maximum predicted sea level height of 2.06 m above MSOL (= 2.17 m above DVD-58).

- At present-day MLOS, predicted inundation occurs predominantly along the north-eastern bank of Tautuku River and on the Tautuku peninsula. Potential inundation extends further upstream than the LiDAR coverage. The southern bank of the river remains clear of inundation.

- Wave run-up is largely confined to the shoreline but the maximum run-up does penetrate a little way inland at the headland to the north of the river mouth. However, this prediction is open to question, since it is not entirely clear whether the waves are running-up from the east, in which case the mapped run-up may be realistic, or from the south, in which case the predicted run-up is less likely to be realistic.

- Rising sea levels increase the extent and depth of inundation along the north bank of the river and on the peninsula, but the south bank of the river remains free of inundation.

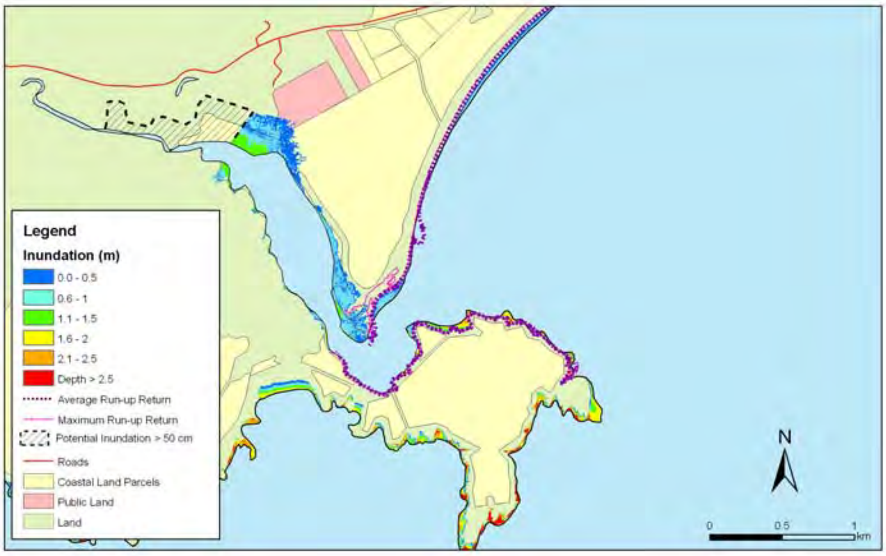

Figure 5.1: Tautuku - 1:20 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

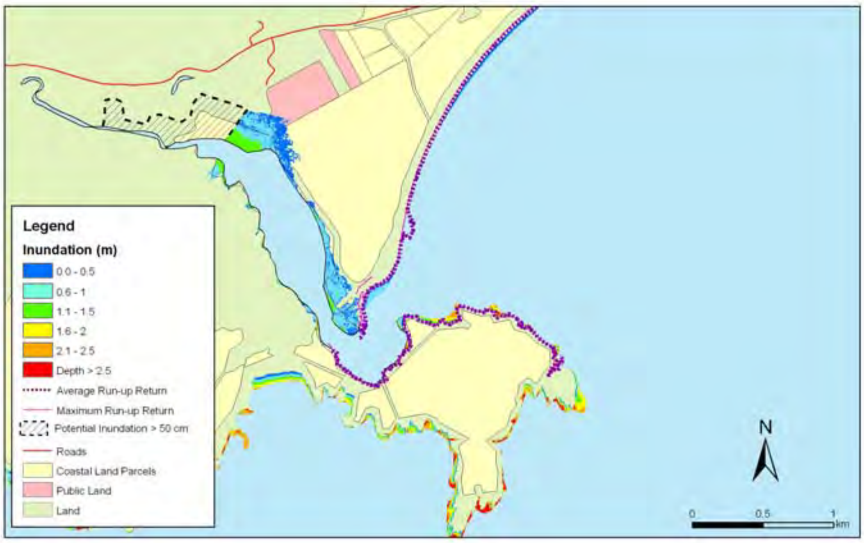

Figure 5.2: Tautuku - 1:50 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

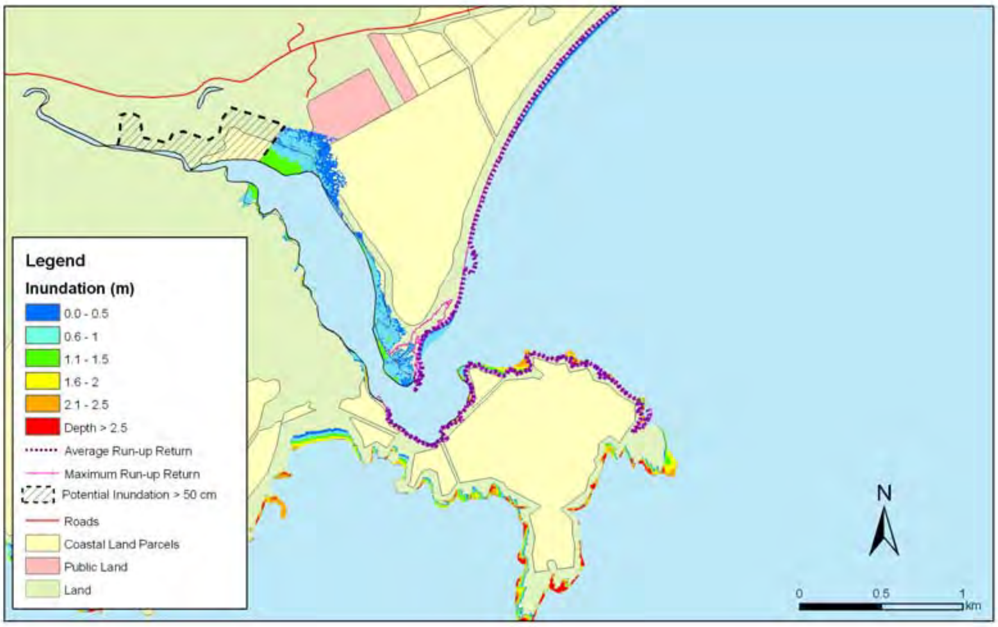

Figure 5.3: Tautuku - 1:100 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

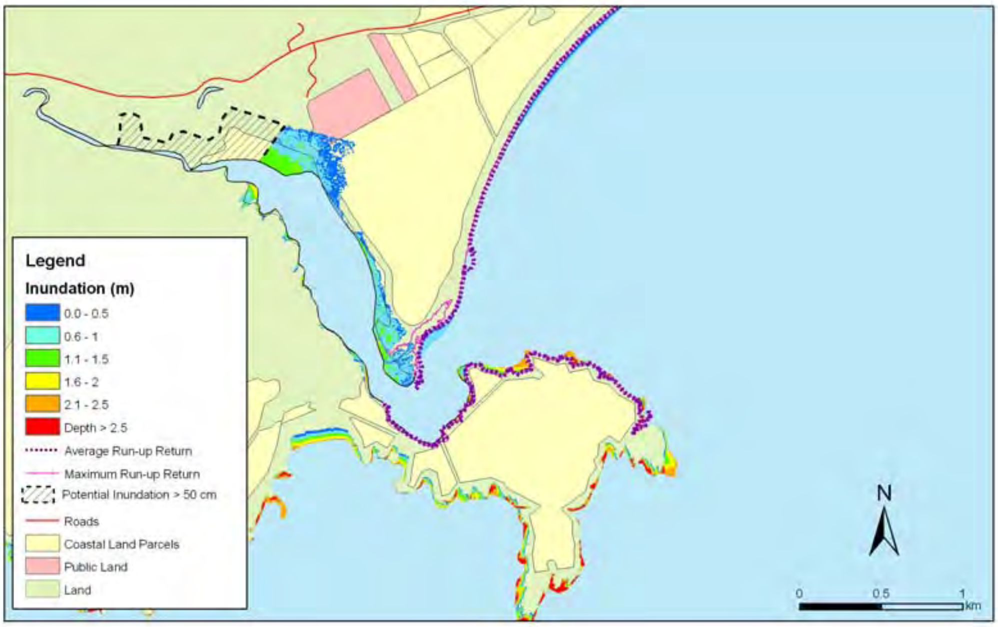

Figure 5.4: Tautuku - 1:500 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up**.**

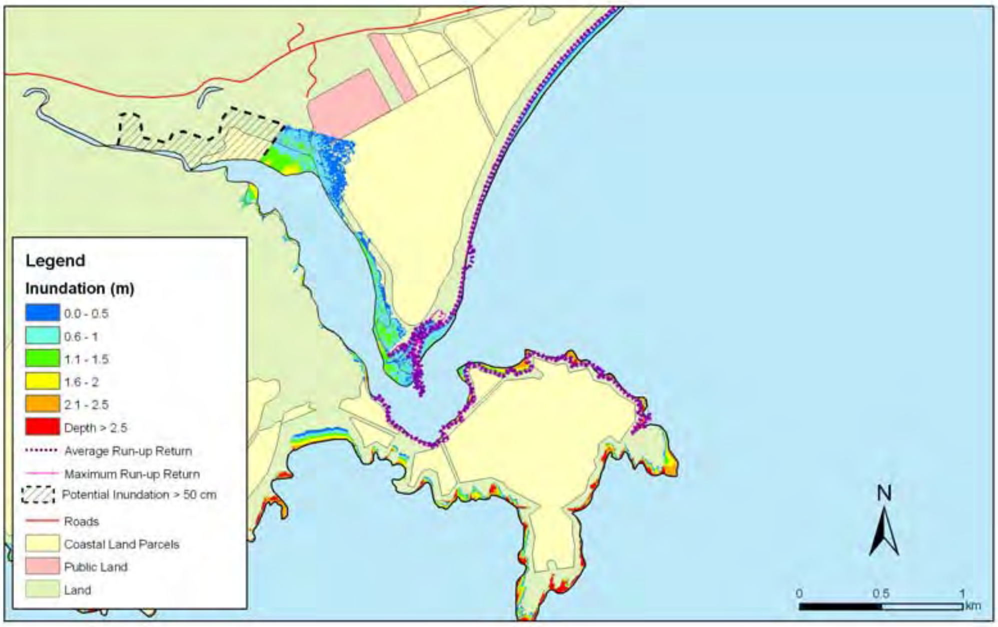

Figure 5.5: Tautuku - 1:20 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

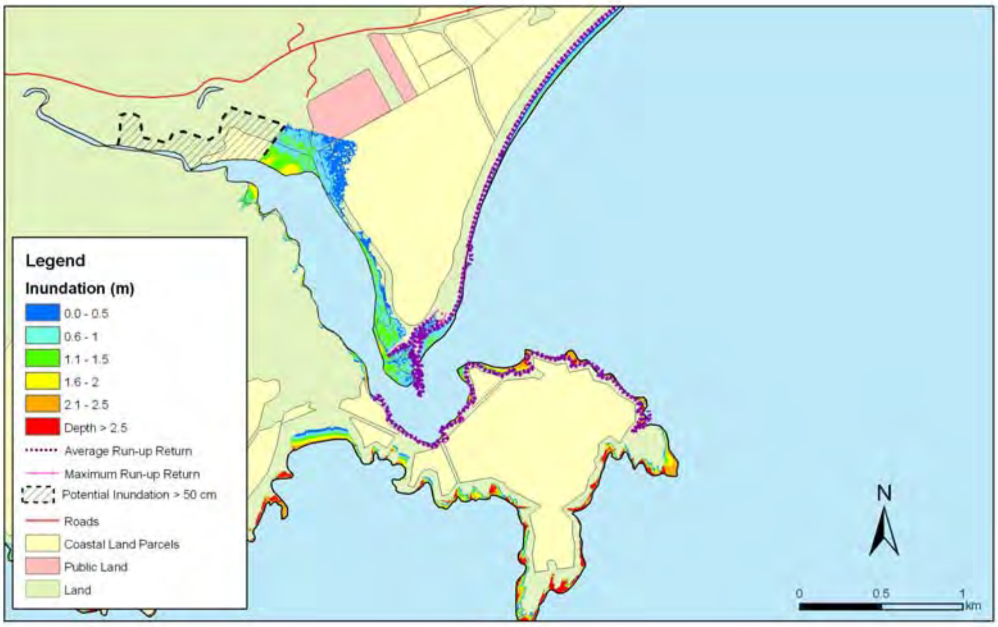

Figure 5.6: Tautuku - 1:50 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

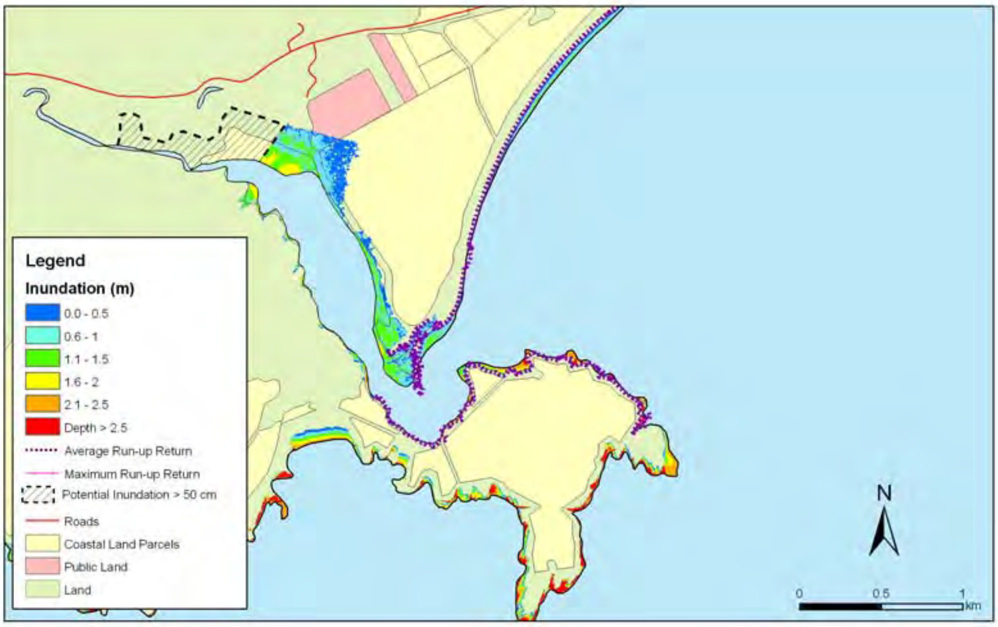

Figure 5.7: Tautuku - 1:100 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

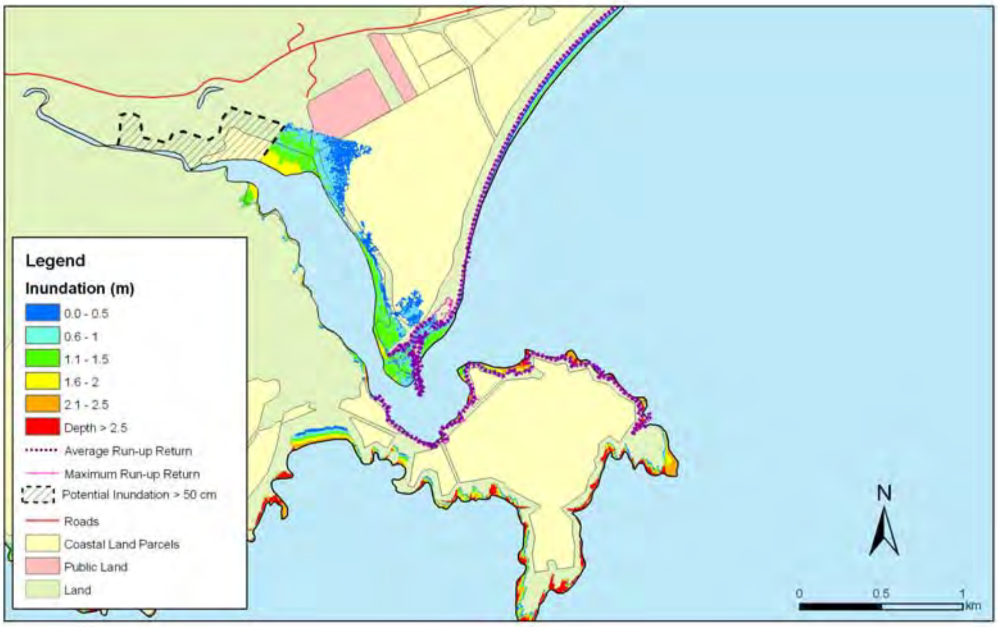

Figure 5.8: Tautuku - 1:500 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

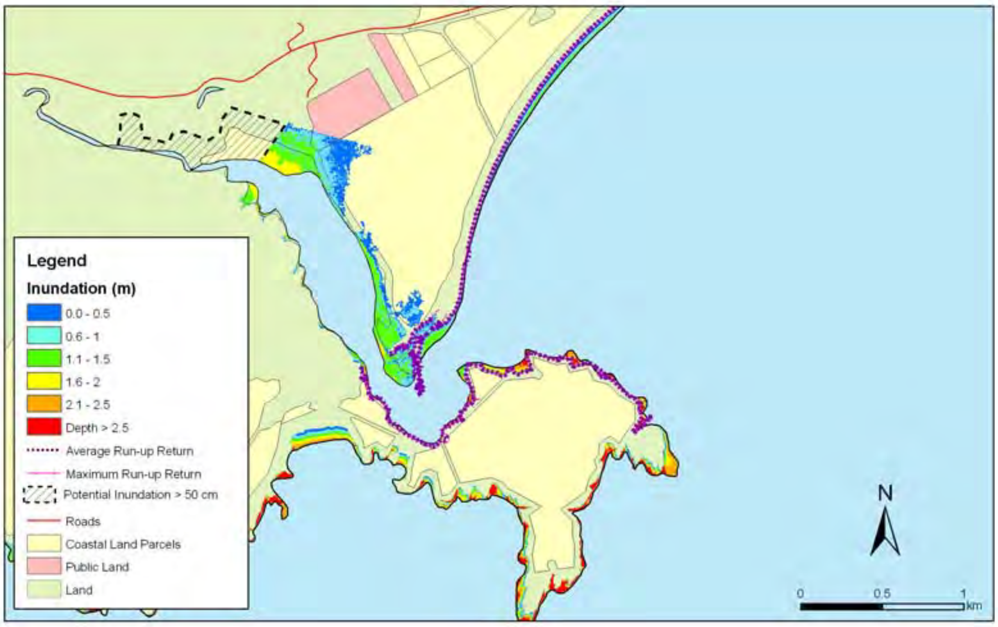

Figure 5.9: Tautuku - 1:20 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

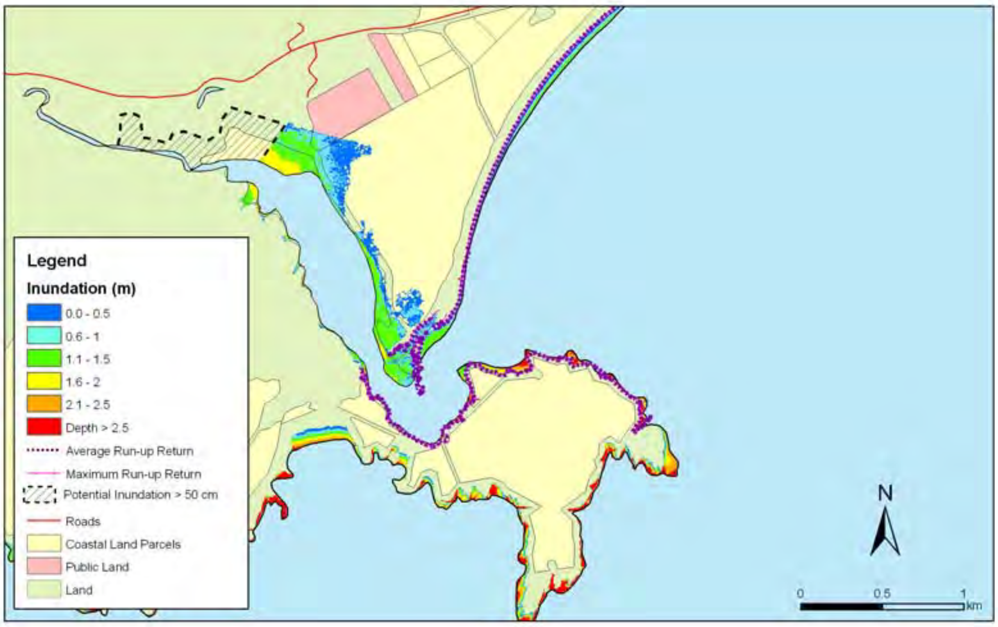

Figure 5.10: Tautuku - 1:50 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

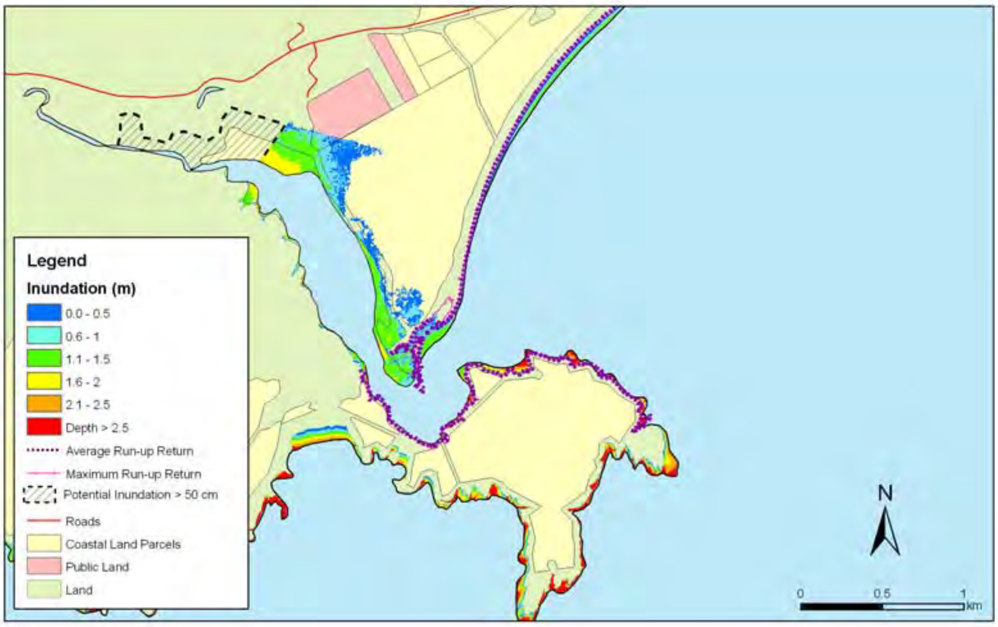

Figure 5.1: Tautuku - 1:100 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

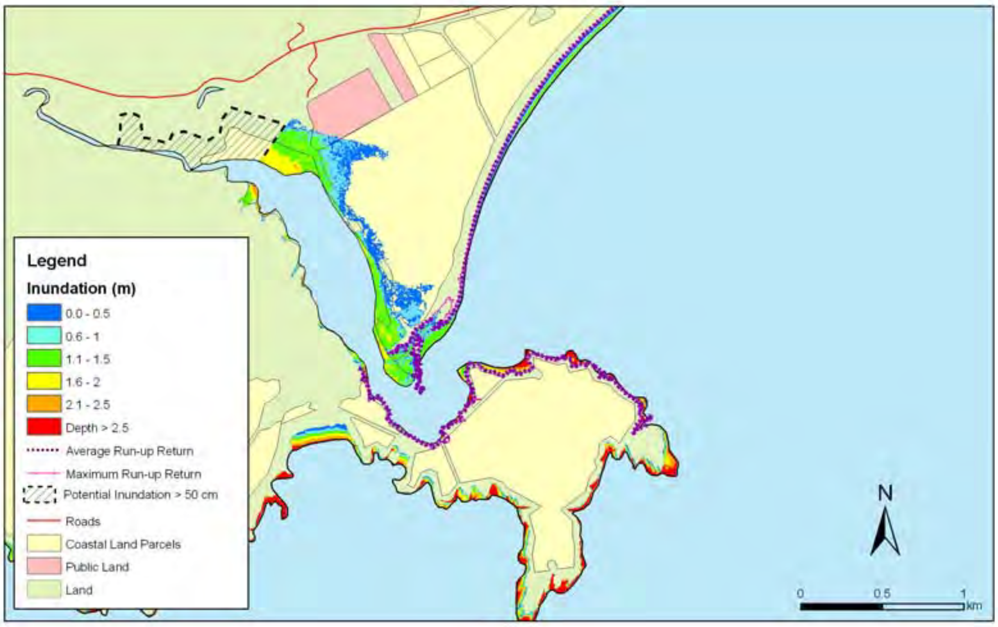

Figure 5.12: Tautuku - 1:500 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

5.2. Papatowai

Predicted inundation and wave run-up extent for present mean sea level are shown in Figures 5.13 – 5.16, for mean sea level + 0.3 m in Figure 5.17 – 5.20, and for mean sea level + 0.5 m in Figure 5.21 – 5.24.

- Maximum predicted sea level height of 2.00 m above MLOS (= 2.11 m above DVD-58).

- Inundation is predicted along both banks of the Tahakopa River. There is very limited inundation along the coastline. Potential areas of inundation, that lie outside the coverage of the LiDAR data, are also marked. These areas are quite extensive to the west of the river.

- Wave run-up is confined to the beach front.

- The depth of inundation increases slightly with increasing return period and with rising sea level. However, the extent of the inundation and wave run-up does not increase significantly.

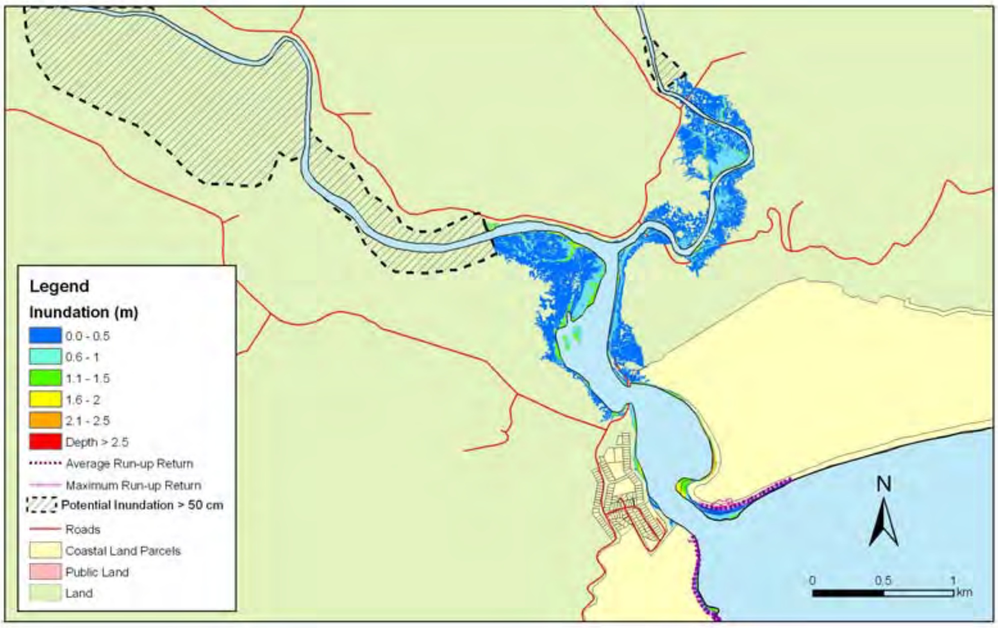

Figure 5.13: Papatowai - 1:20 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

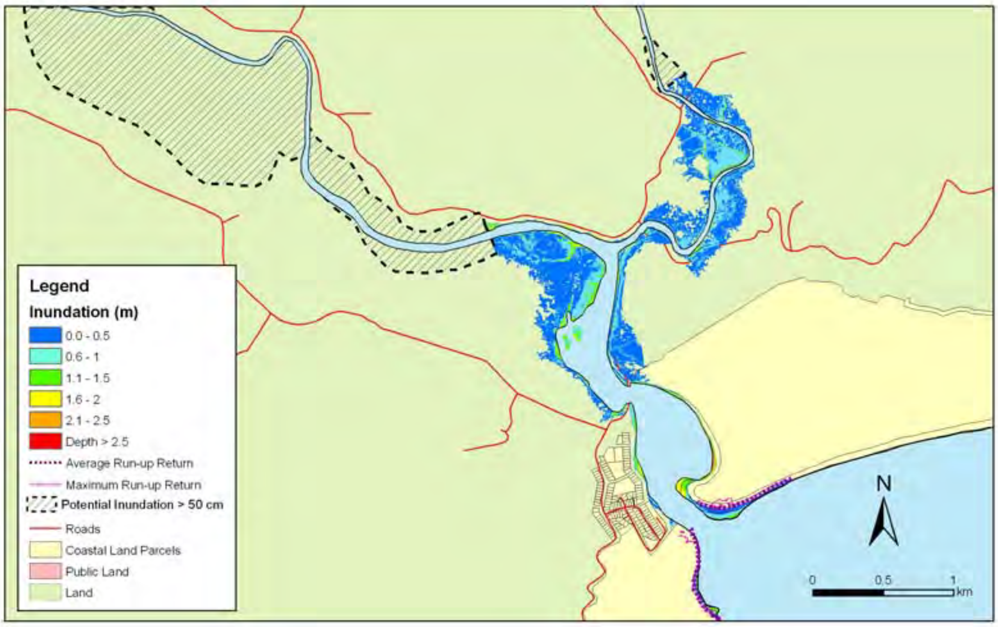

Figure 5.14: Papatowai - 1:50 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

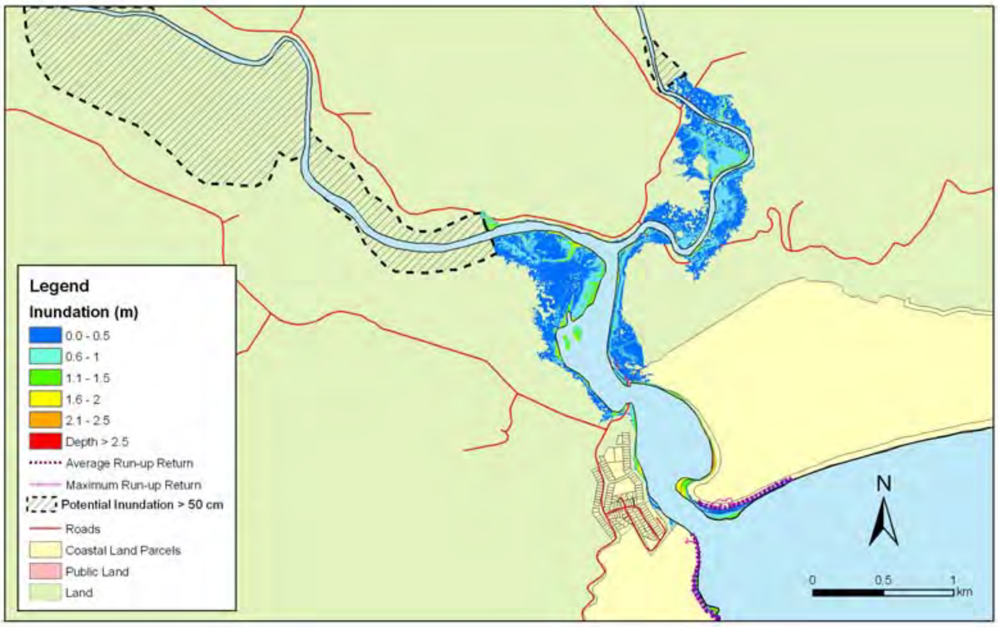

Figure 5.15: Papatowai - 1:100 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

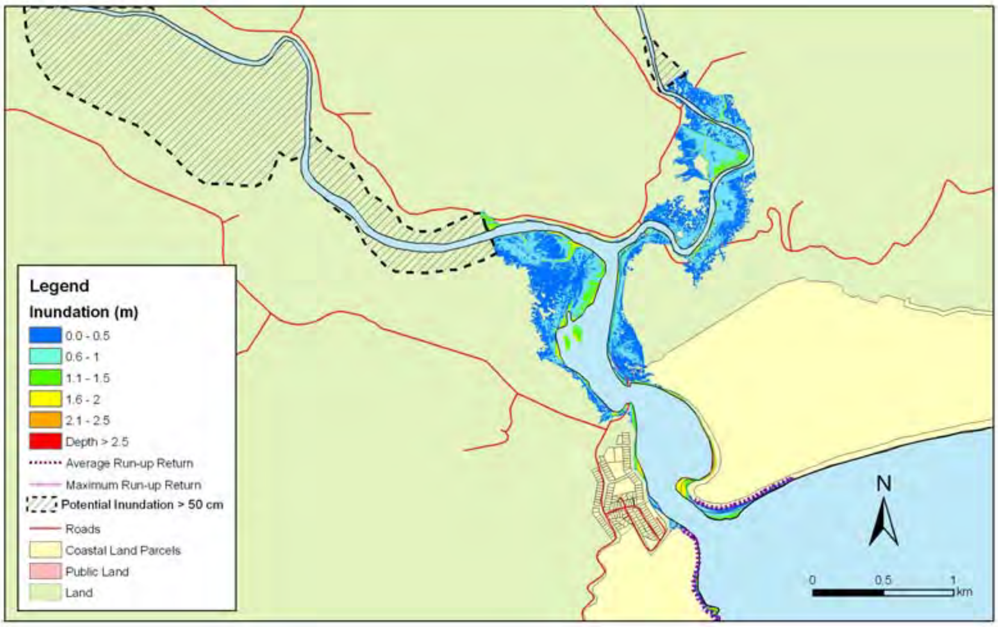

Figure 5.16: Papatowai - 1:500 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

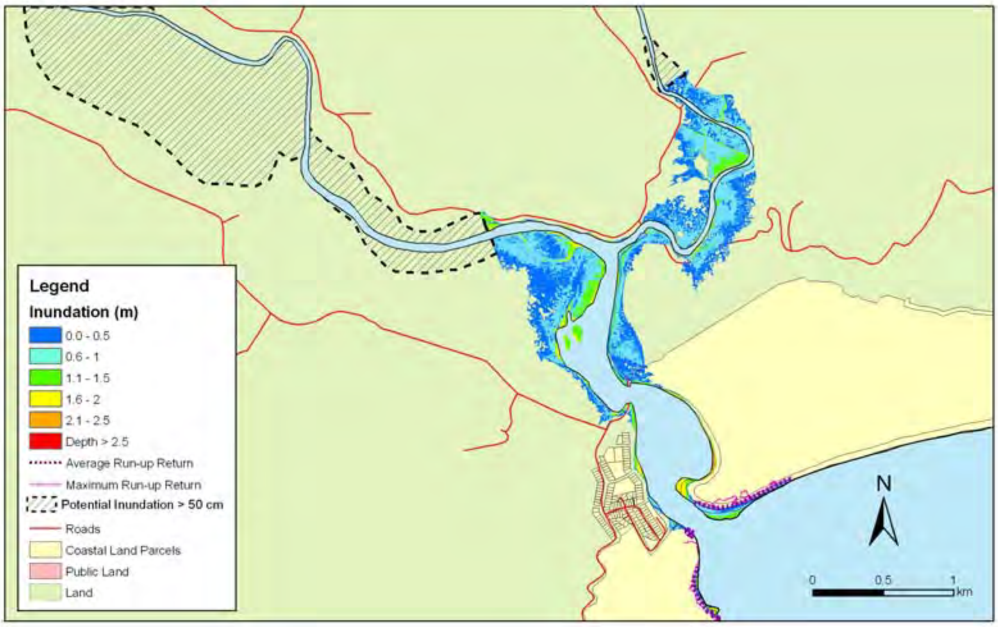

Figure 5.17: Papatowai - 1:20 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

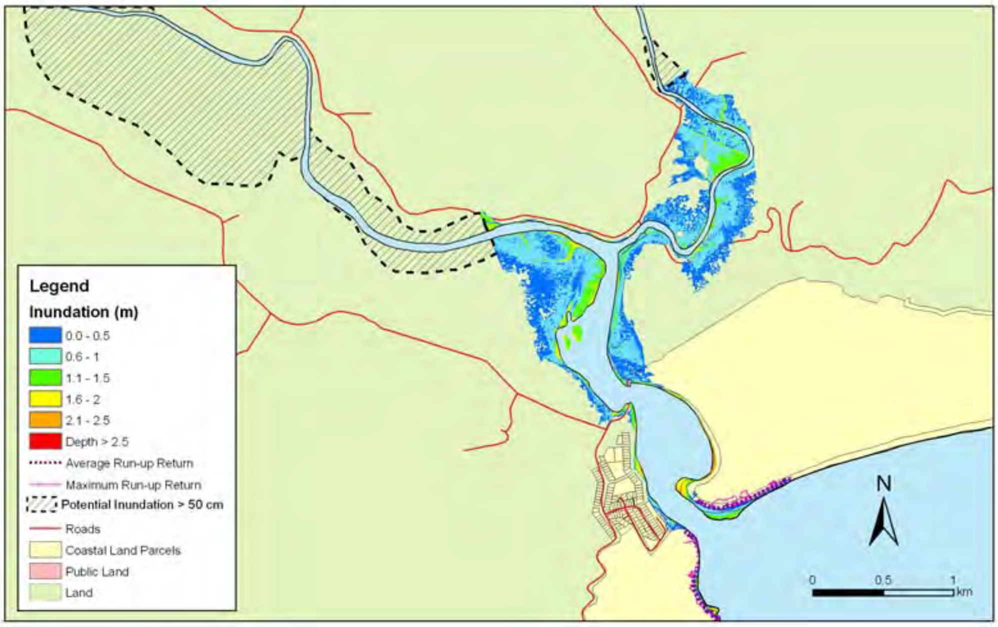

Figure 5.18: Papatowai - 1:50 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

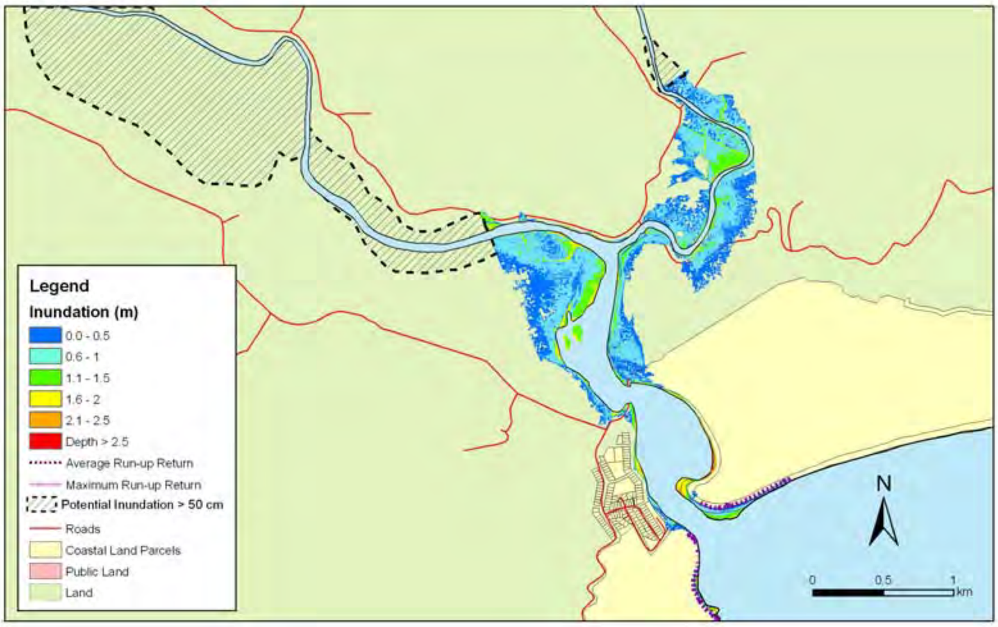

Figure 5.19: Papatowai - 1:100 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

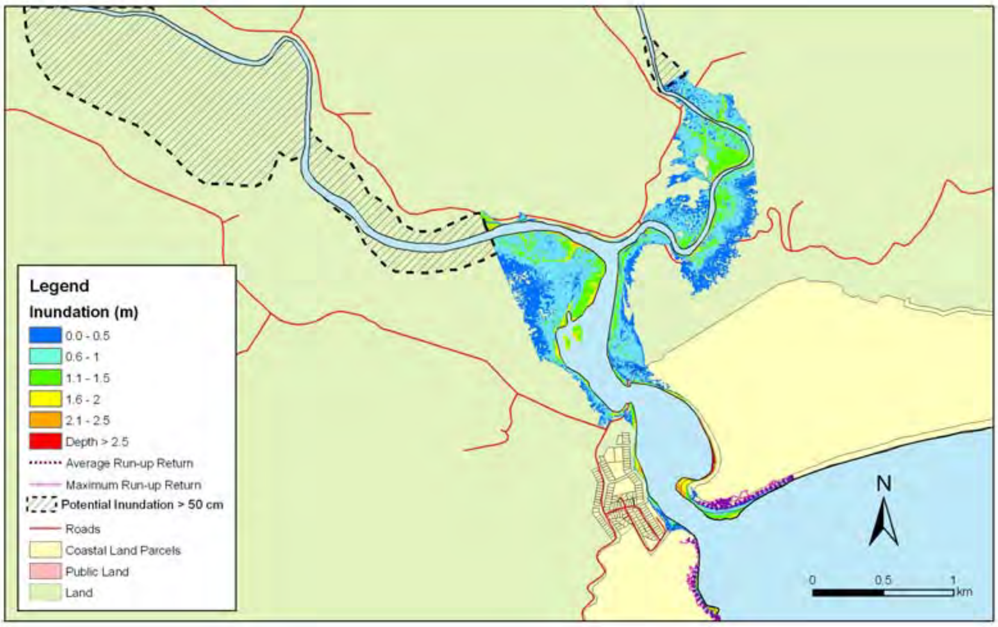

Figure 5.20: Papatowai - 1:500 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

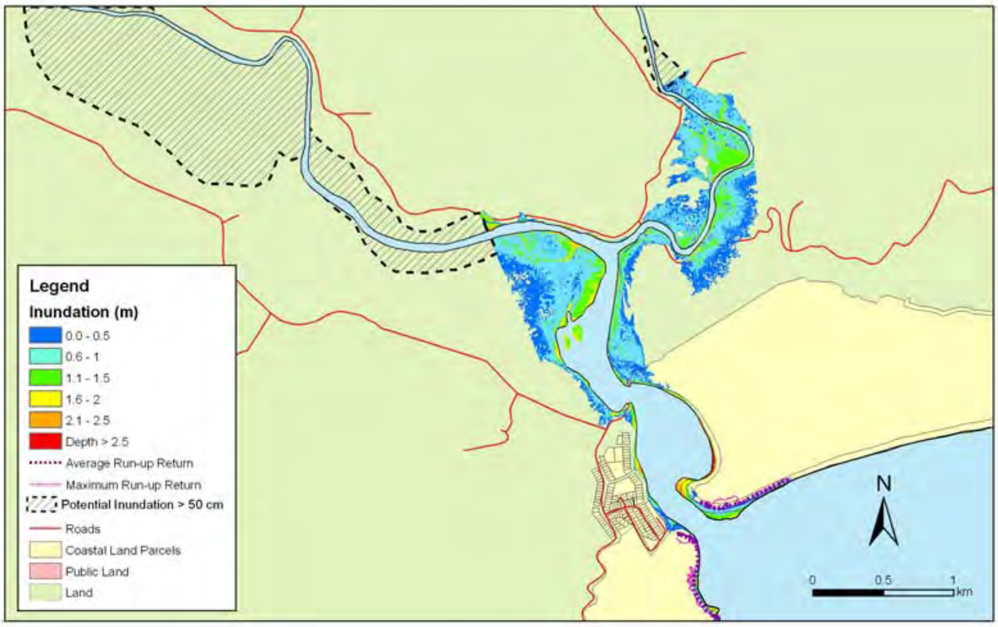

Figure 5.21: Papatowai - 1:20 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

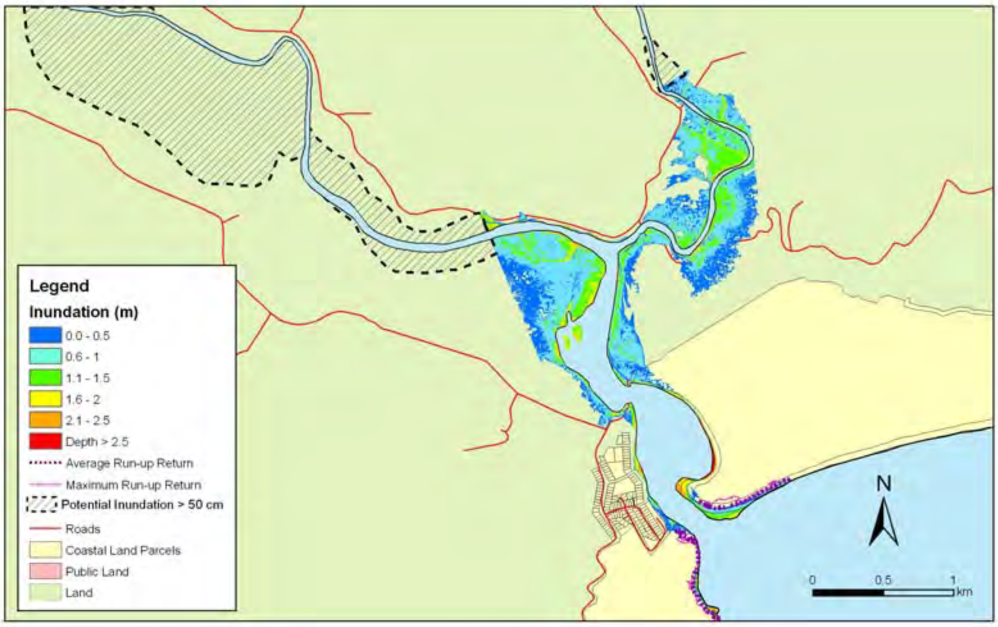

Figure 5.22: Papatowai - 1:50 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

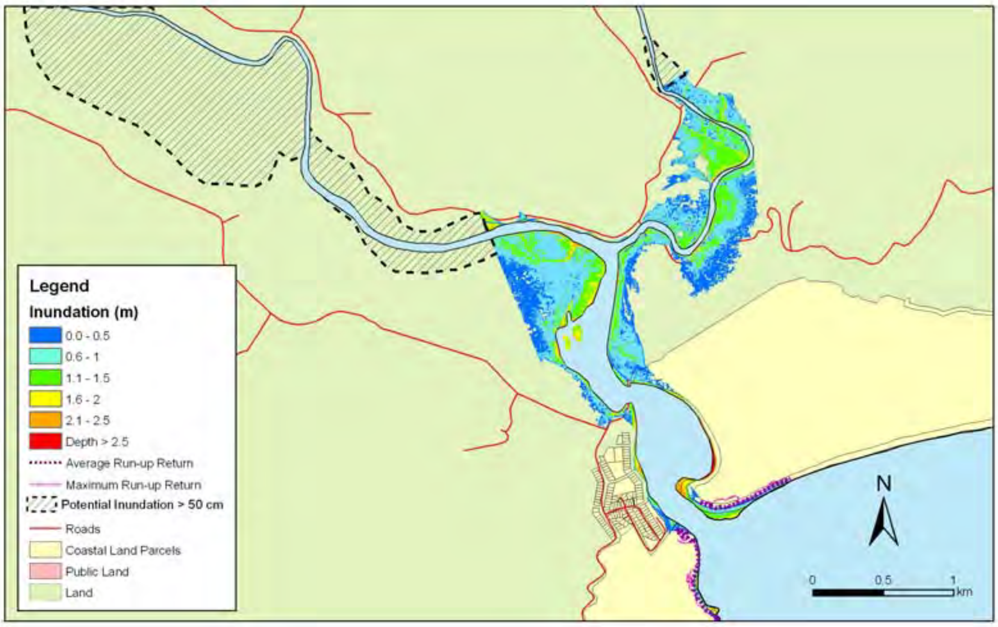

Figure 5.23: Papatowai - 1:100 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

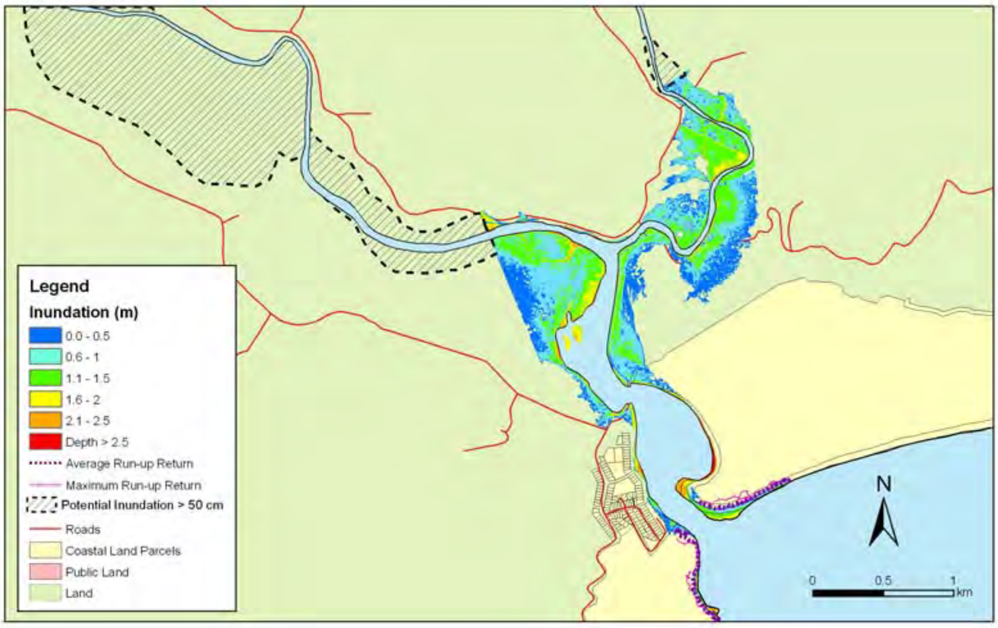

Figure 5.24: Papatowai - 1:500 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

5.3. Catlins

Predicted inundation and wave run-up extent for present mean sea level are shown in Figures 5.25 – 5.28, for mean sea level + 0.3 m in Figure 5.29 – 5.32, and for mean sea level + 0.5 m in Figure 5.33 – 5.36.

- Maximum predicted sea level height of 1.99 m above MLOS (2.10 m above DVD-58).
- At present MLOS, predicted inundation is predicted along the banks of the Catlins River on both shores. The land to the south is particularly affected.
- Wave run-up is confined to the coastline.
- Rising sea level exacerbates the depth of inundation, although the extent is not significantly increased.

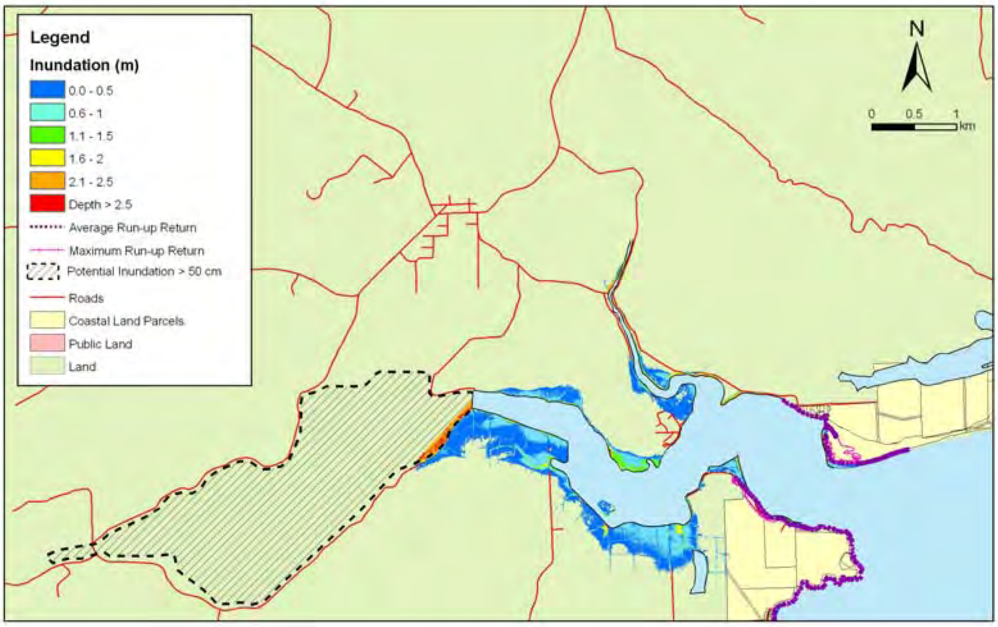

Figure 5.25: Catlins - 1:20 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

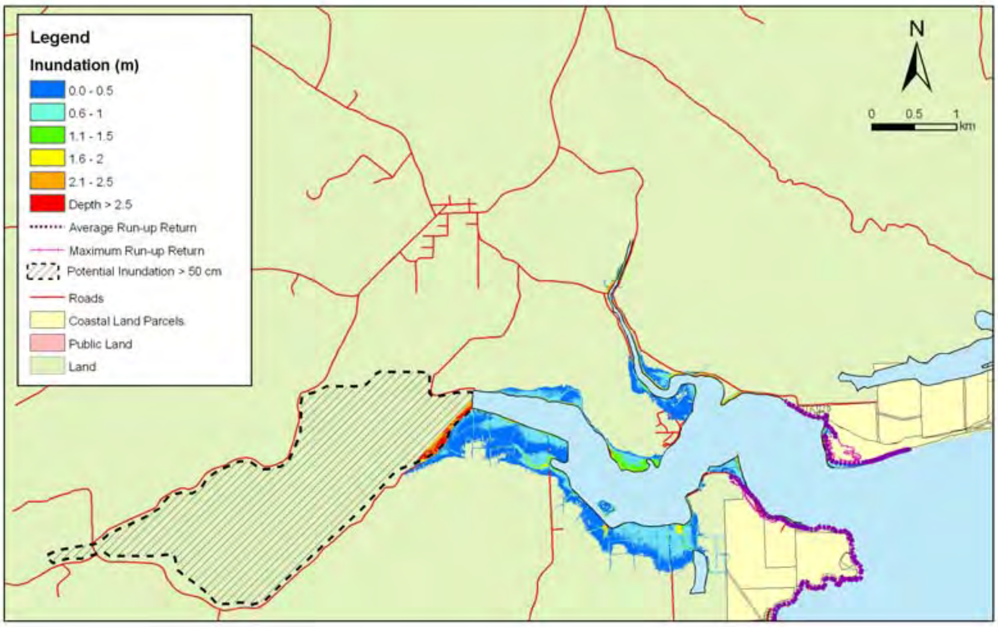

Figure 5.26: Catlins - 1:50 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

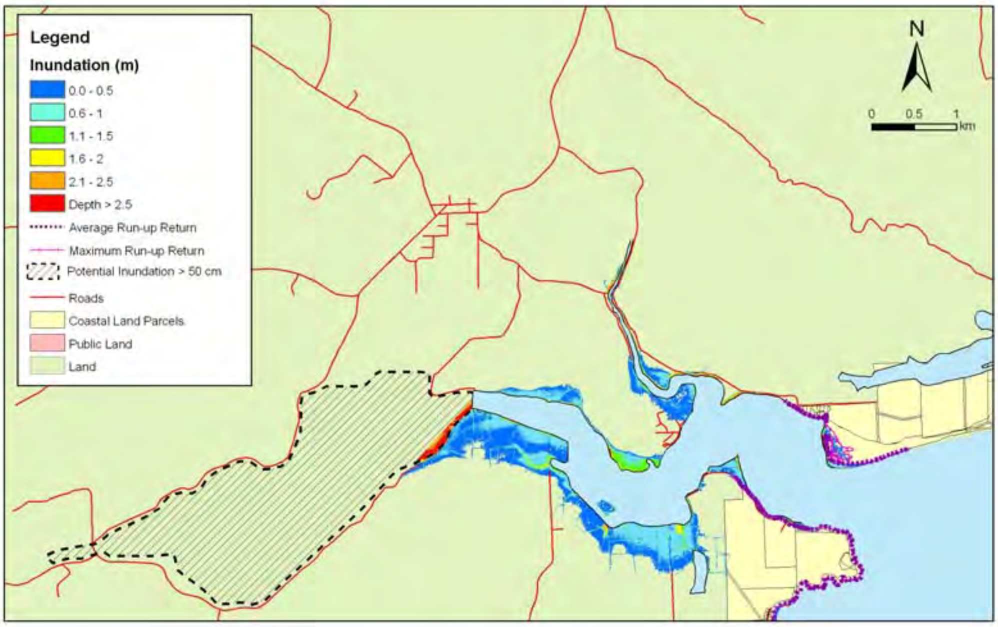

Figure 5.27: Catlins - 1:100 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

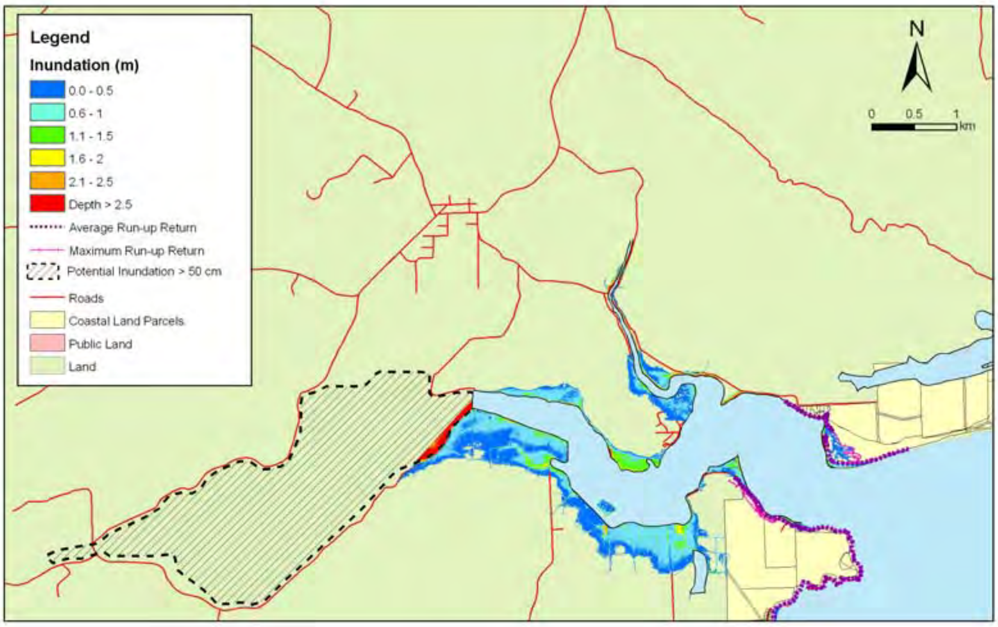

Figure 5.28: Catlins - 1:500 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

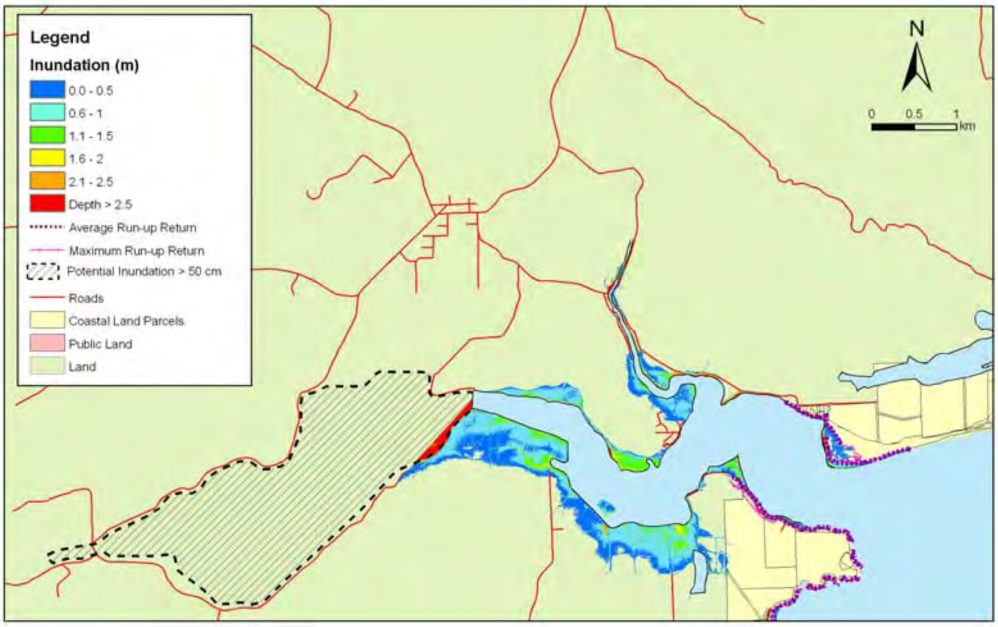

Figure 5.29: Catlins - 1:20 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

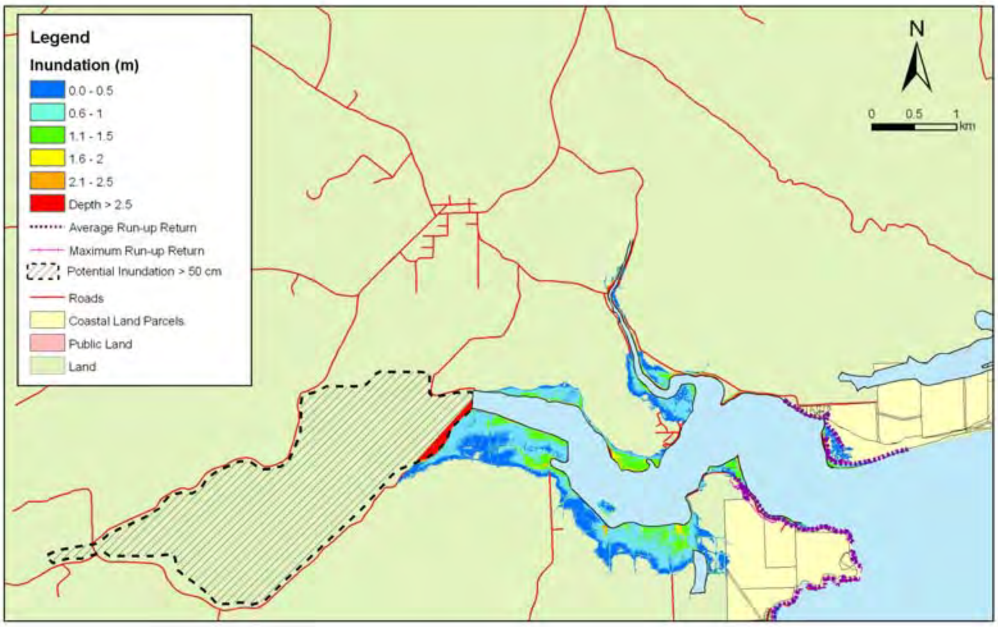

Figure 5.30: Catlins - 1:50 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

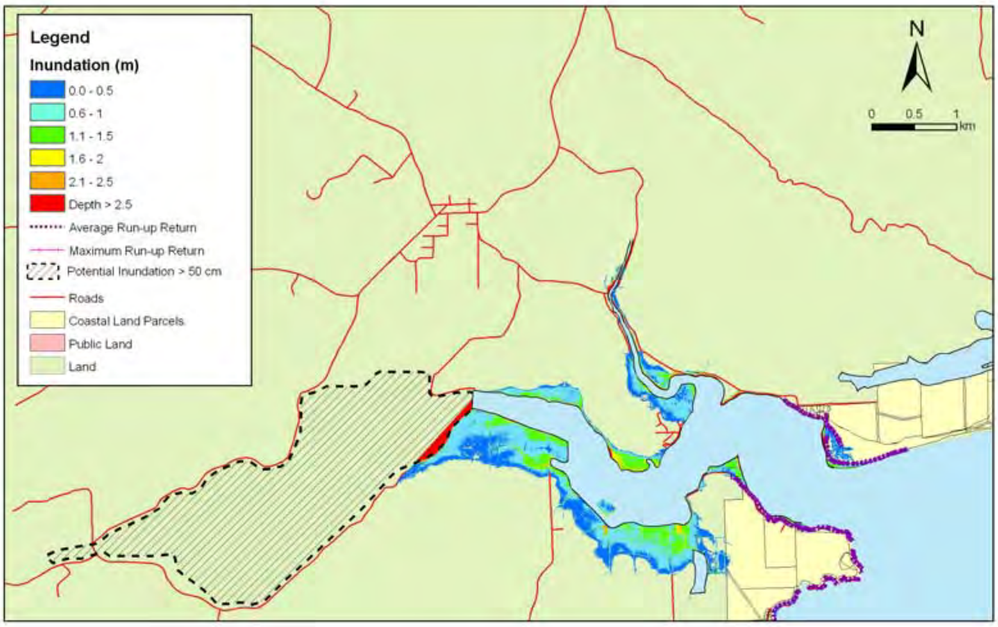

Figure 5.31: Catlins - 1:100 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

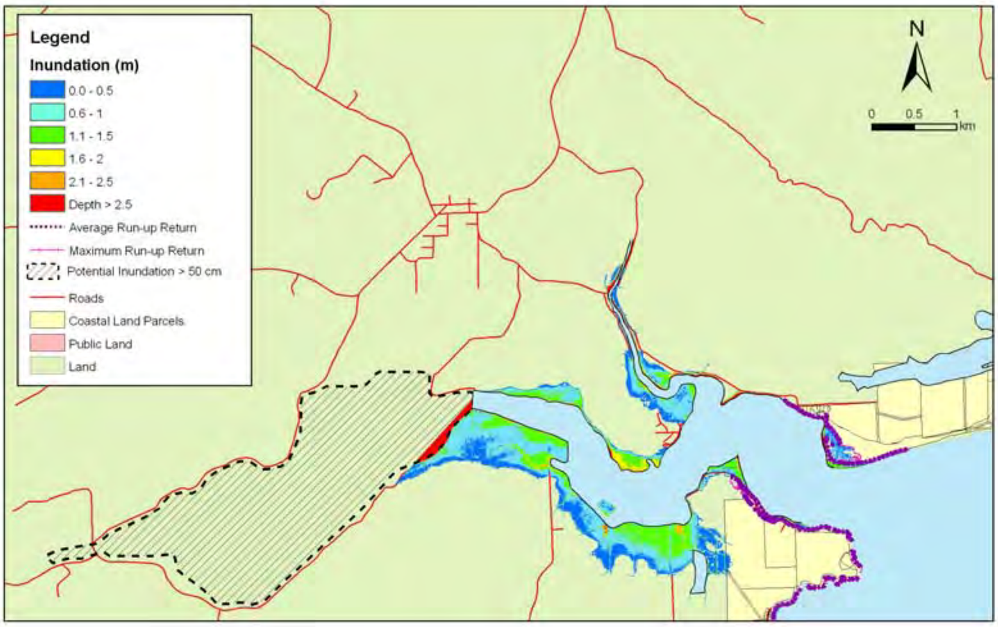

Figure 5.32: Catlins - 1:500 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

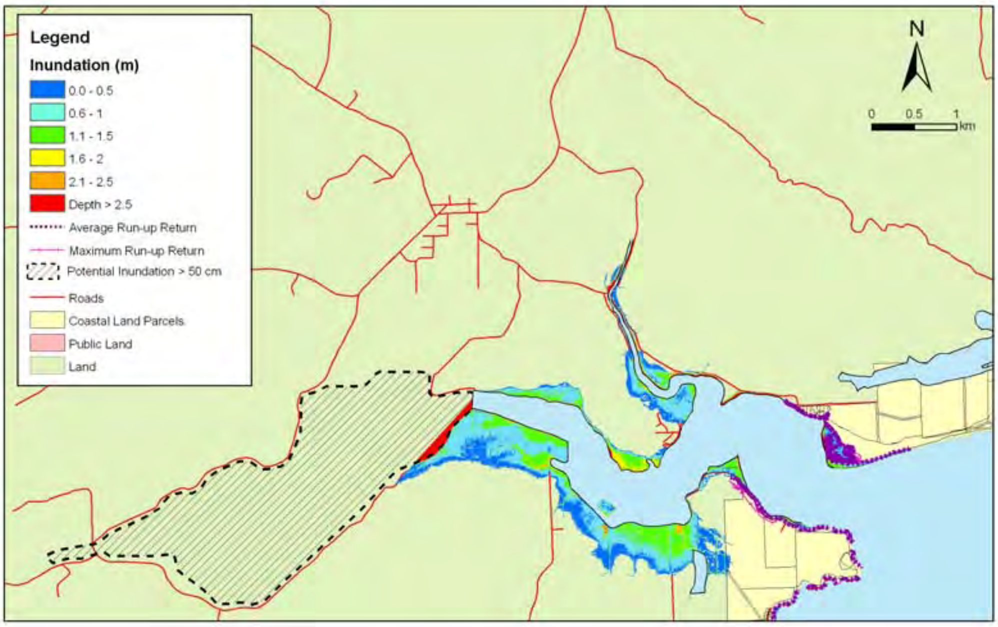

Figure 5.33: Catlins - 1:20 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up**.**

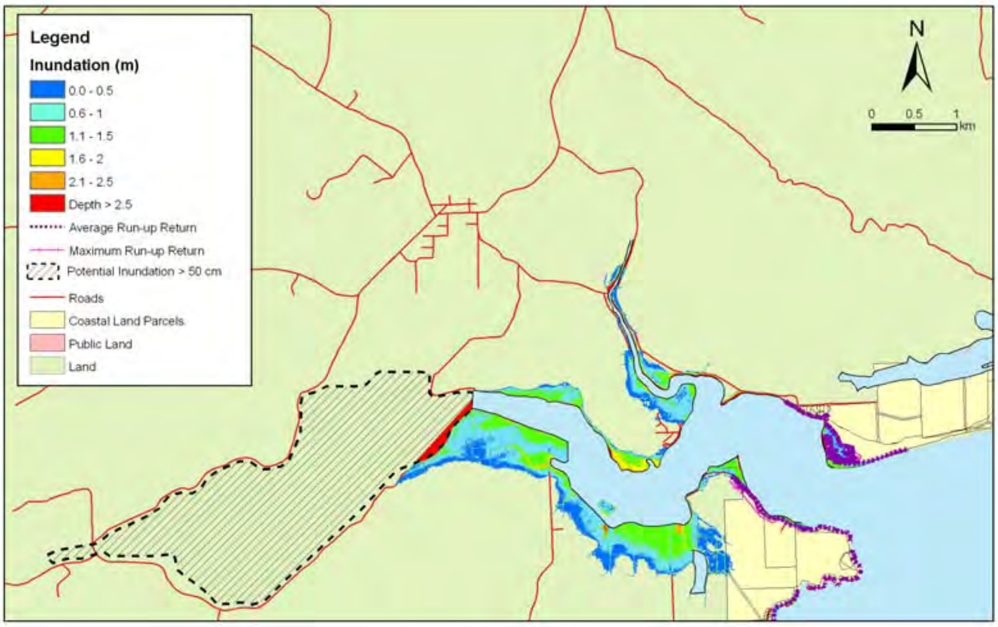

Figure 5.34: Catlins - 1:50 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

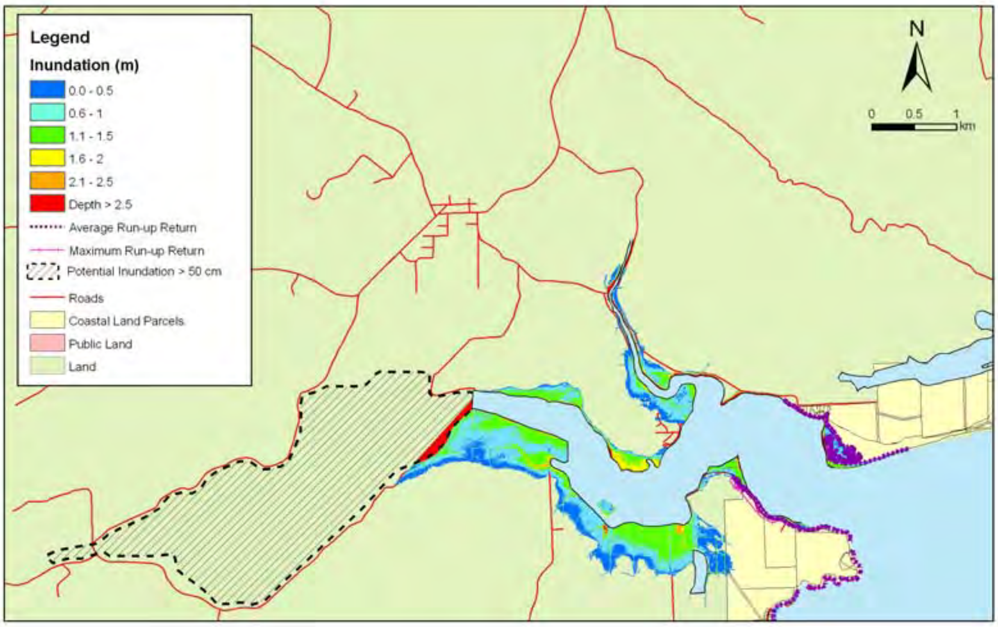

Figure 5.35: Catlins - 1:100 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

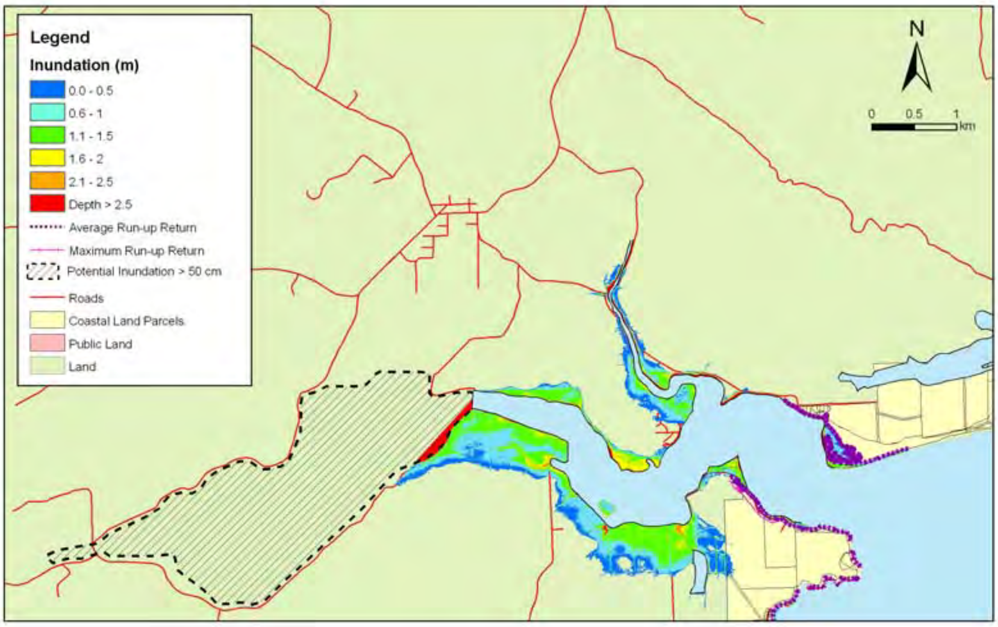

Figure 5.36: Catlins - 1:500 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up

5.4. Kaka Point and Clutha

Predicted inundation and wave run-up extent for present mean sea level are shown in Figures 5.37 – 5.40, for mean sea level + 0.3 m in Figure 5.41 – 5.44, and for mean sea level + 0.5 m in Figure 5.45 – 5.48.

- Maximum predicted sea level height of 2.25 m above MLOS (2.36 m above DVD-58) at Clutha and 1.97 m above MLOS (2.08 m above DVD-58) at Kaka Point.

- Predicted inundation is confined to a strip about 0.5 km across immediately inshore of the coastline and along the banks of the Clutha. The flood defences prevent further inundation (N.B. the LiDAR data do not fully resolve the flood banks, but for the purposes of this study, we have assumed that the flood banks are in good repair and effective at retaining floodwater). Erosion processes are not included in this modelling process, and therefore areas which may be susceptible to erosion are represented as resilient features in the model due to the fixed topographic bed.

- Wave run-up effects are confined to the coastline.

- Rising sea levels increase the depth of inundation but do not increase its extent.

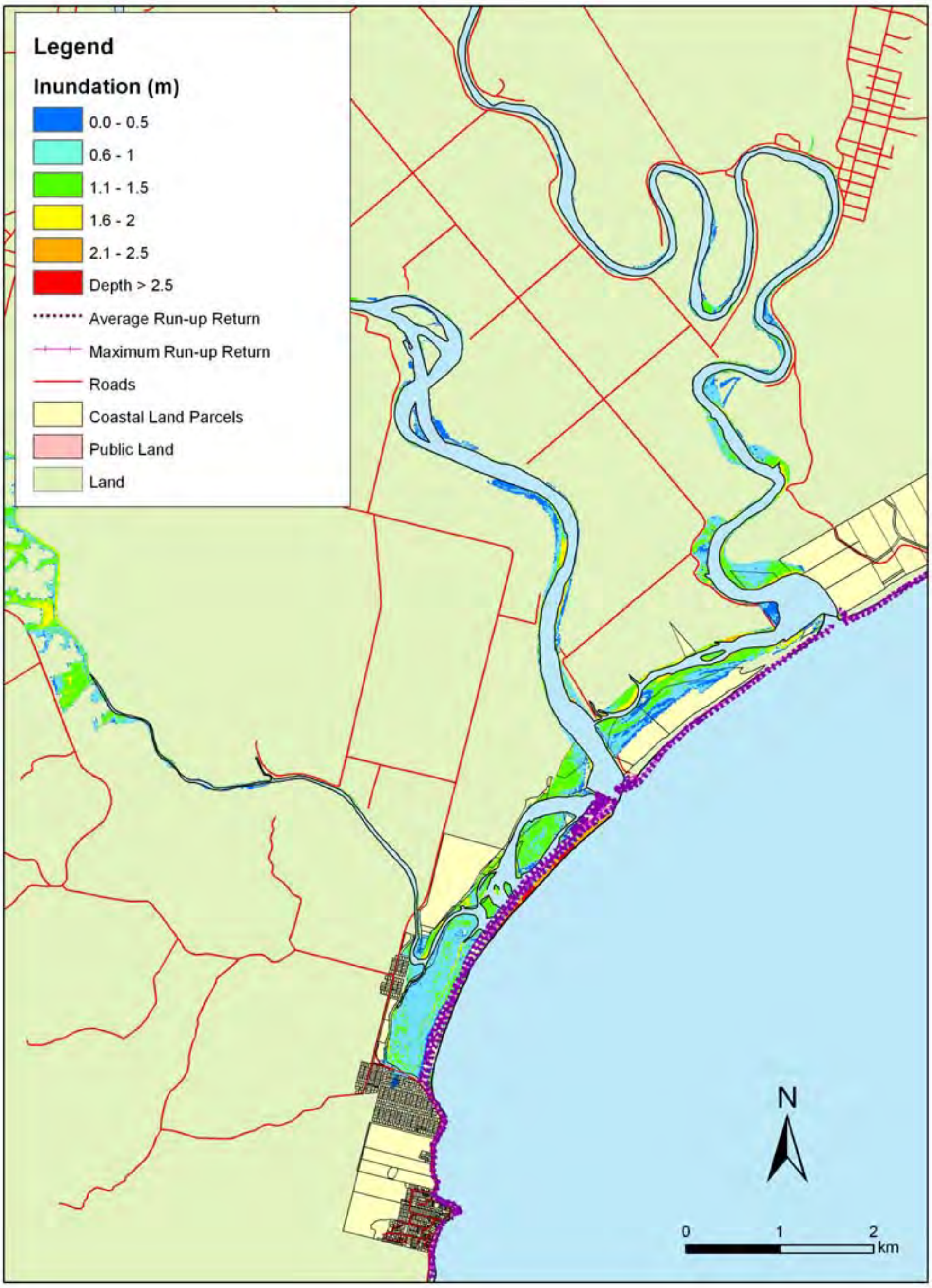

Figure 5.37: Kaka Point and Clutha - 1:20 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

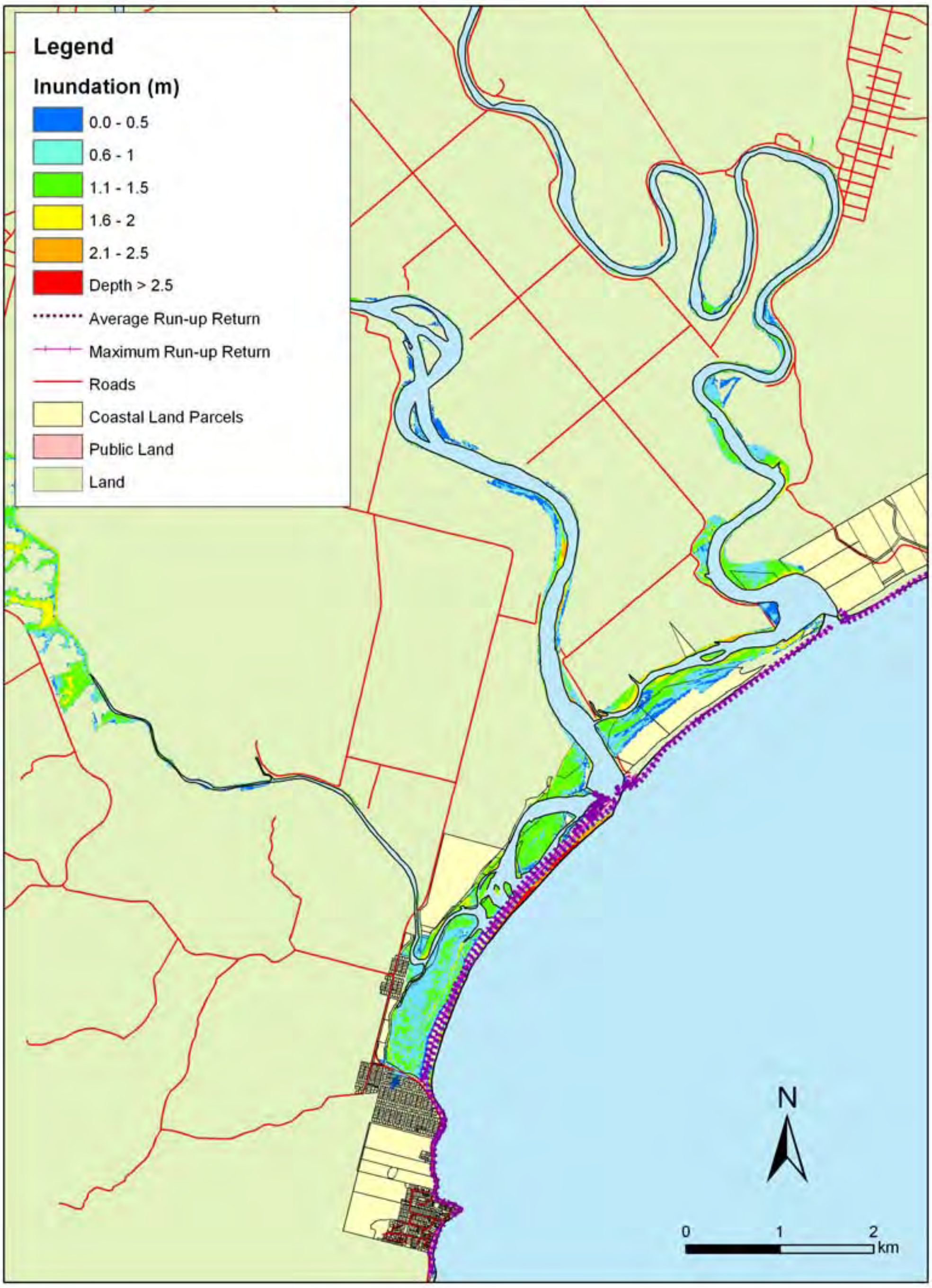

Figure 5.88: Kaka Point and Clutha - 1:50 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

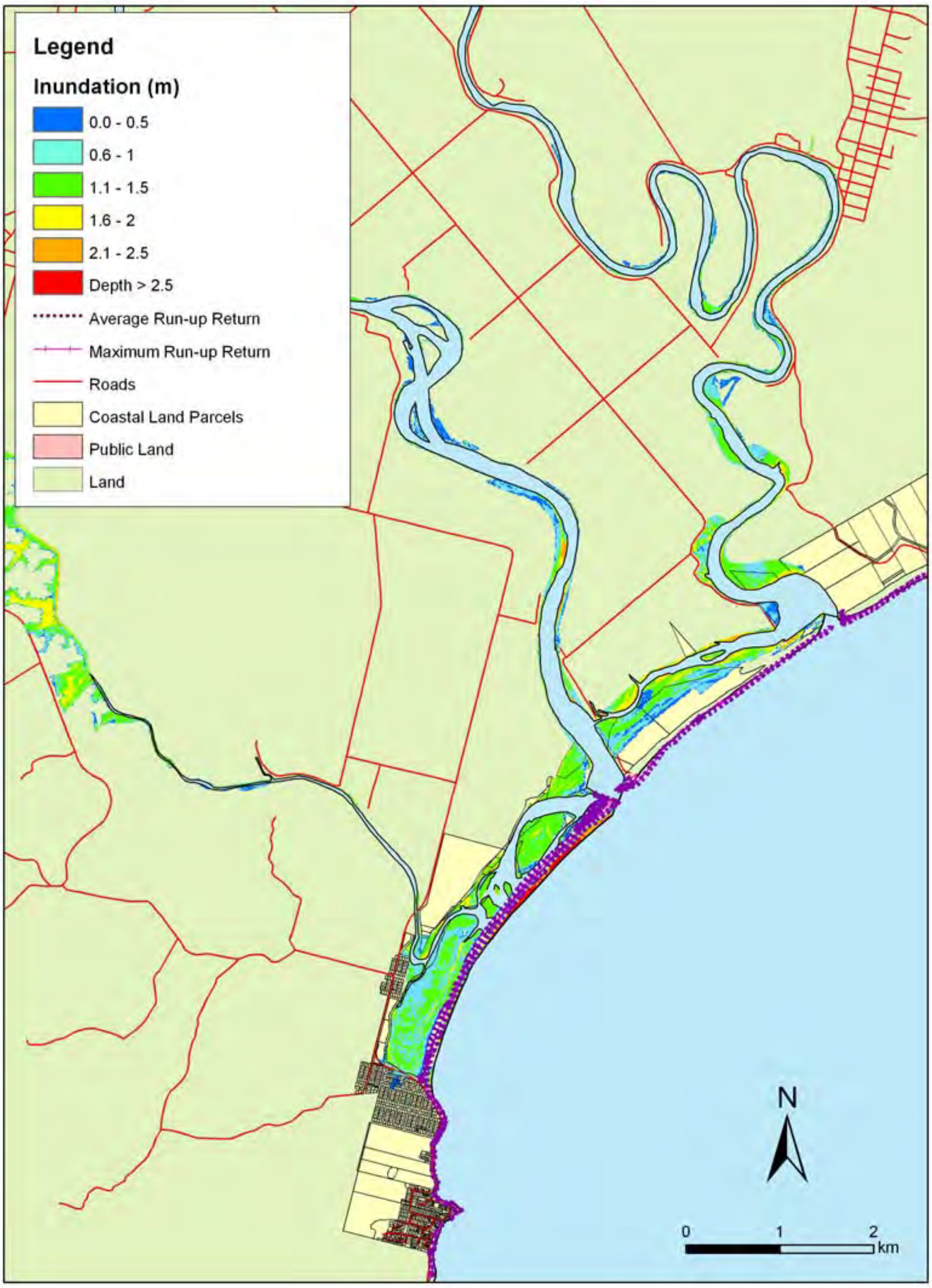

Figure 5.39: Kaka Point and Clutha - 1:100 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

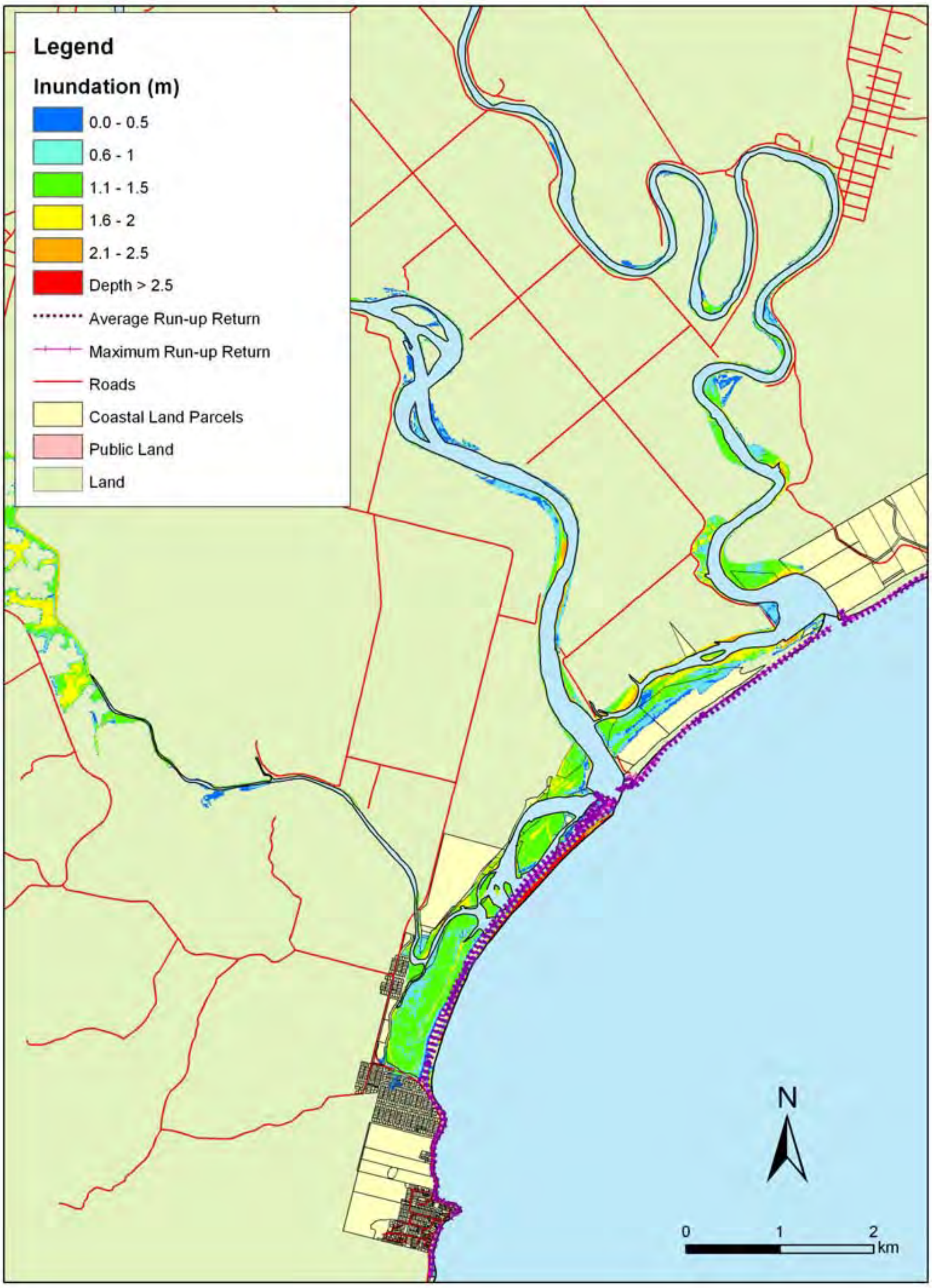

Figure 5.40: Kaka Point and Clutha - 1:500 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

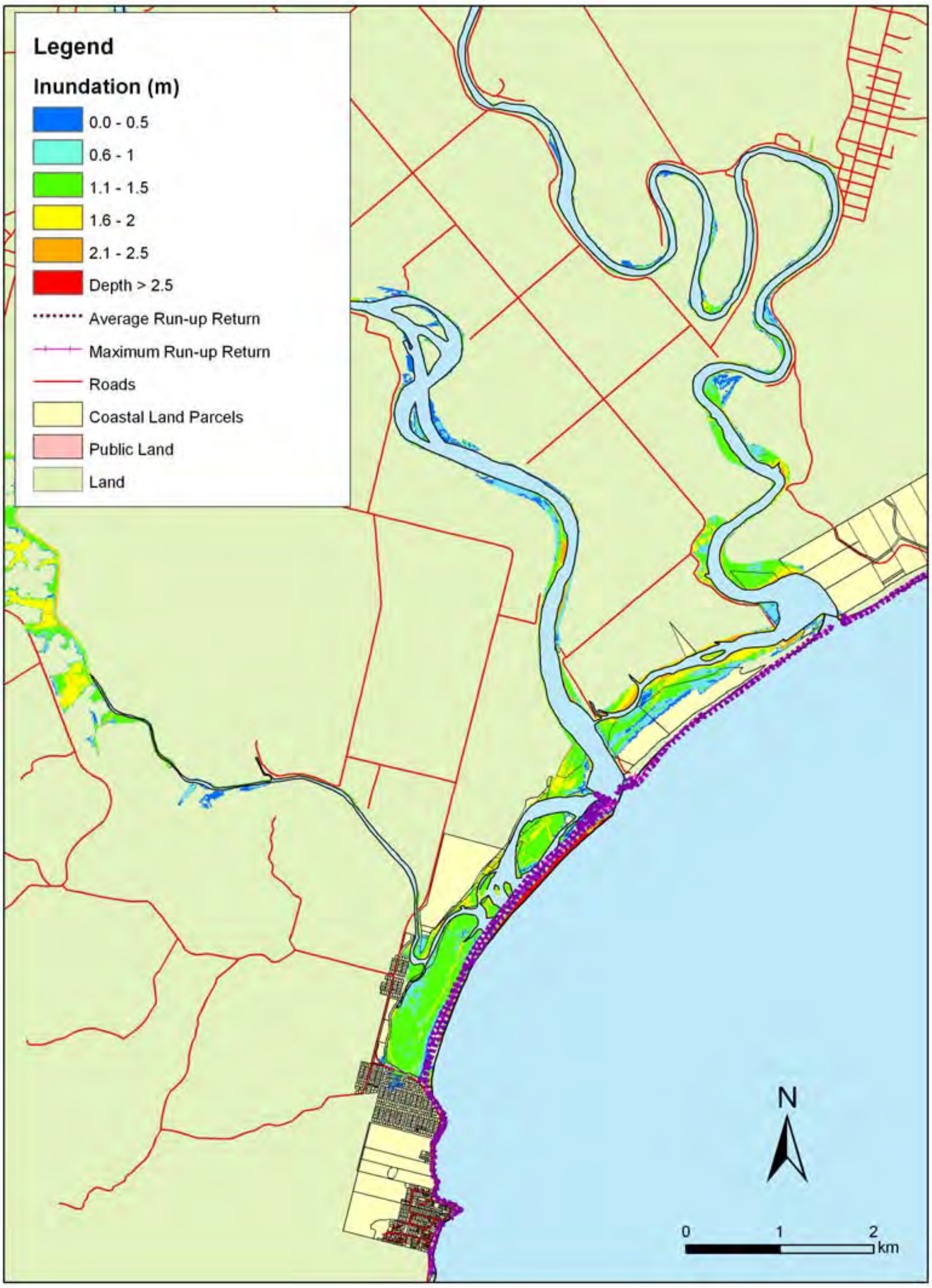

Figure 5.41: Kaka Point and Clutha - 1:20 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

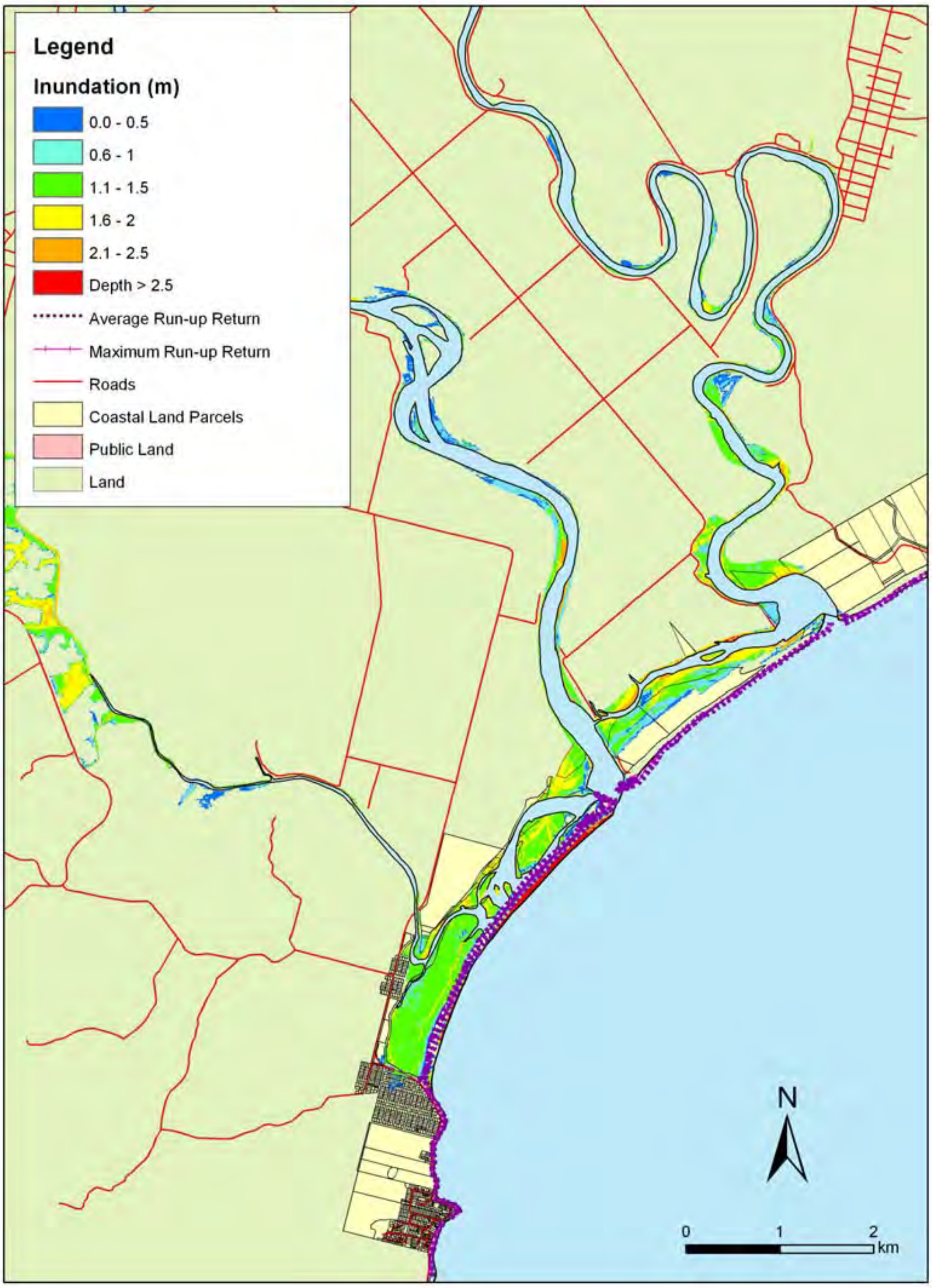

Figure 5.42: Kaka Point and Clutha - 1:50 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

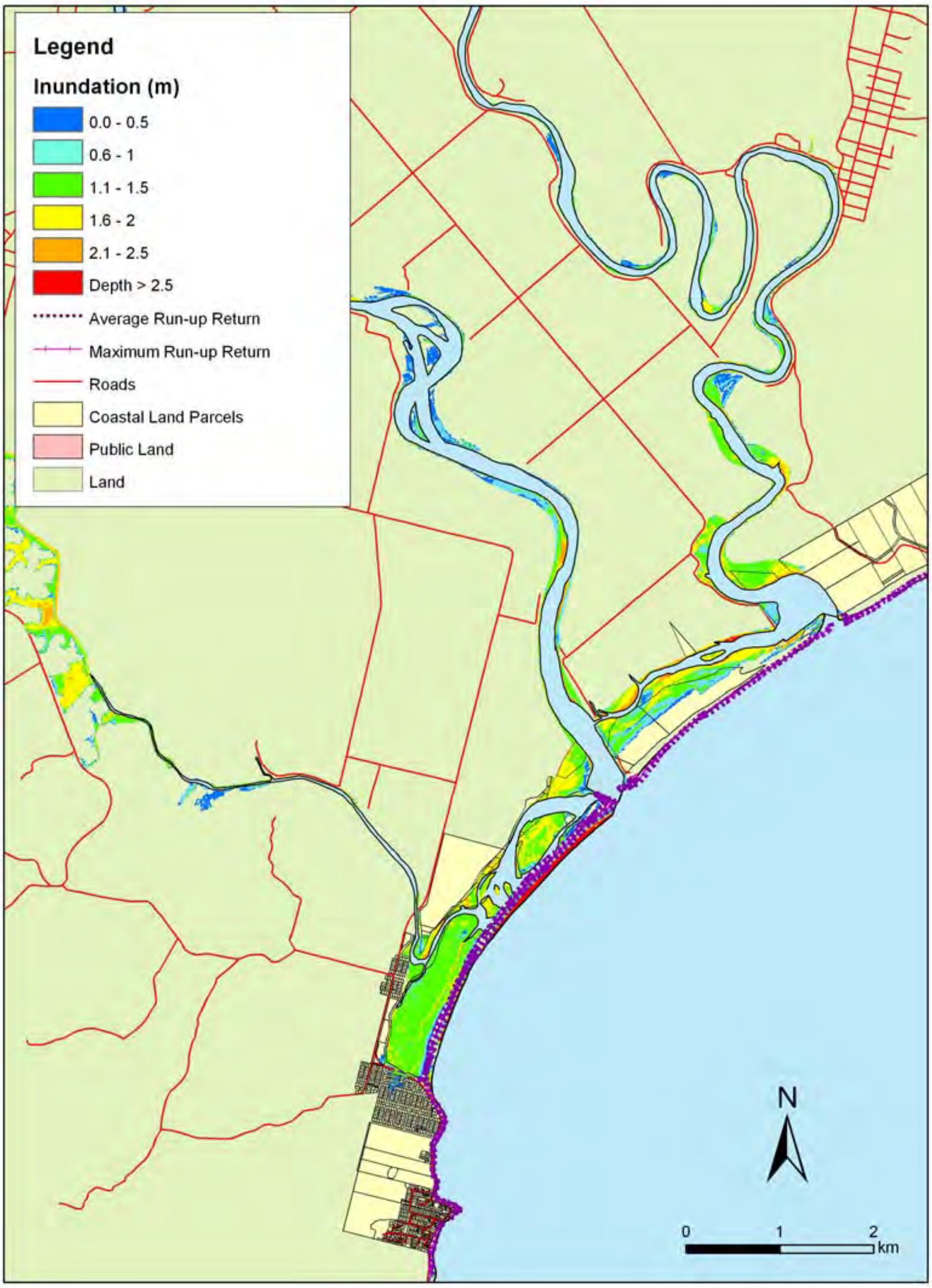

Figure 5.43: Kaka Point and Clutha - 1:100 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

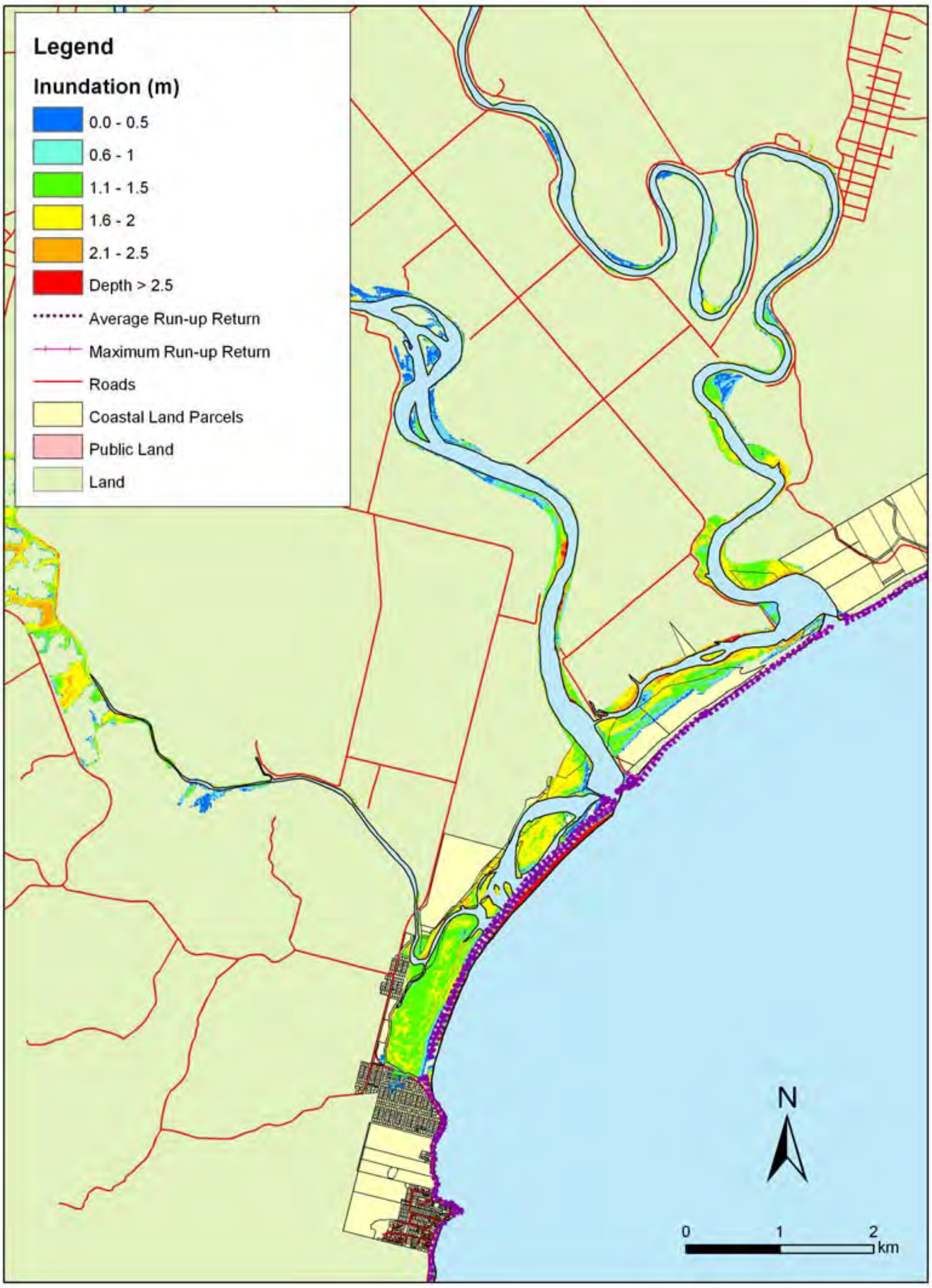

Figure 5.44: Kaka Point and Clutha - 1:500 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up**.**

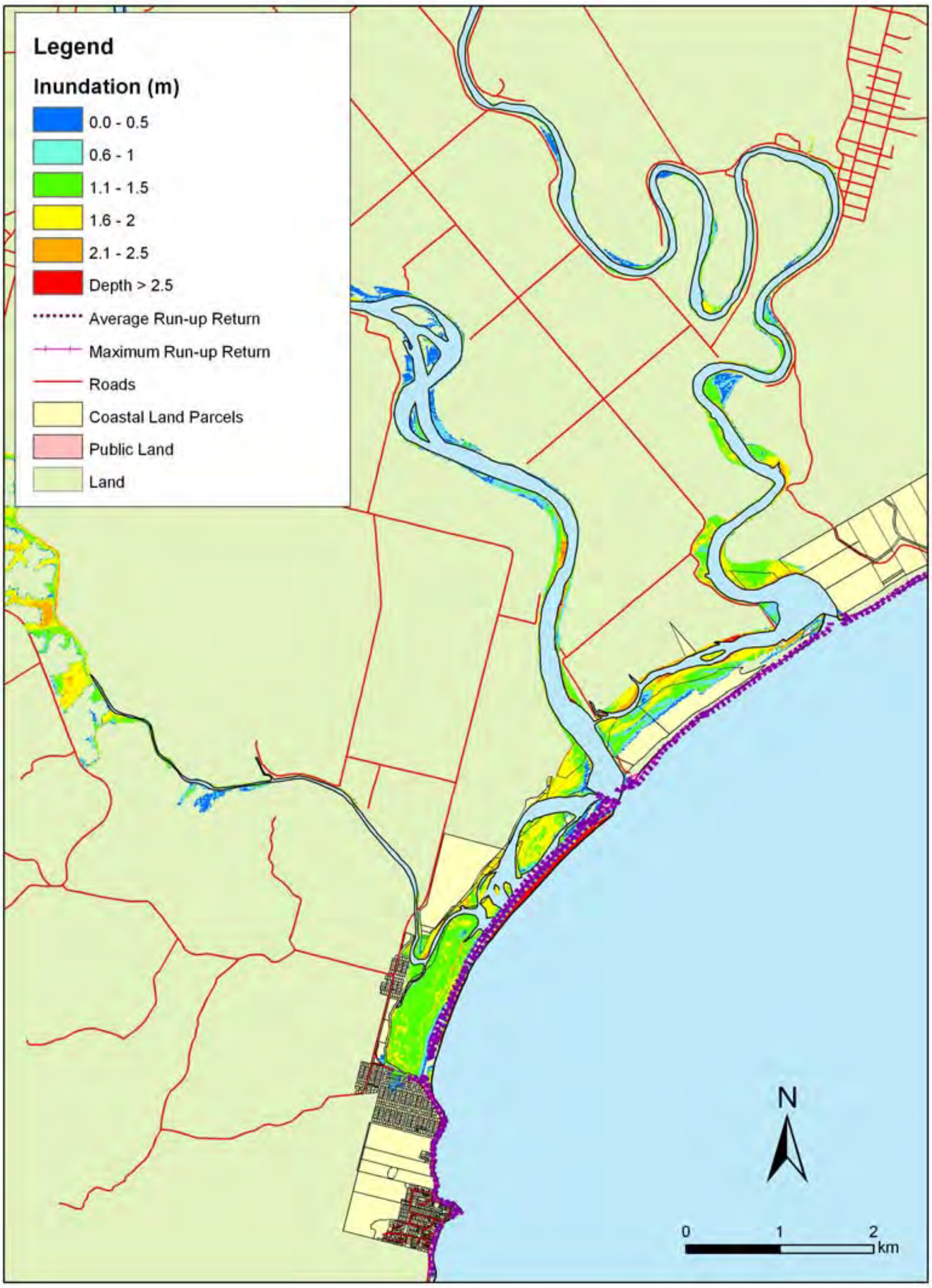

Figure 5.45: Kaka Point and Clutha - 1:20 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

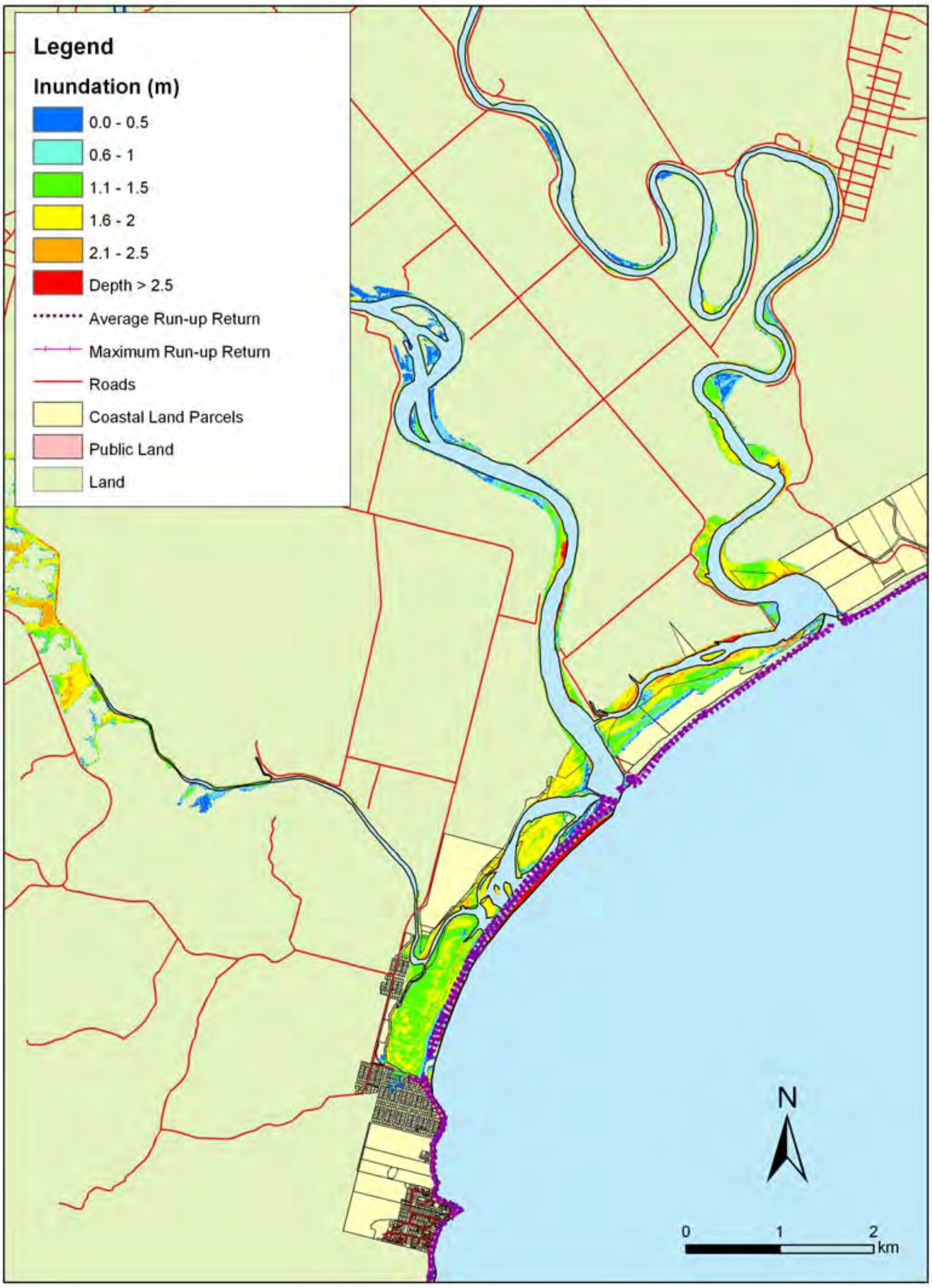

Figure 5.46: Kaka Point and Clutha - 1:50 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

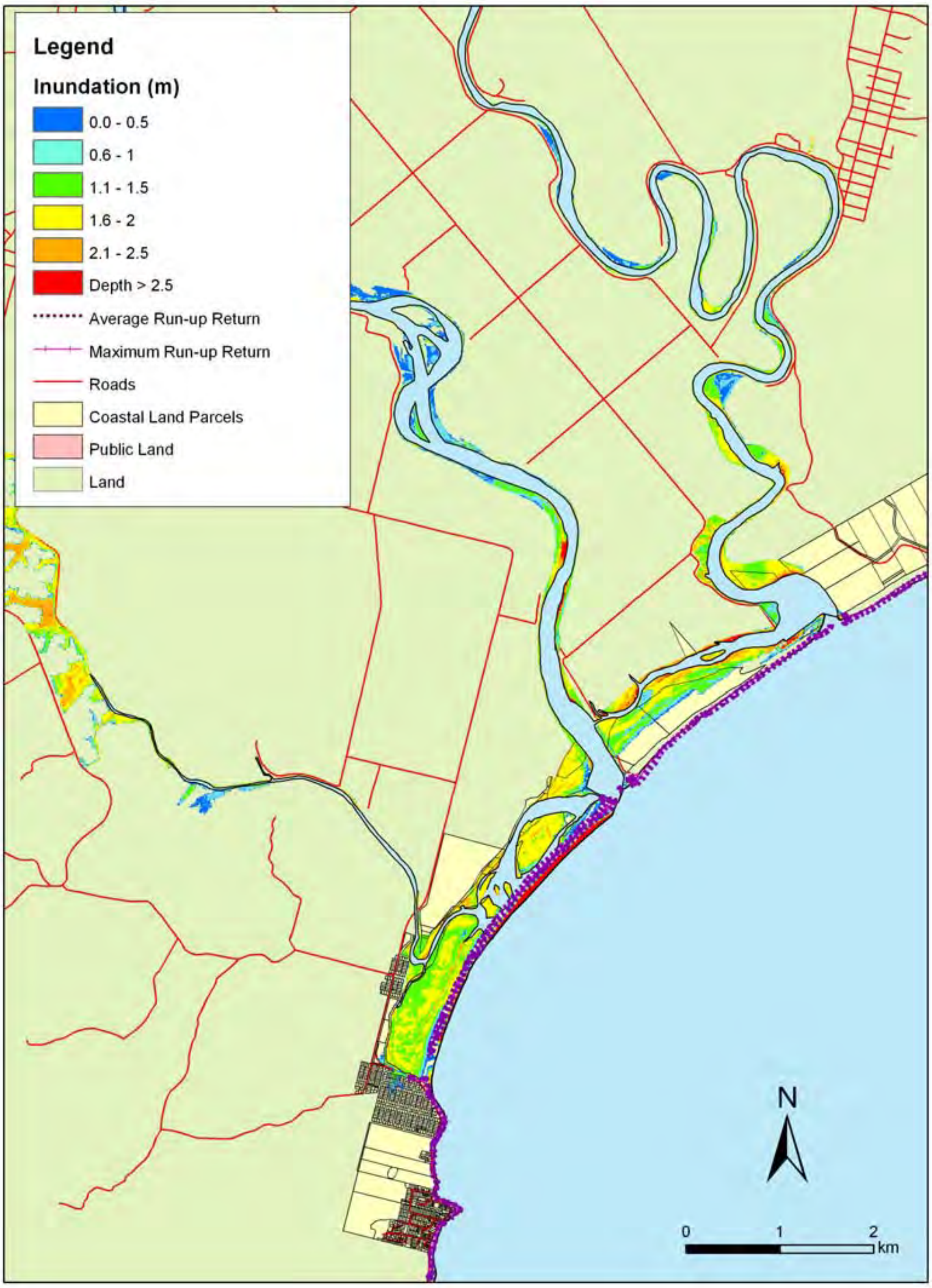

Figure 5.47: Kaka Point and Clutha - 1:100 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

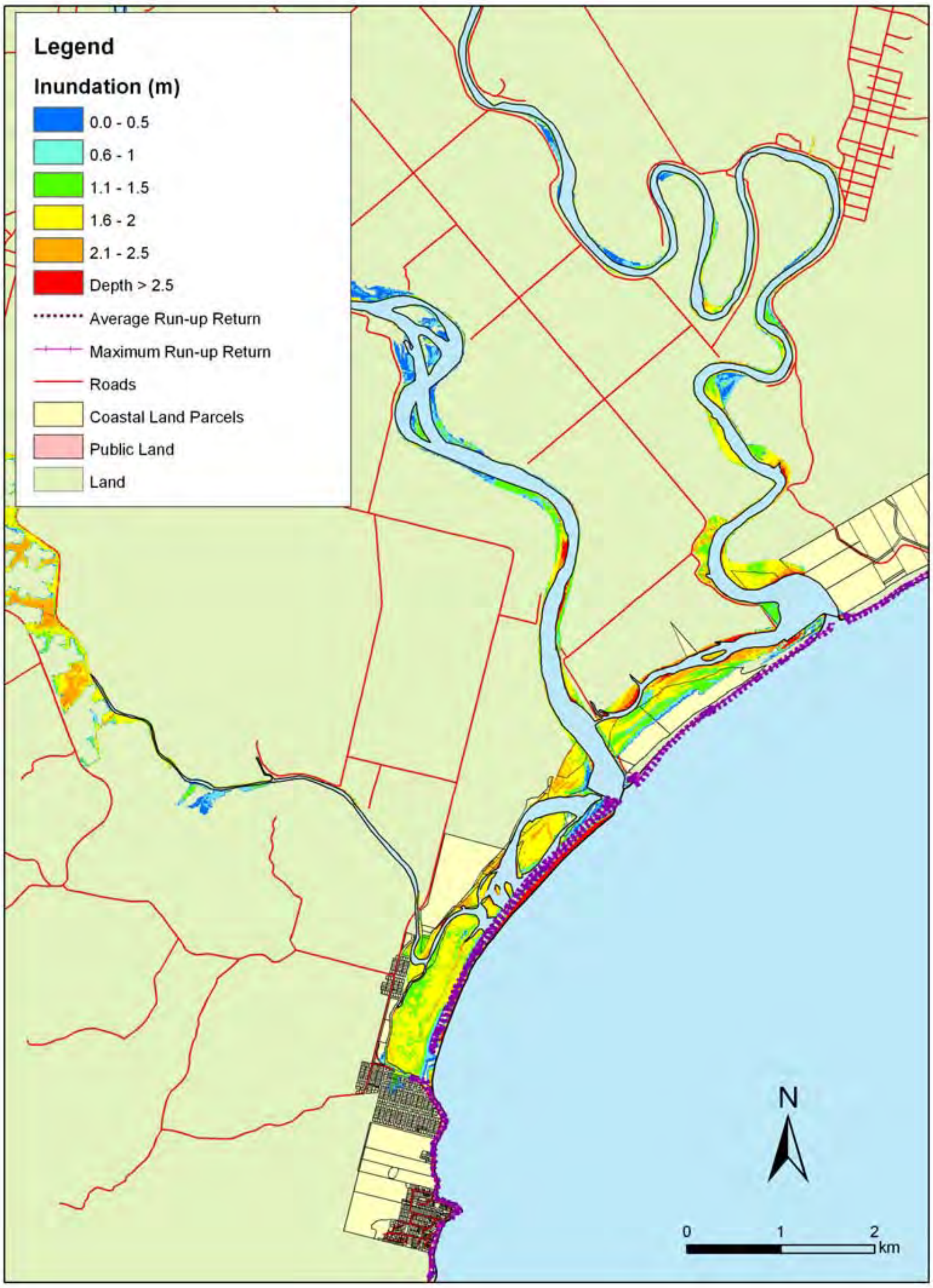

Figure 5.48: Kaka Point and Clutha - 1:500 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

5.5. Toko Mouth

Predicted inundation and wave run-up extent for present mean sea level are shown in Figures 5.49 – 5.52, for mean sea level + 0.3 m in Figure 5.53 – 5.56, and for mean sea level + 0.5 m in Figure 5.57 – 5.60.

- Maximum predicted sea level height of 2.63 m above MLOS (2.74 m above DVD-58).
- Significant inundation along the banks of the Toko River is predicted for present-day MLOS, particularly to the north-east. A strip of low land to the west is also deeply inundated. Potential inundation is also marked further upstream beyond the coverage of the LiDAR data.
- Wave run-up extends the predicted zone of impact in the coastal zone, with the maximum wave run-up exhibiting noticeably greater extent than the inundated area.
- Rising sea levels increase the depth and extent of inundation which, for a 50 cm rise, extends to the wave run-up boundary of present-day MLOS predictions.

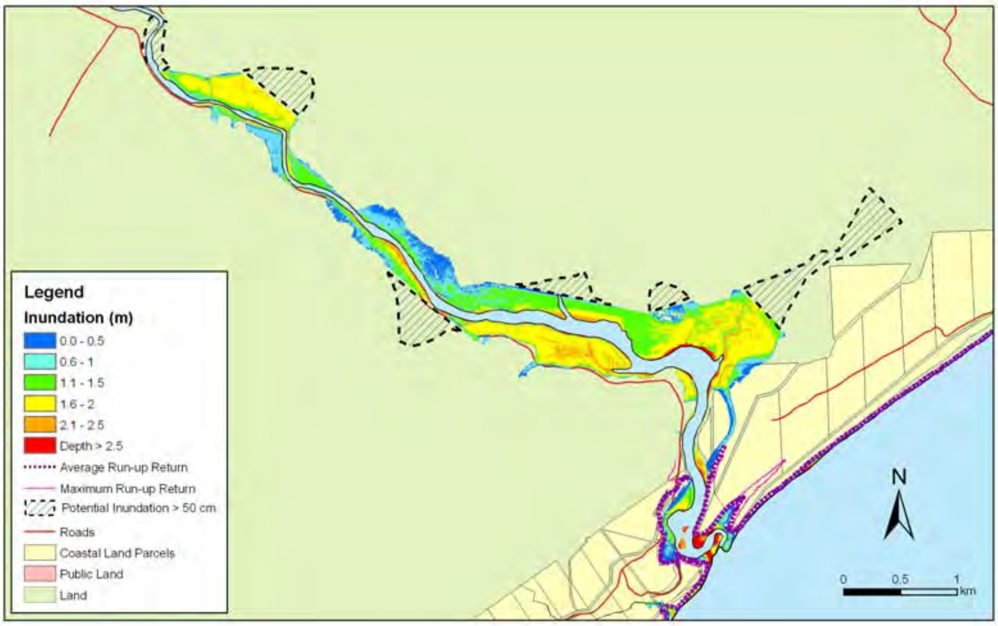

Figure 5.49: Toko Mouth - 1:20 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

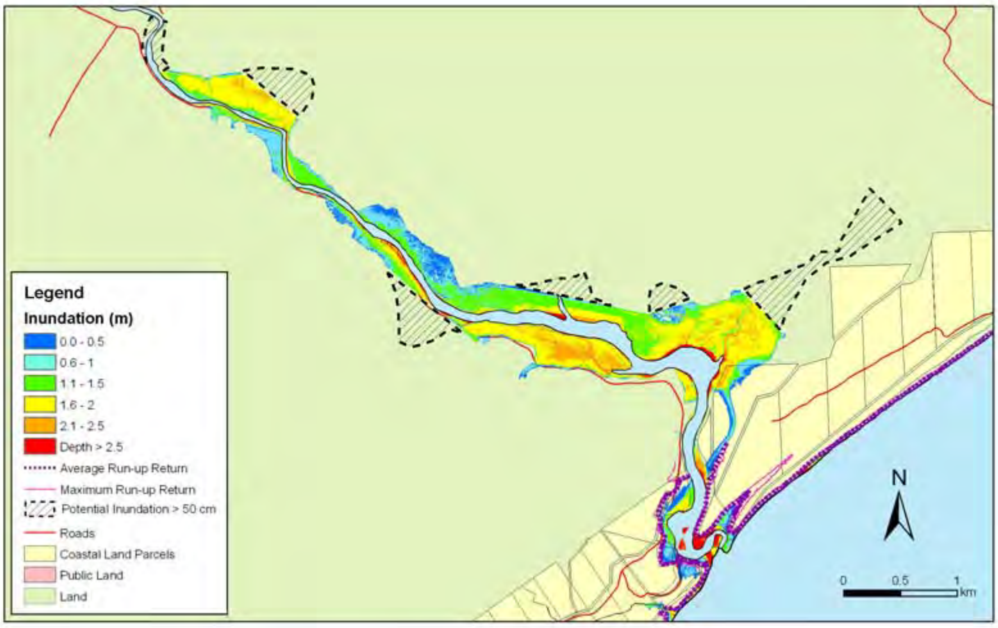

Figure 5.50: Toko Mouth - 1:50 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

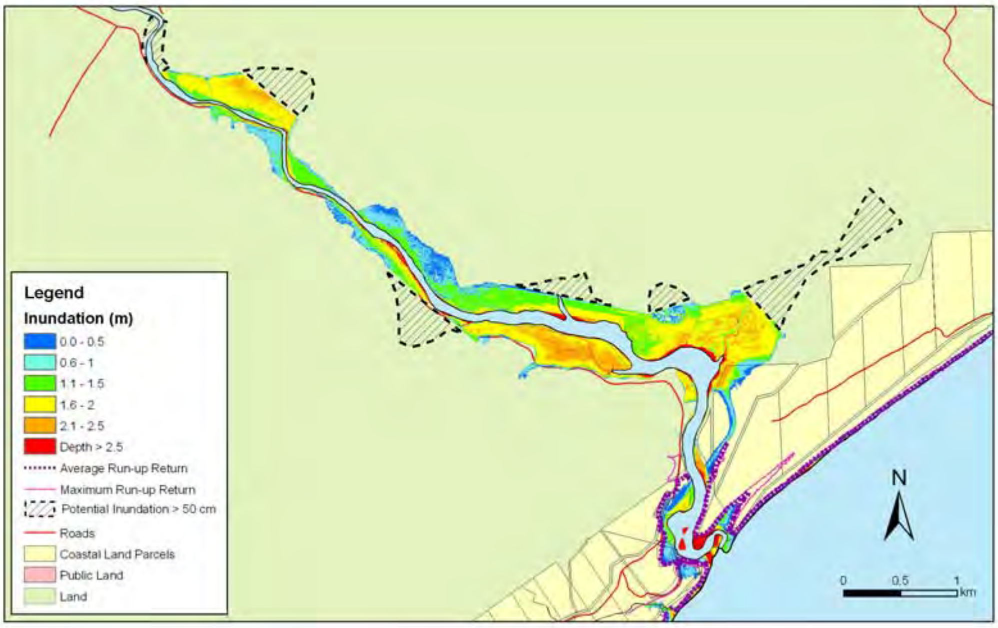

Figure 5.51: Toko Mouth - 1:100 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

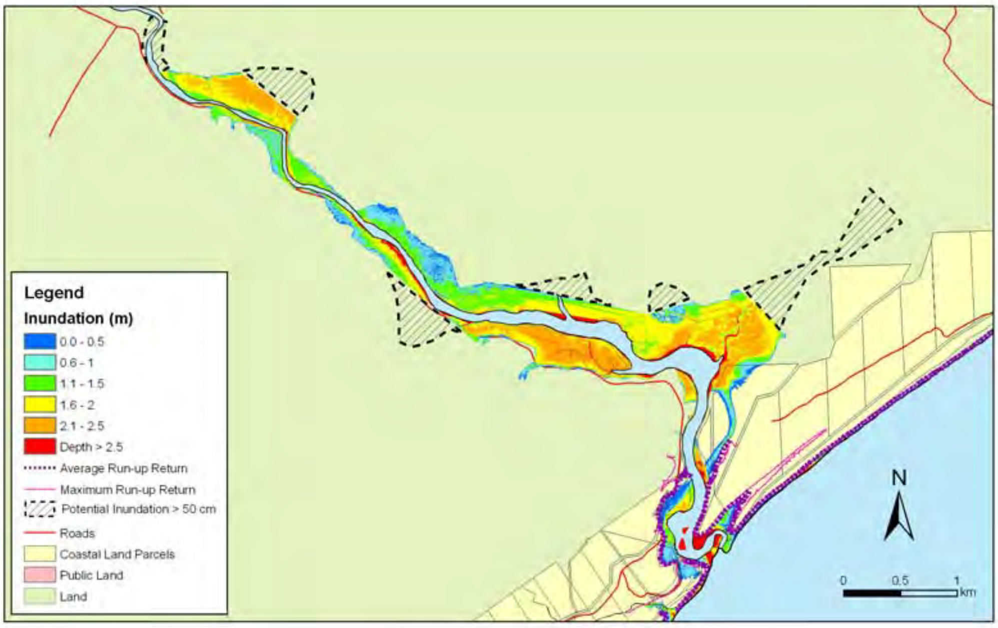

Figure 5.52: Toko Mouth - 1:500 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

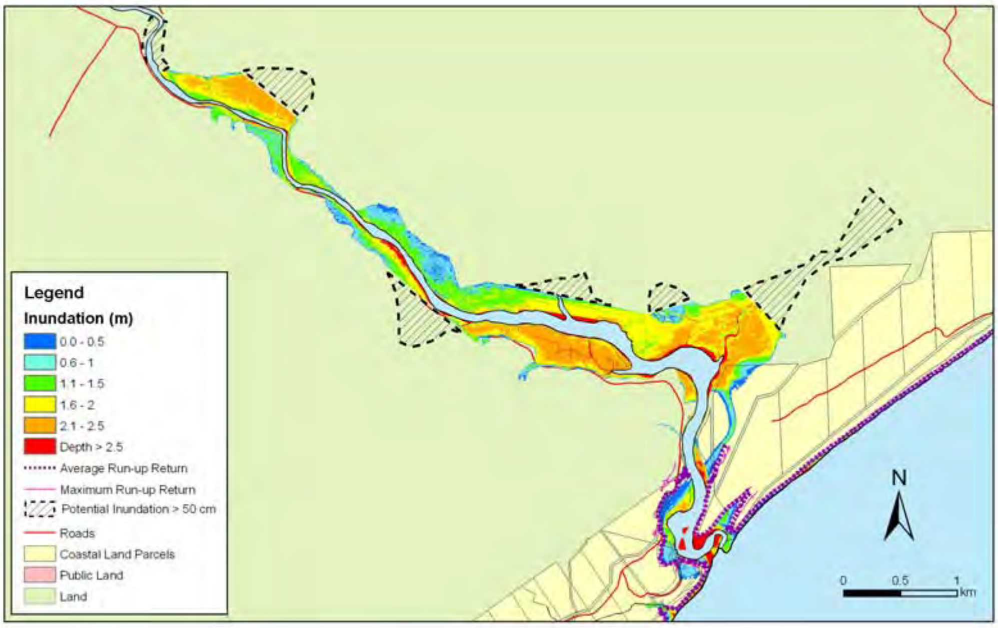

Figure 5.53: Toko Mouth - 1:20 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

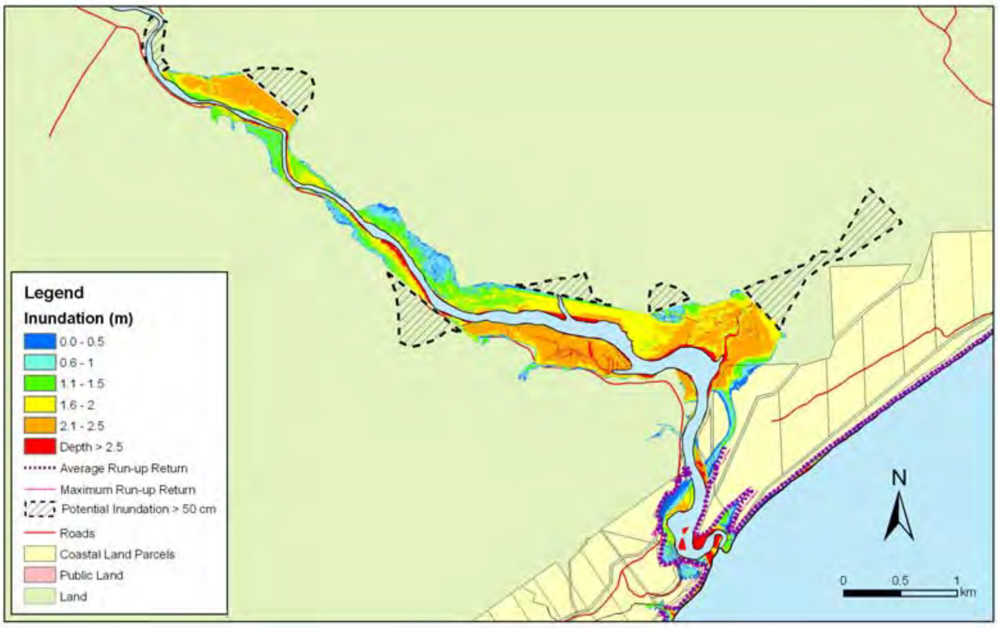

Figure 5.54: Toko Mouth - 1:50 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

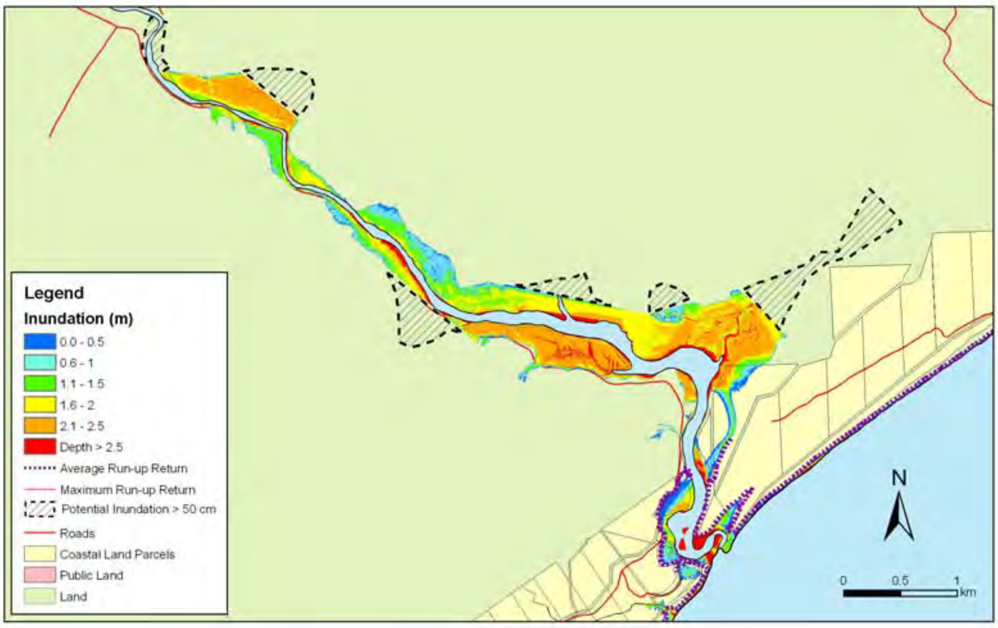

Figure 5.55: Toko Mouth - 1:100 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

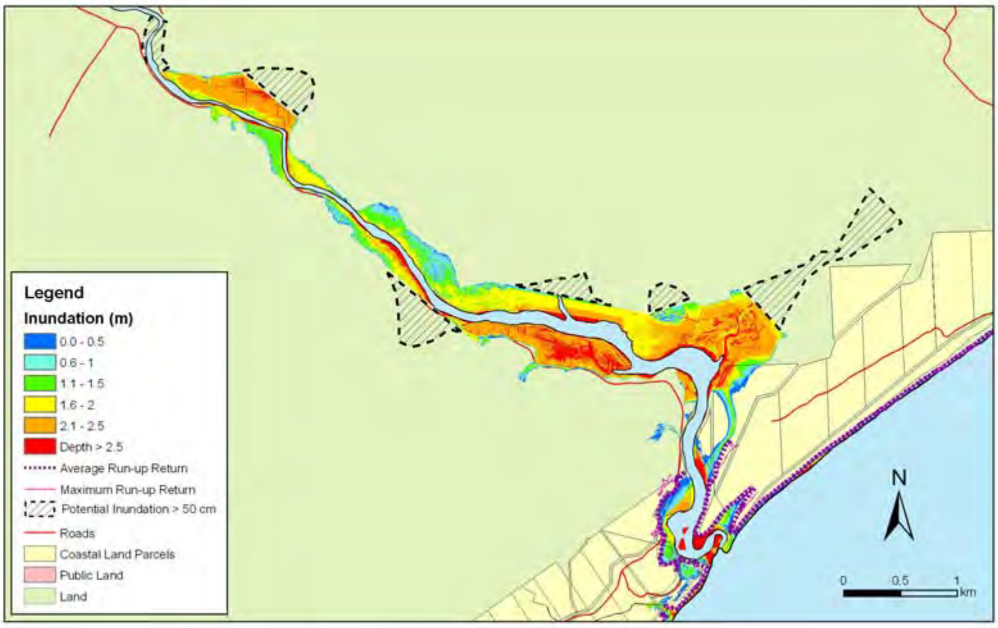

Figure 5.56: Toko Mouth - 1:500 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

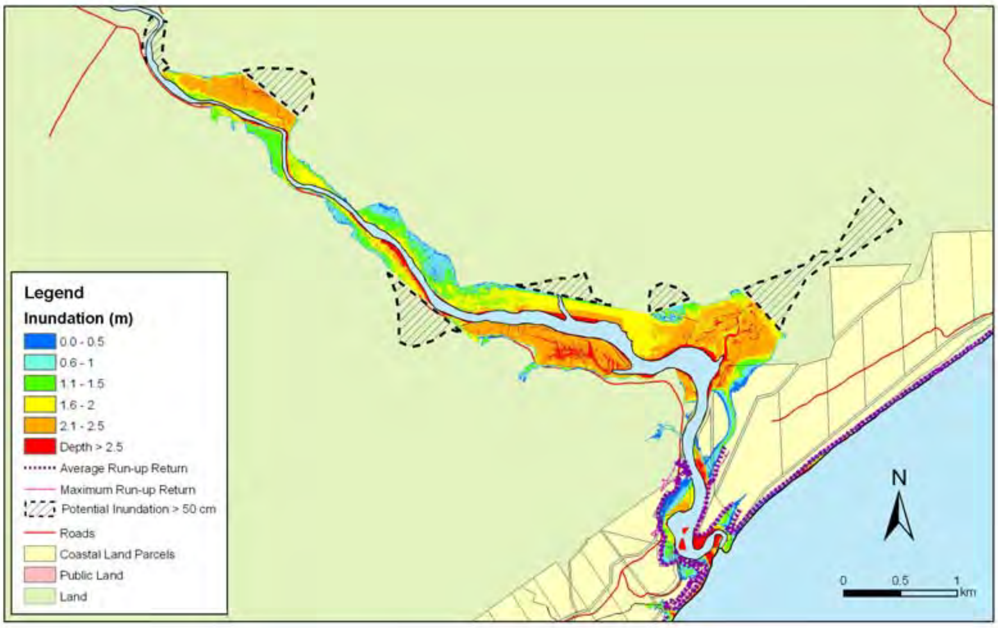

Figure 5.57: Toko Mouth - 1:20 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

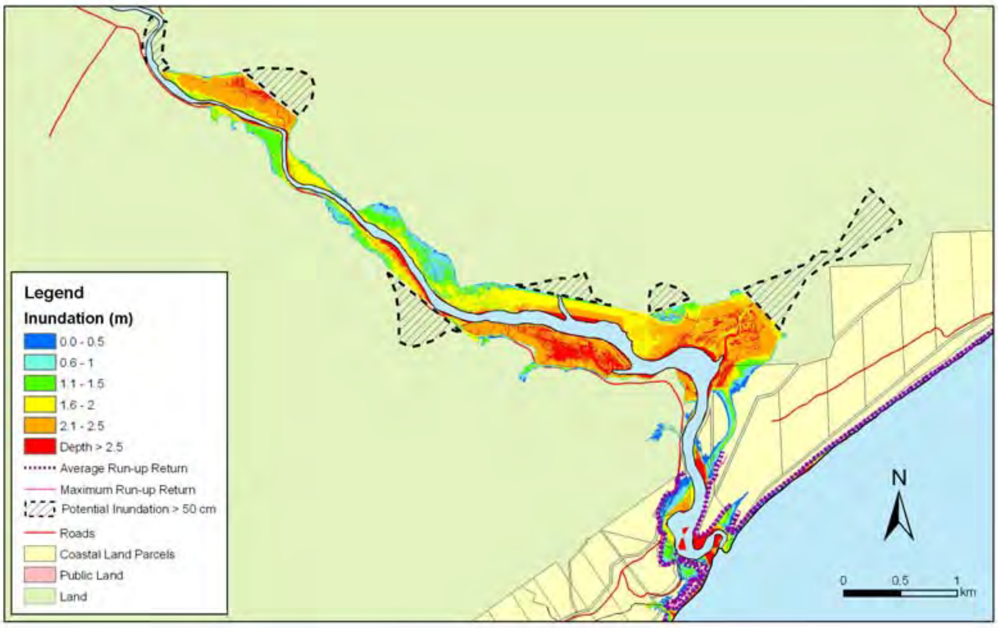

Figure 5.58: Toko Mouth - 1:50 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

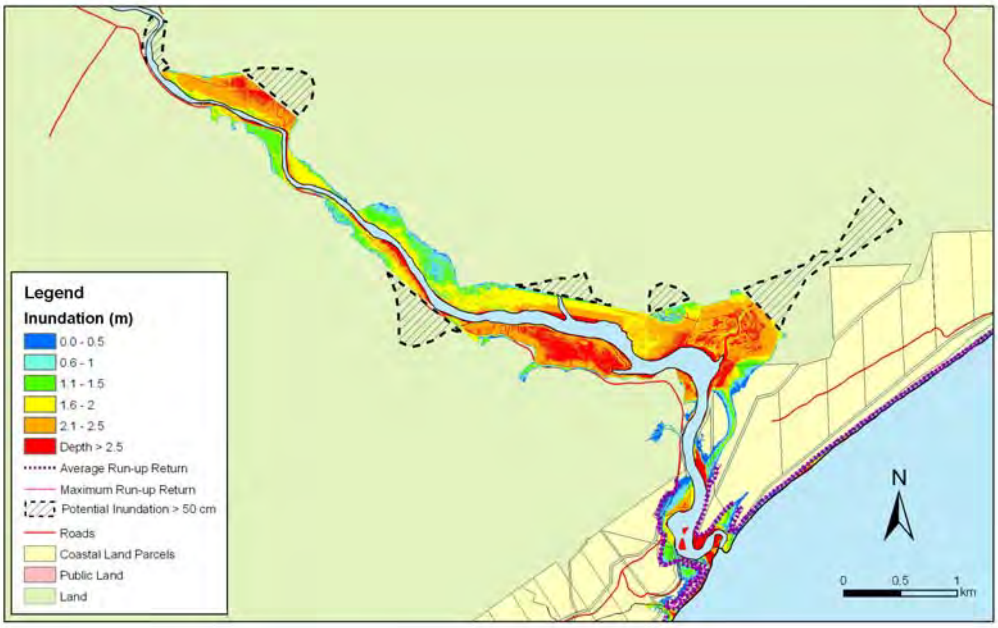

Figure 5.59.: Toko Mouth - 1:100 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

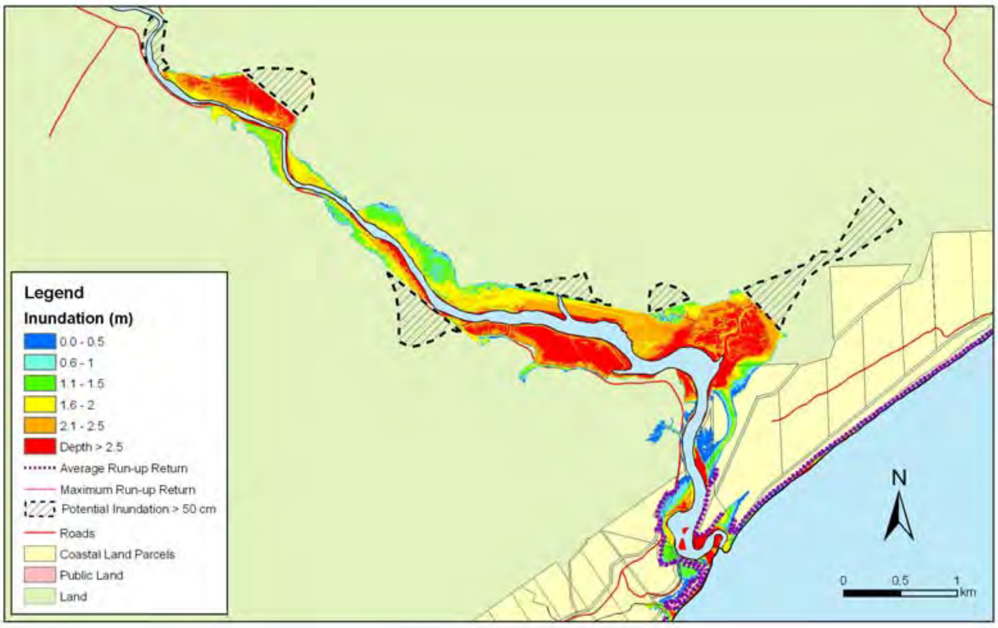

Figure 5.60: Toko Mouth - 1:500 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

5.6. Taieri Mouth

Predicted inundation and wave run-up extent for present mean sea level are shown in Figures 5.61 – 5.64, for mean sea level + 0.3 m in Figure 5.65 – 5.68, and for mean sea level + 0.5 m in Figure 5.69 – 5.72.

- Maximum predicted sea level height of 2.01 m above MLOS (2.12 m above DVD-58).

- There is limited inundation predicted on both shores of the Taieri River in the river mouth. Inland, land elevation rises considerably, preventing inundation from the river. There is inundation predicted inshore of the beach to the south of the river mouth which penetrates inshore via the small stream. This inundation stretches more than a kilometre southwards.

- Wave run-up bounds the inundation area. It is not plotted for the region inshore of the southbound road.

- Rising sea levels increase the depth of predicted inundation through the region, and its extent inshore of the south beach.

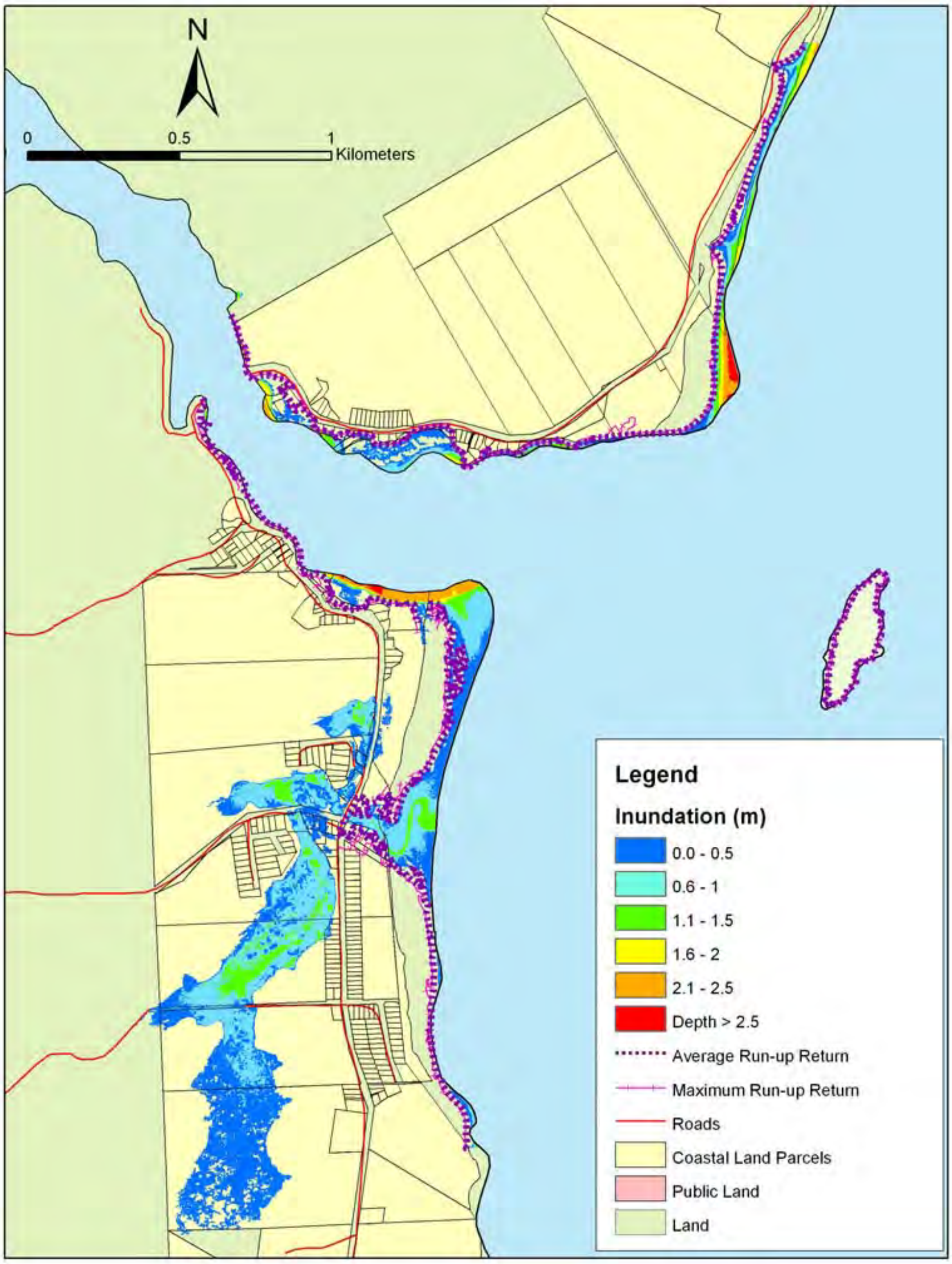

Figure 5.61: Taieri Mouth - 1:20 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

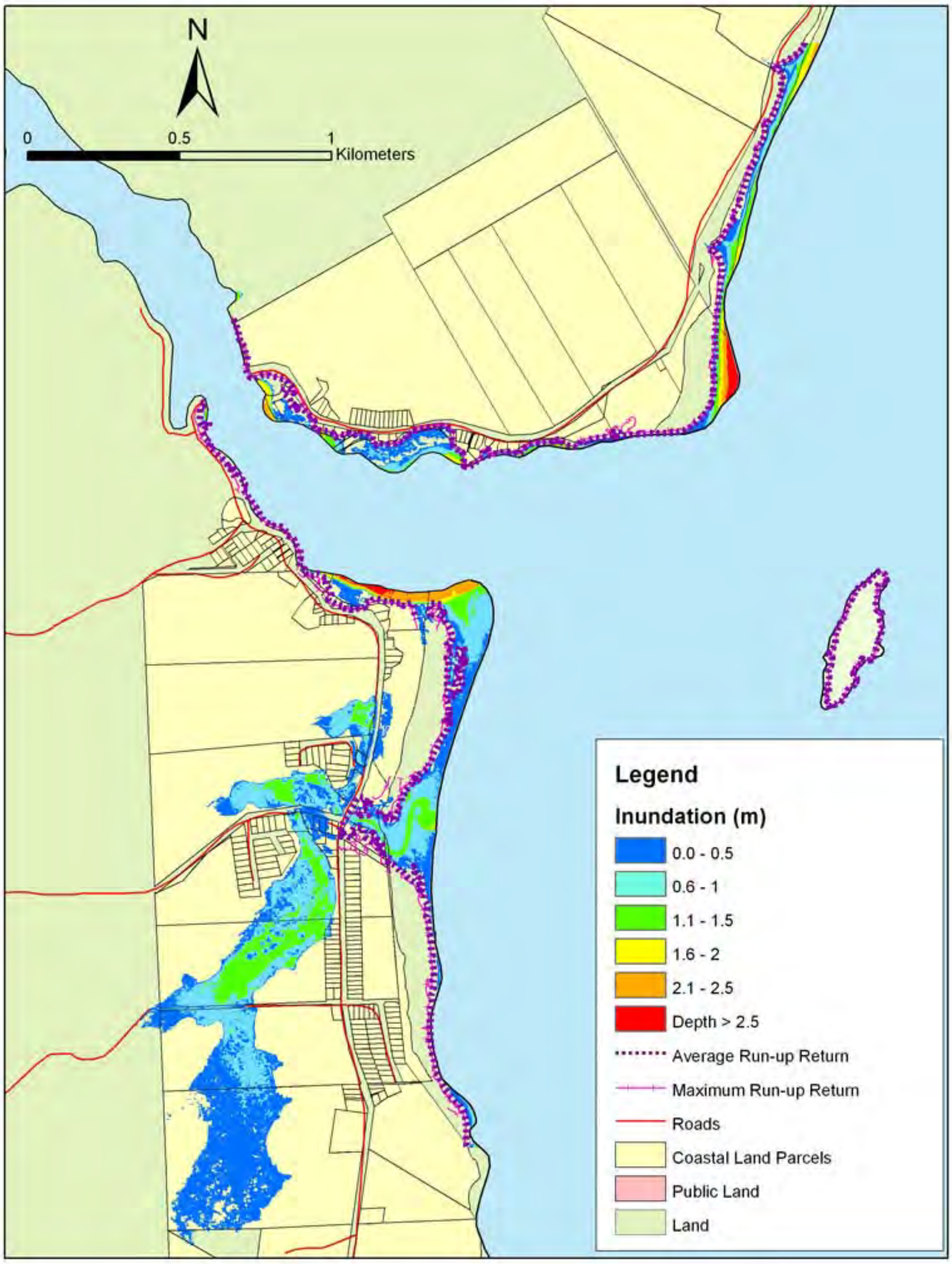

Figure 5.62: Taieri Mouth - 1:50 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

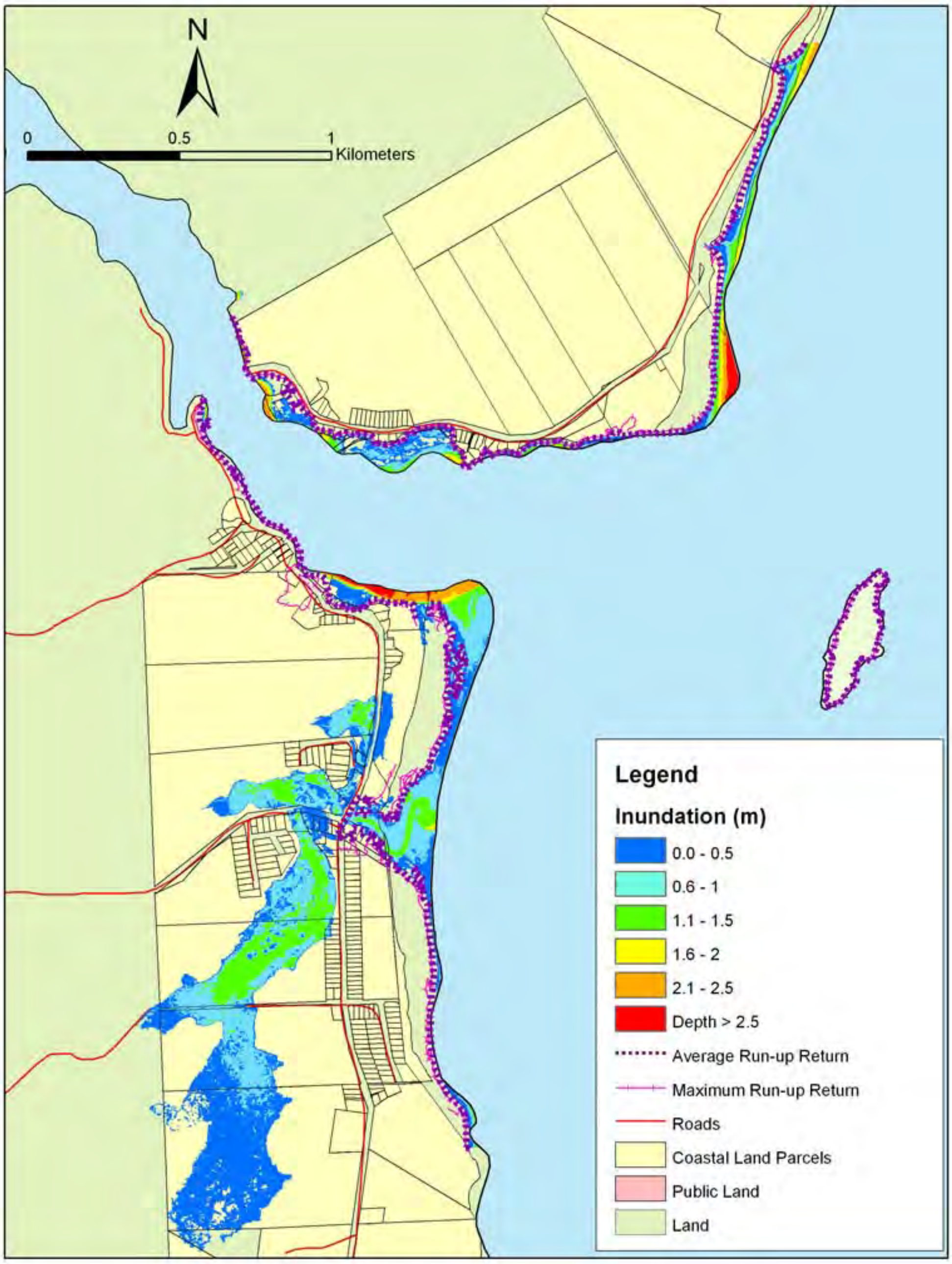

Figure 5.63: Taieri Mouth - 1:100 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

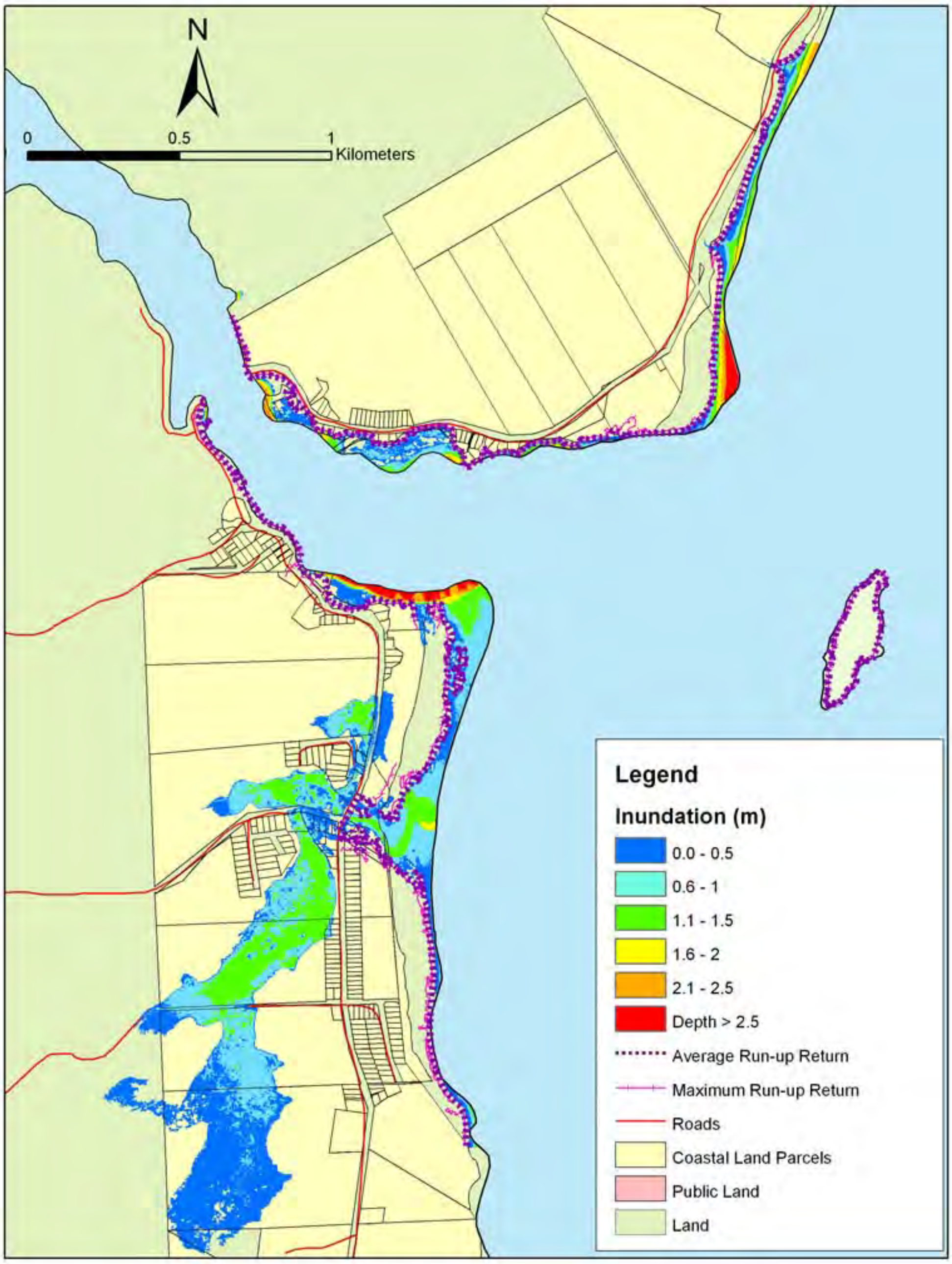

Figure 5.64: Taieri Mouth - 1:500 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

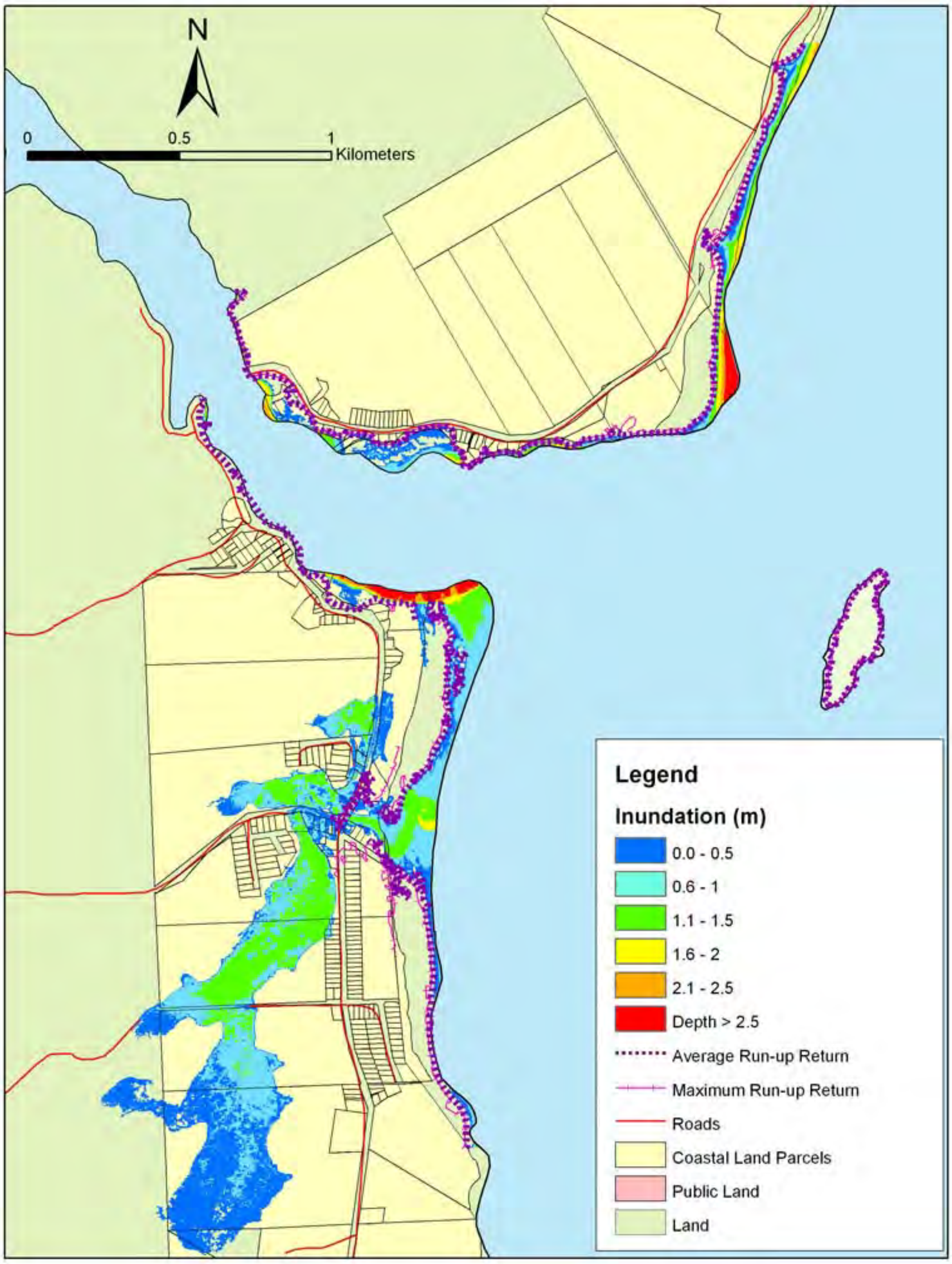

Figure 5.65: Taieri Mouth - 1:20 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

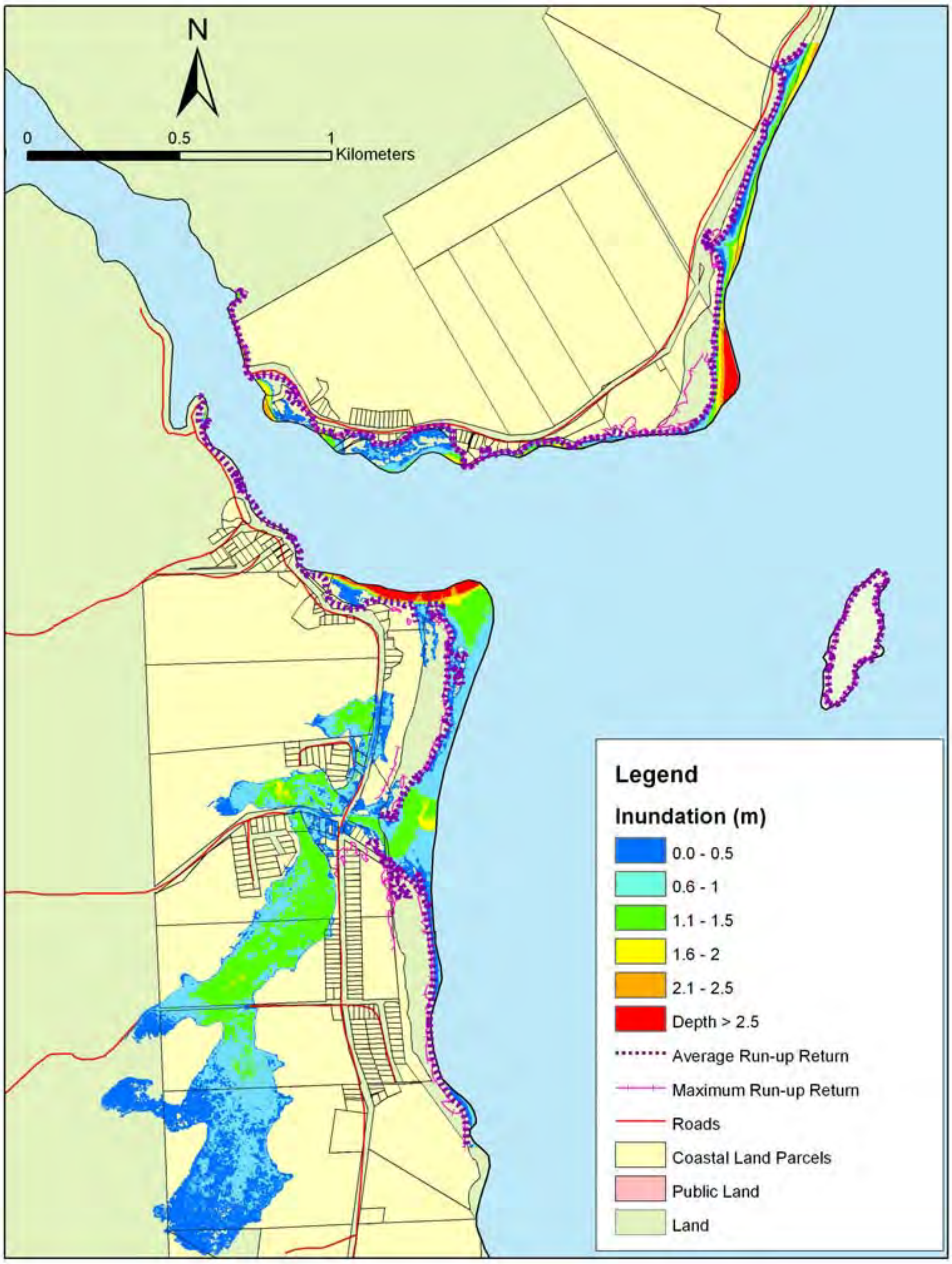

Figure 5.66: Taieri Mouth - 1:50 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

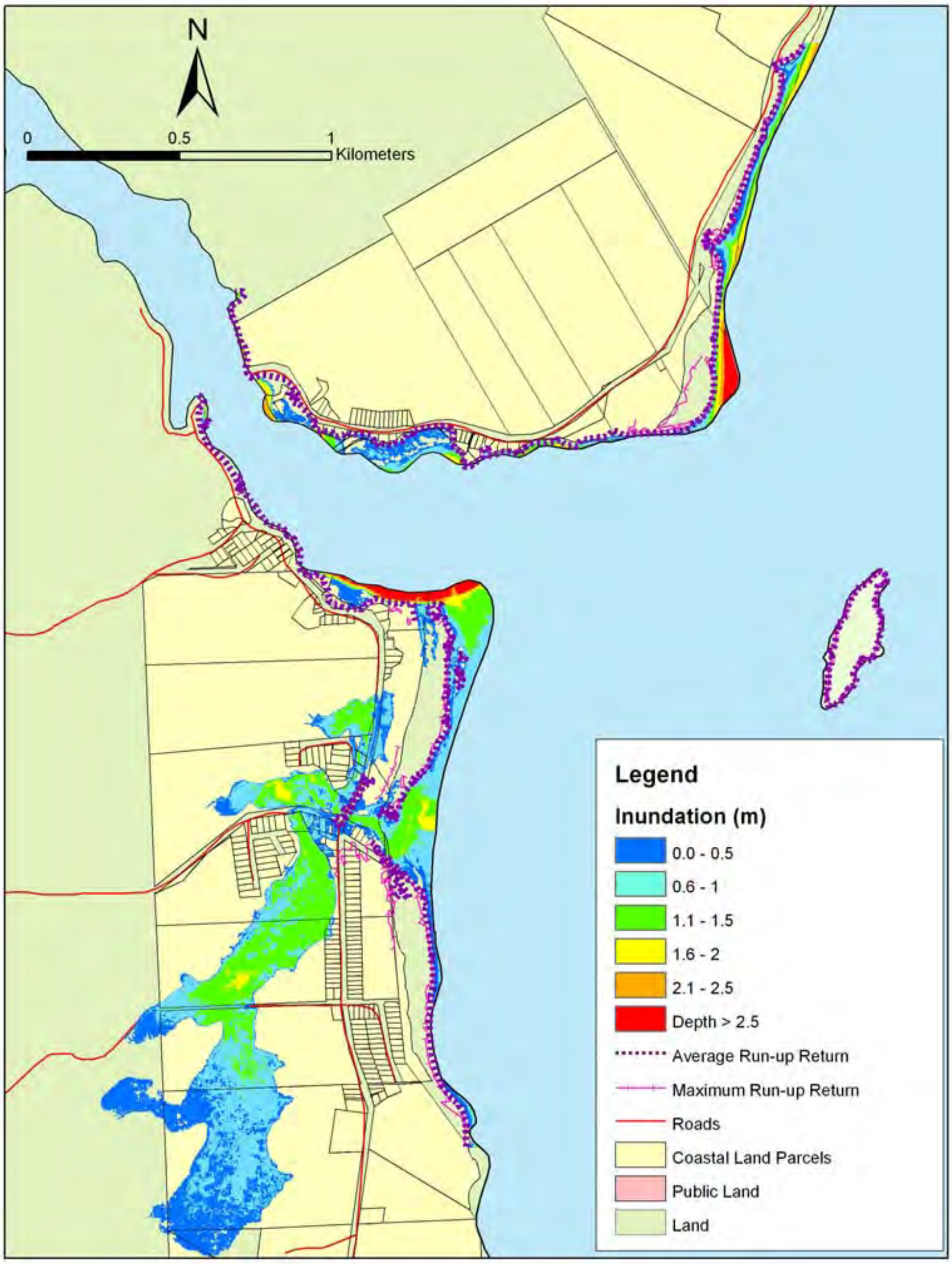

Figure 5.67: Taieri Mouth - 1:100 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

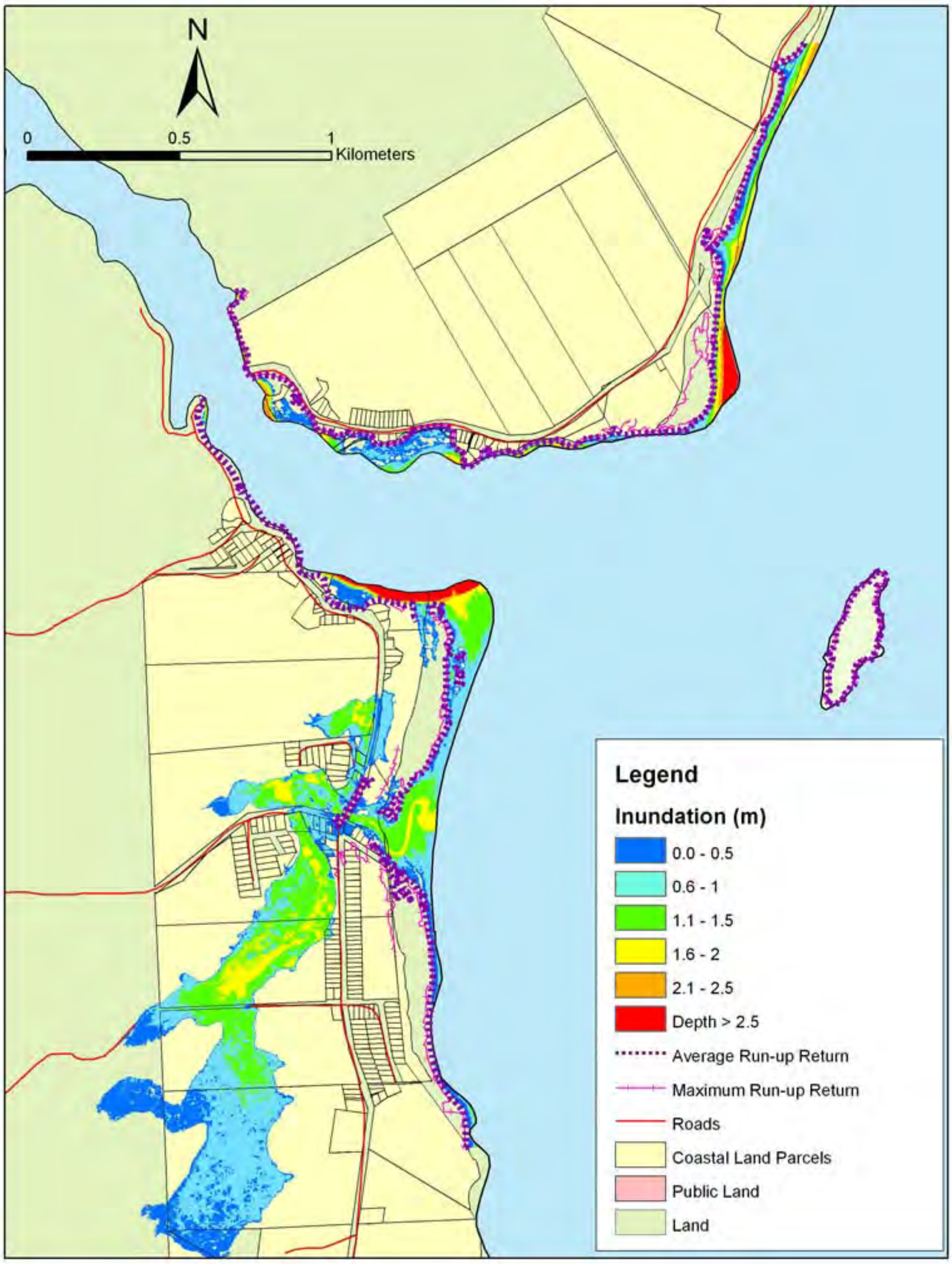

Figure 5.68: Taieri Mouth - 1:500 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

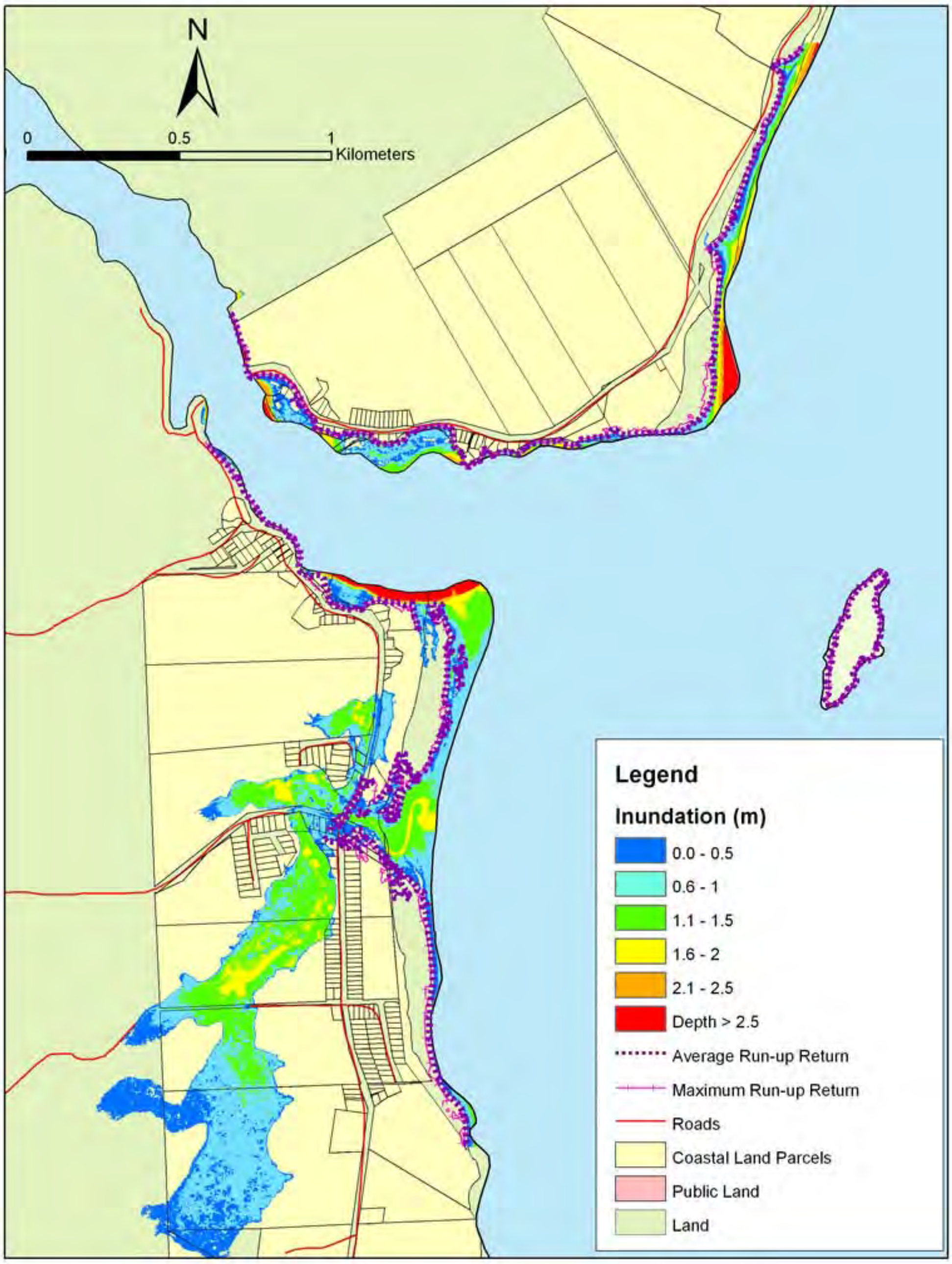

Figure 5.69: Taieri Mouth - 1:20 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

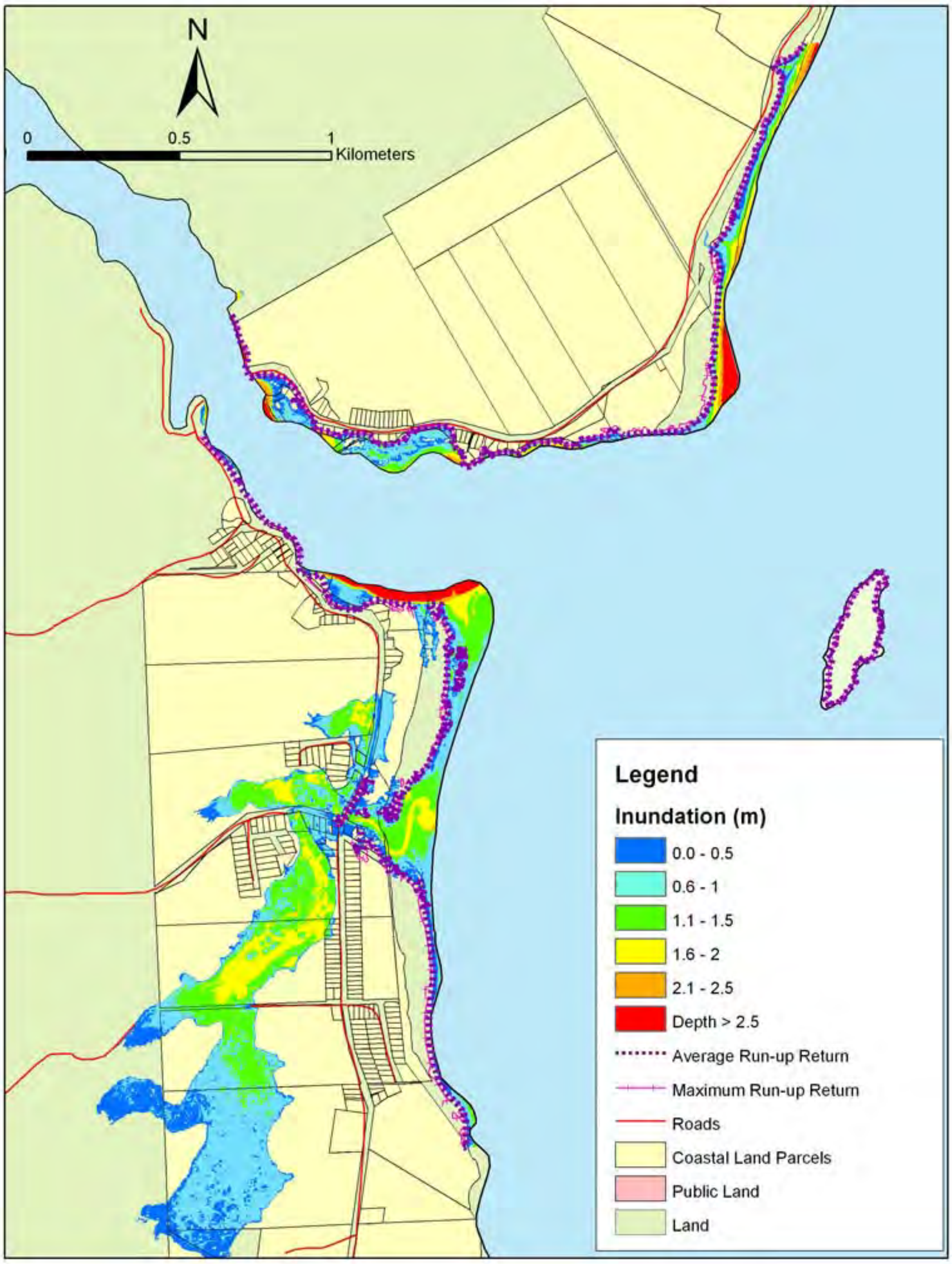

Figure 5.70: Taieri Mouth - 1:50 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

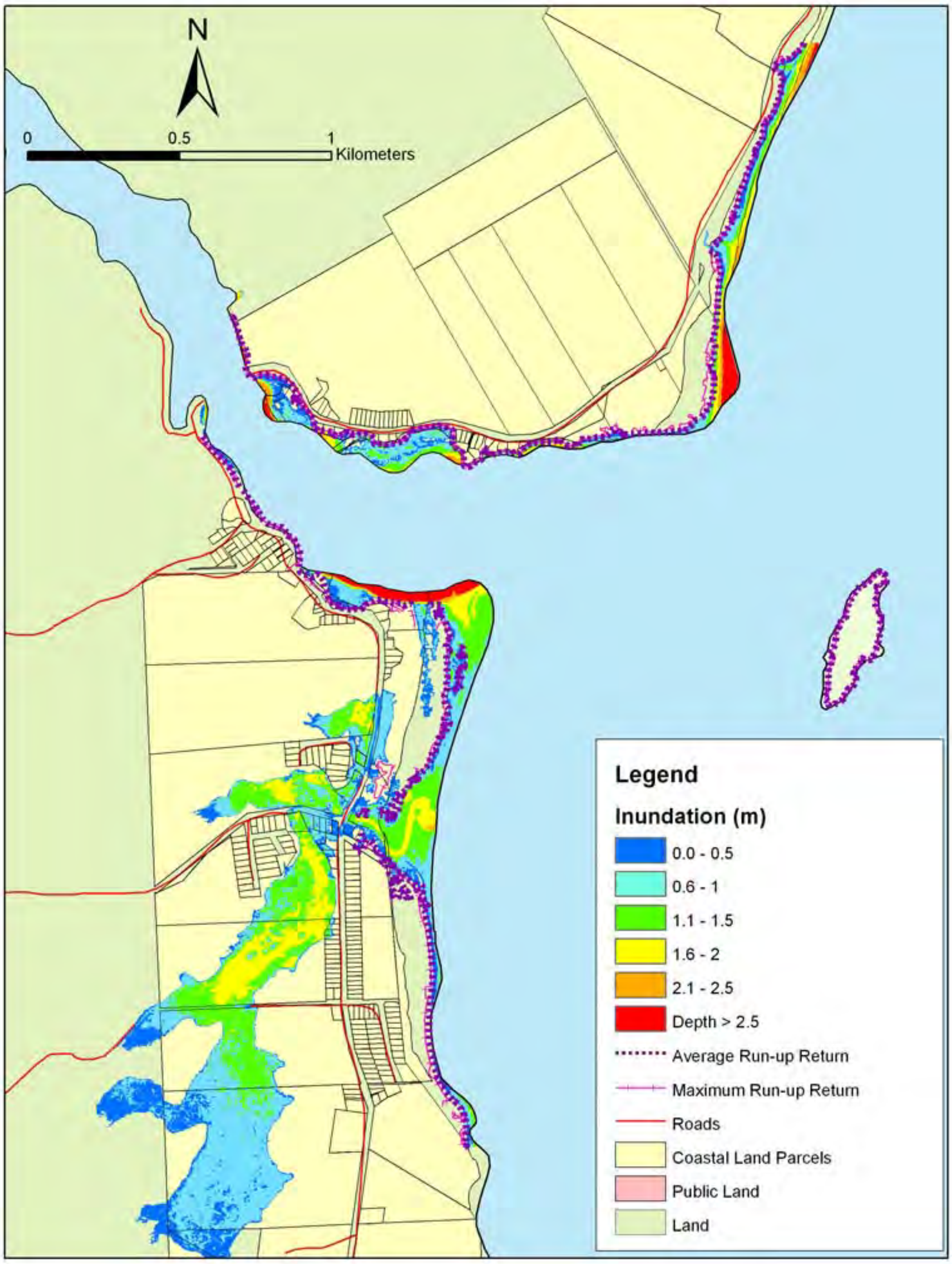

Figure 5.71: Taieri Mouth - 1:100 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

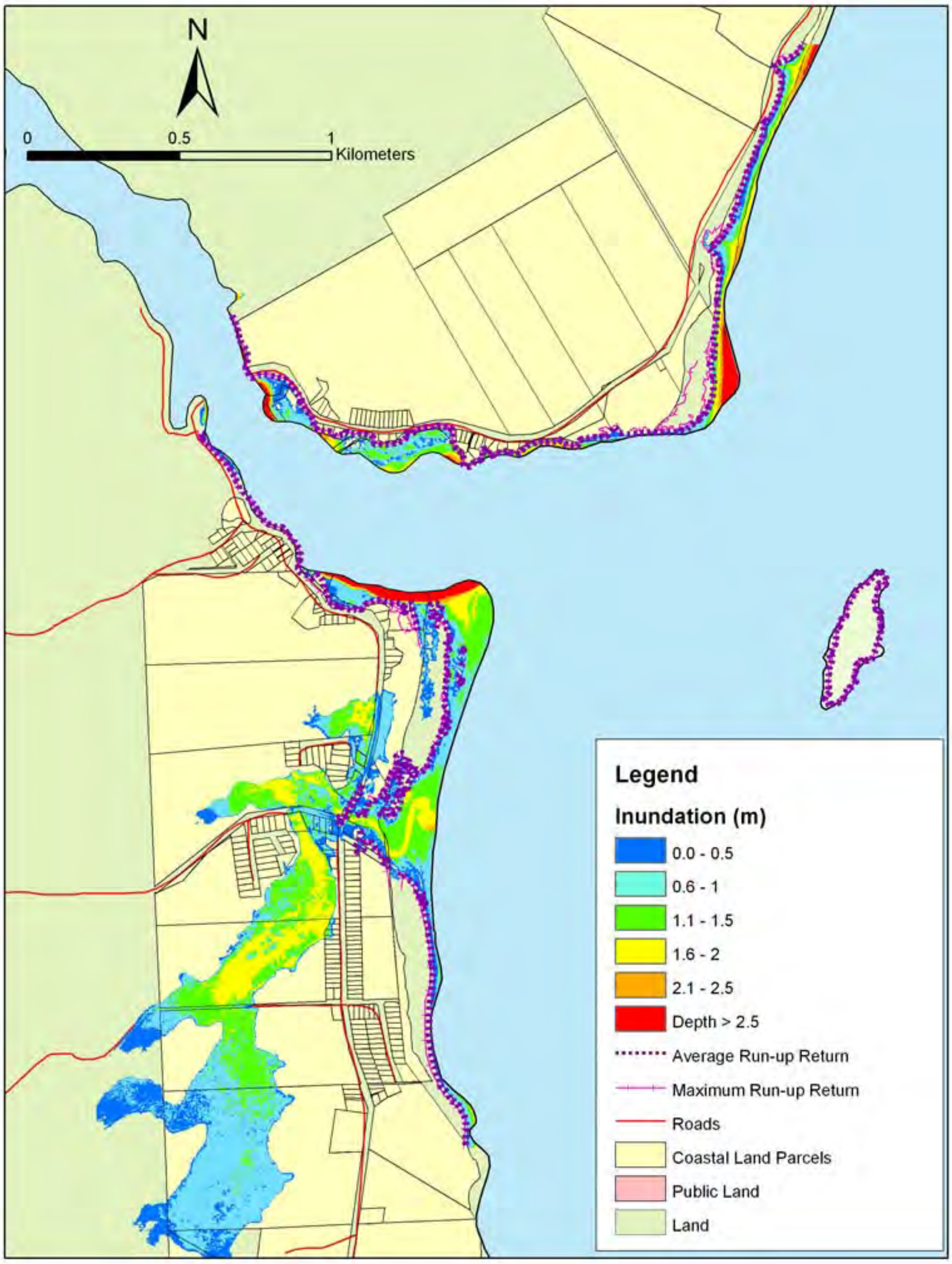

Figure 5.72: Taieri Mouth - 1:500 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up

5.7. Brighton

Predicted inundation and wave run-up extent for present mean sea level are shown in Figures 5.73 – 5.76, for mean sea level + 0.3 m in Figure 5.77 – 5.80, and for mean sea level + 0.5 m in Figure 5.81 – 5.84.

- Maximum predicted sea level height of 2.09 m above MLOS (2.20 m above DVD-58).

- With present MLOS, inundation is predicted along the banks, particularly the north bank, of the Otokia creek and at locations along the coastline.

- Wave run-up along the coastline does not significantly extend beyond the inundation zone.

- Rising sea level significantly increases the extent of predicted inundation along the north bank of the Otokia creek.

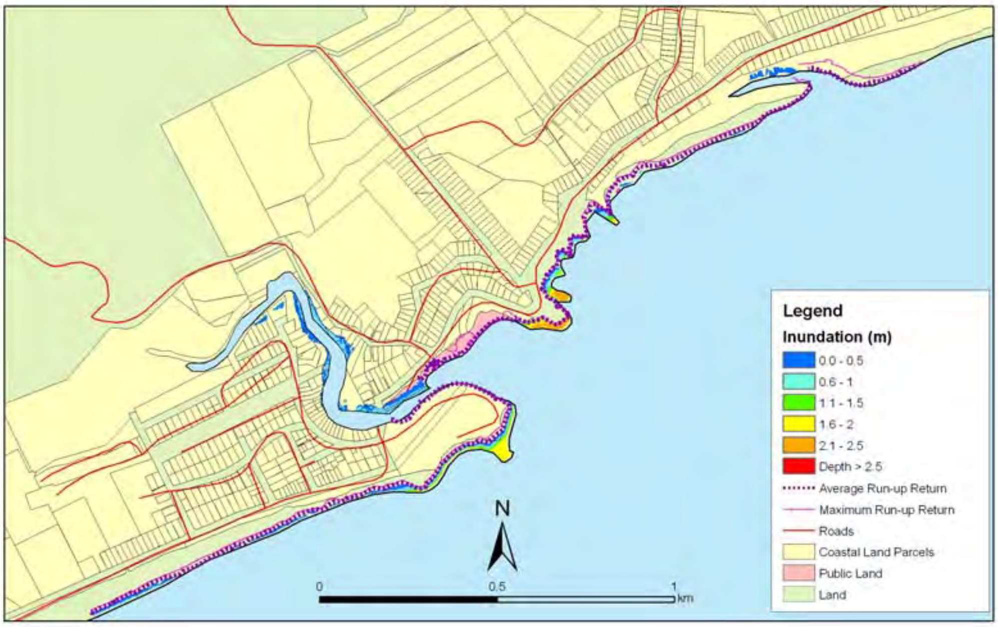

Figure 5.73: Brighton - 1:20 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

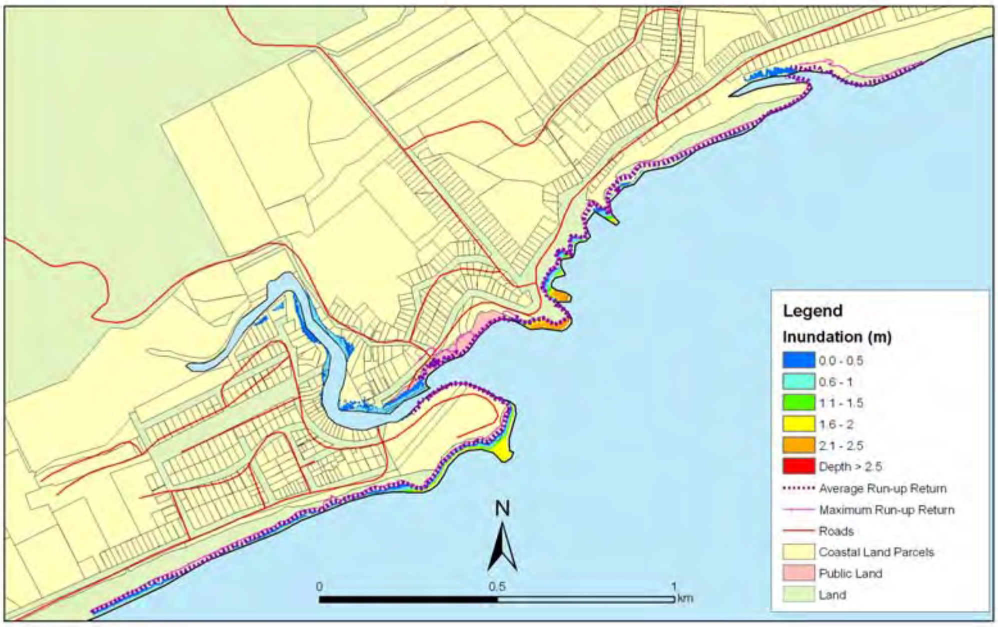

Figure 5.74: Brighton - 1:50 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

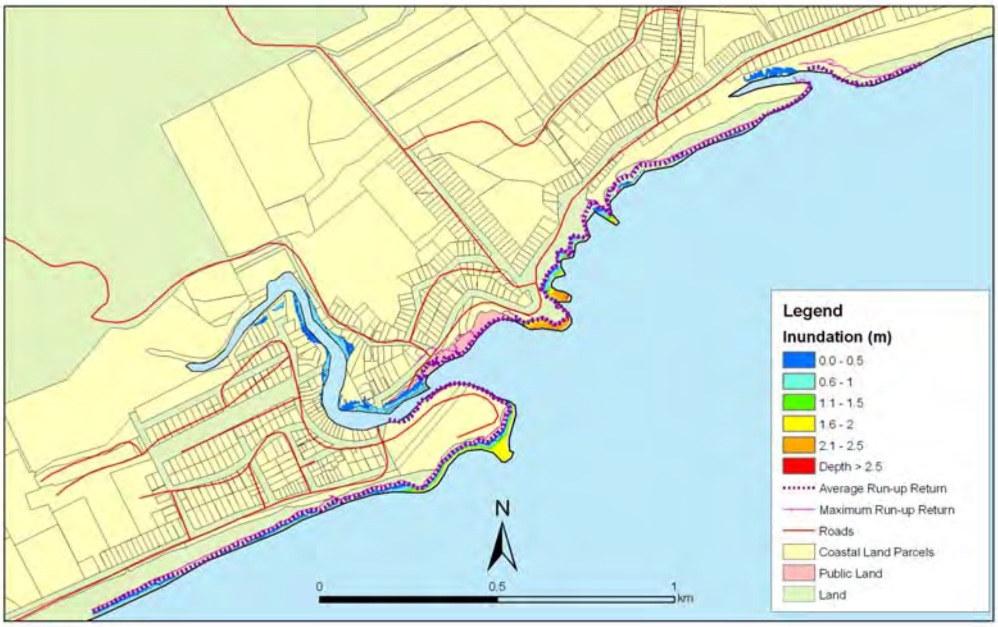

Figure 5.75: Brighton - 1:100 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

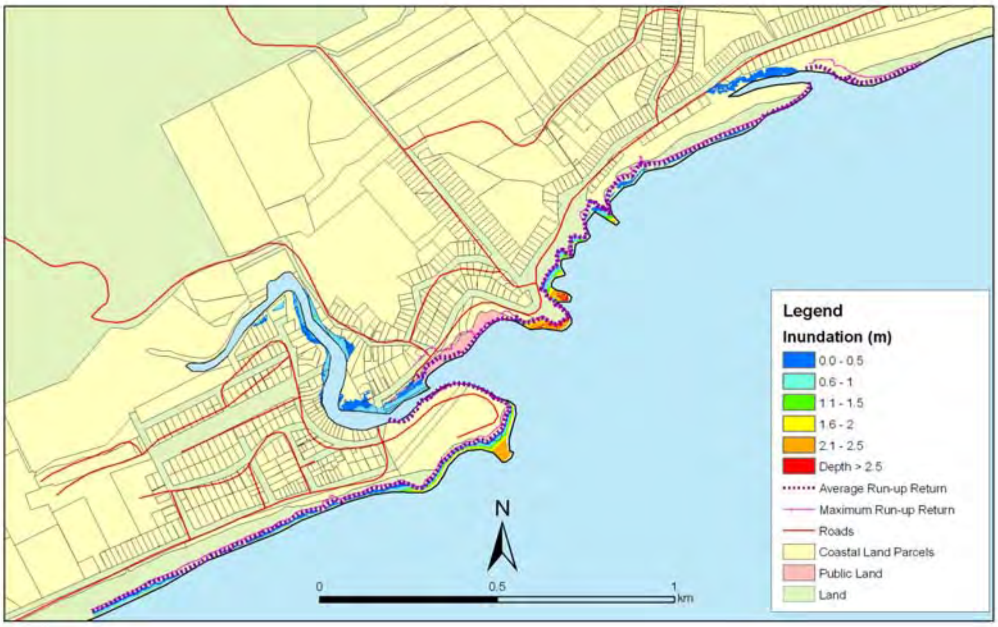

Figure 5.76: Brighton - 1:500 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

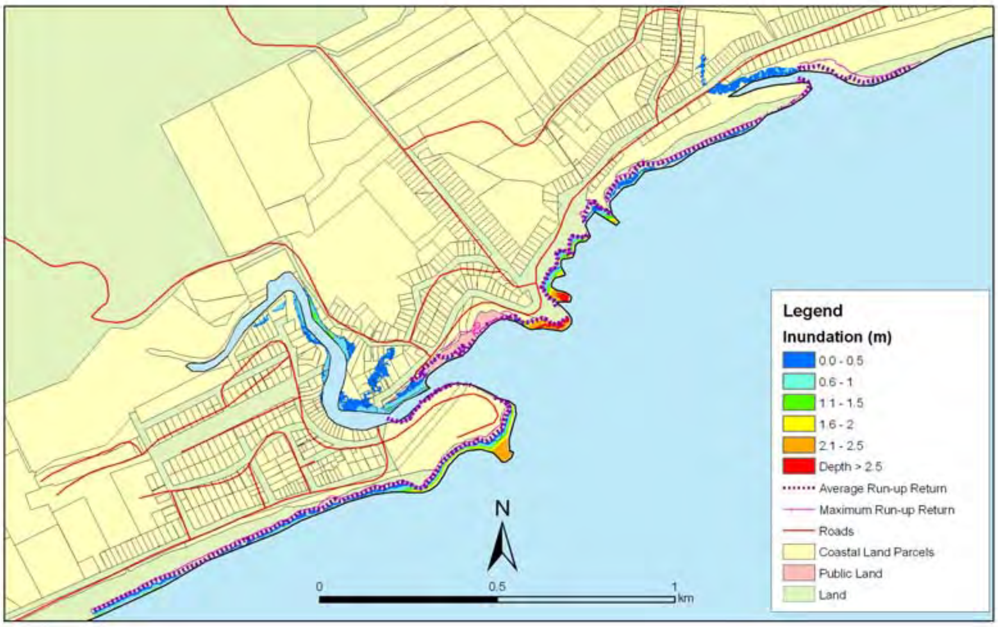

Figure 5.77: Brighton - 1:20 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

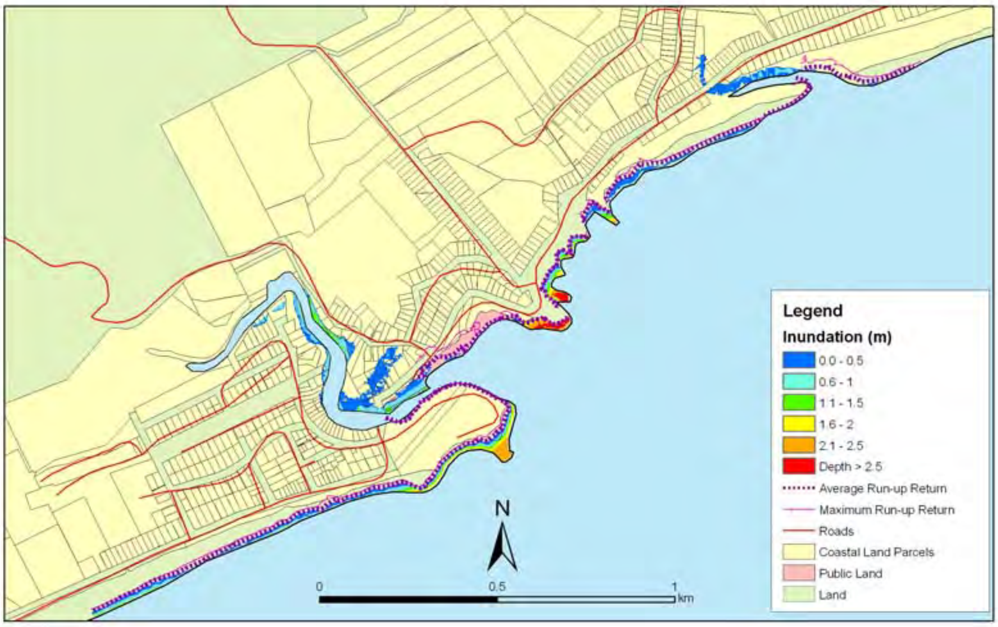

Figure 5.78: Brighton - 1:50 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

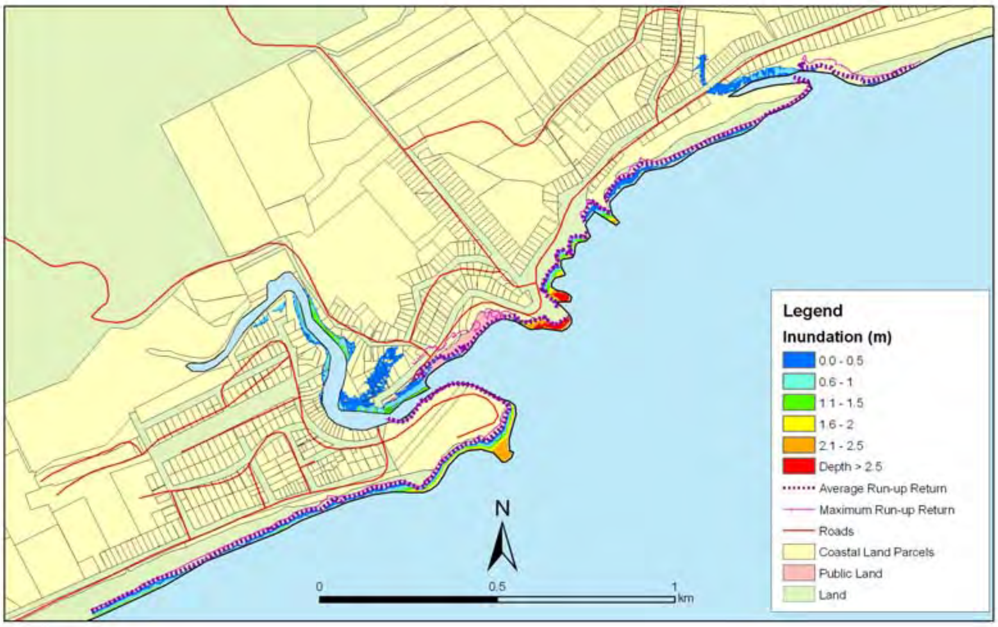

Figure 5.79: Brighton - 1:100 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

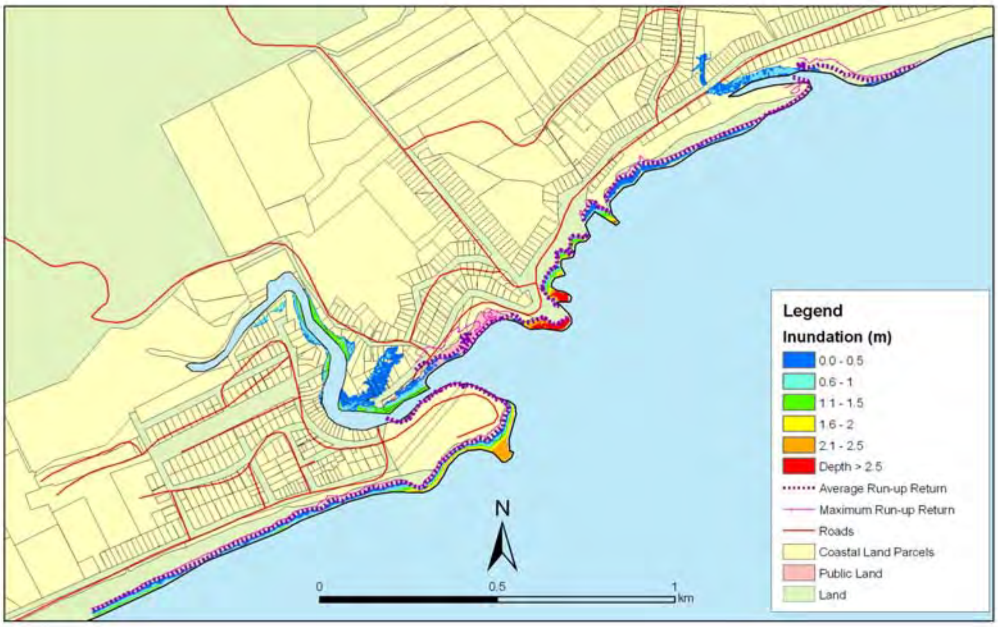

Figure 5.80: Brighton - 1:500 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

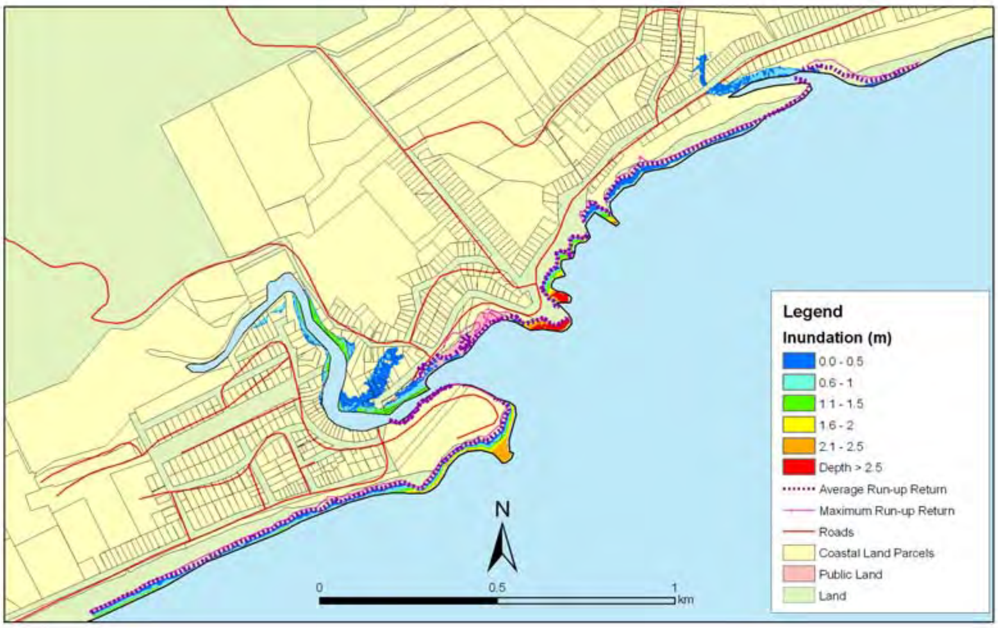

Figure 5.81: Brighton - 1:20 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

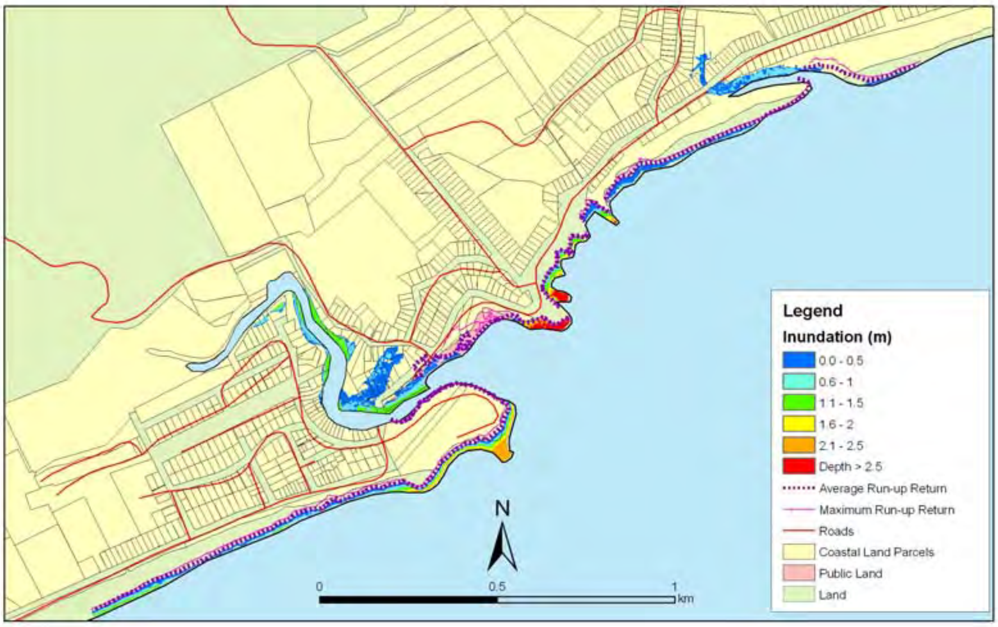

Figure 5.82: Brighton - 1:50 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up**.**

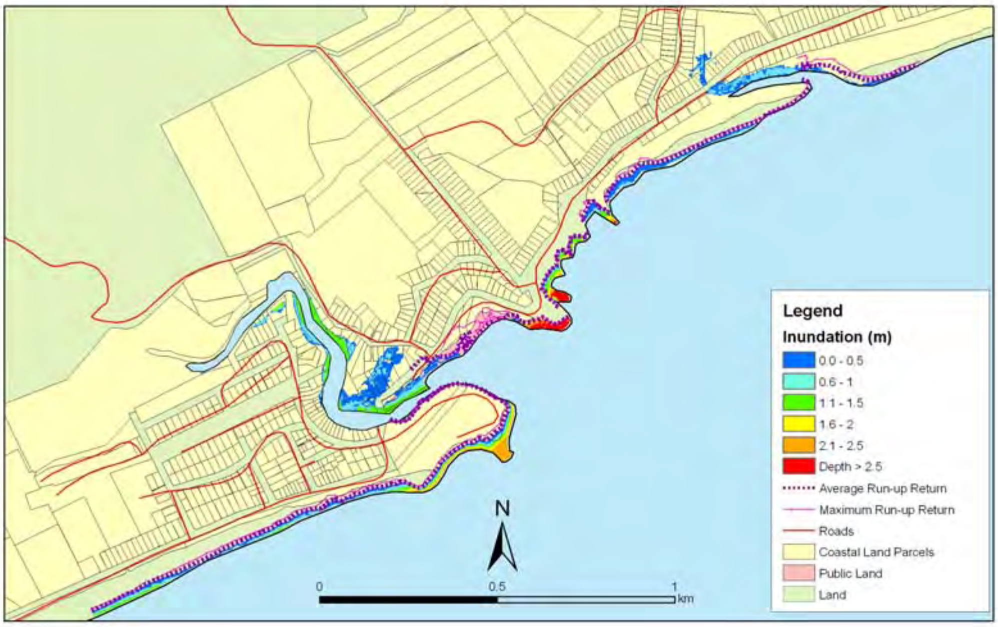

Figure 5.83: Brighton - 1:100 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

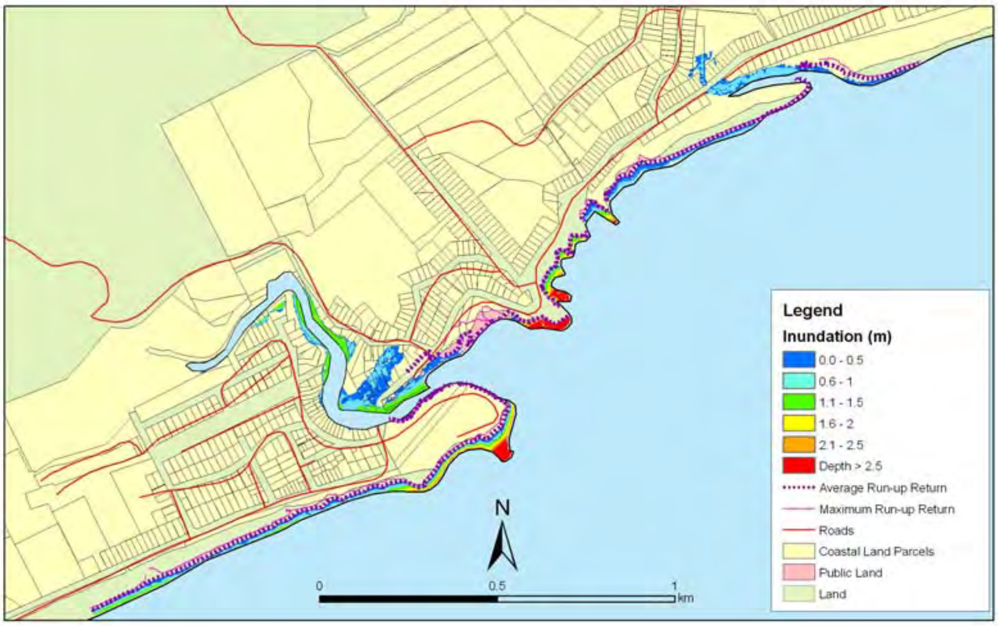

Figure 5.84: Brighton - 1:500 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up

5.8. Kaikorai and Waldronville

Predicted inundation and wave run-up extent for present mean sea level are shown in Figures 5.85 – 5.88, for mean sea level + 0.3 m in Figure 5.89 – 5.92, and for mean sea level + 0.5 m in Figure 5.93 – 5.96.

- Maximum predicted sea level height of 2.04 m above MLOS (2.15 m above DVD-58).
- Predicted inundation is negligible at present MLOS, except for a small extent at the mouth of the Kaikorai stream for a 1:500 year event. Potential areas of inundation are shown further upstream. The exact heights of the land within the marked area are not known (since LiDAR data are not available) and this will critically affect whether sea levels inundate the area.
- Wave run-up is confined to the coastline.
- Predicted inundation and run-up extent at the mouth of the Kaikorai stream does increase noticeably with rising sea level.

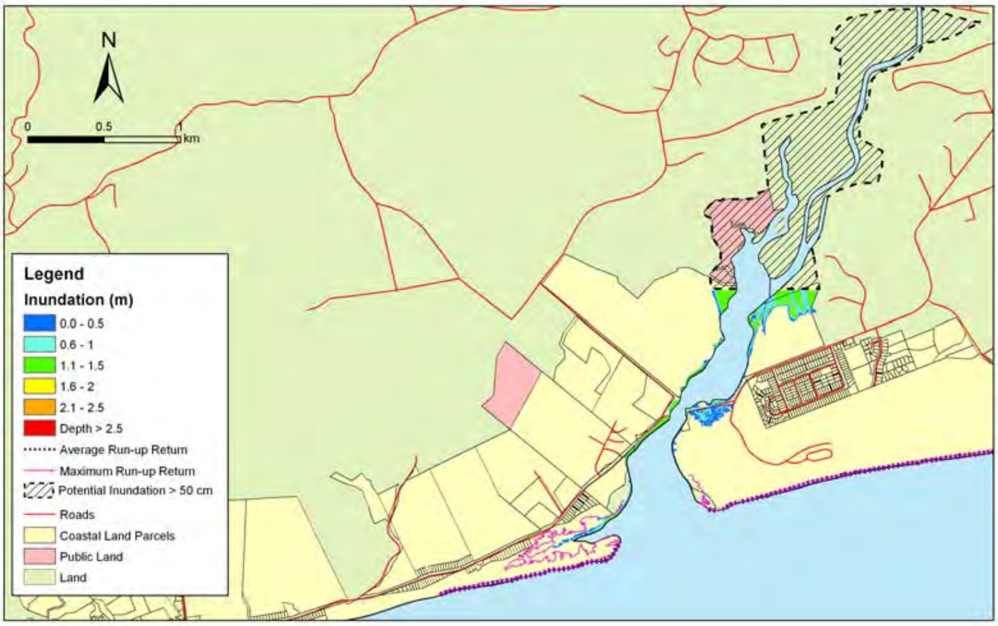

Figure 5.85: Kaikorai and Waldronville - 1:20 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

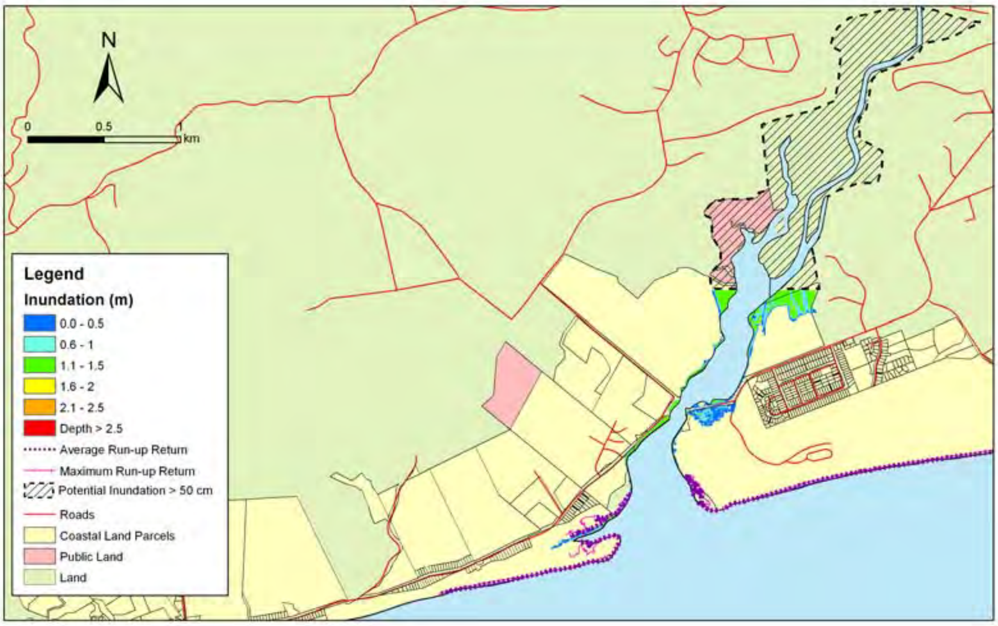

Figure 5.86: Kaikorai and Waldronville - 1:50 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

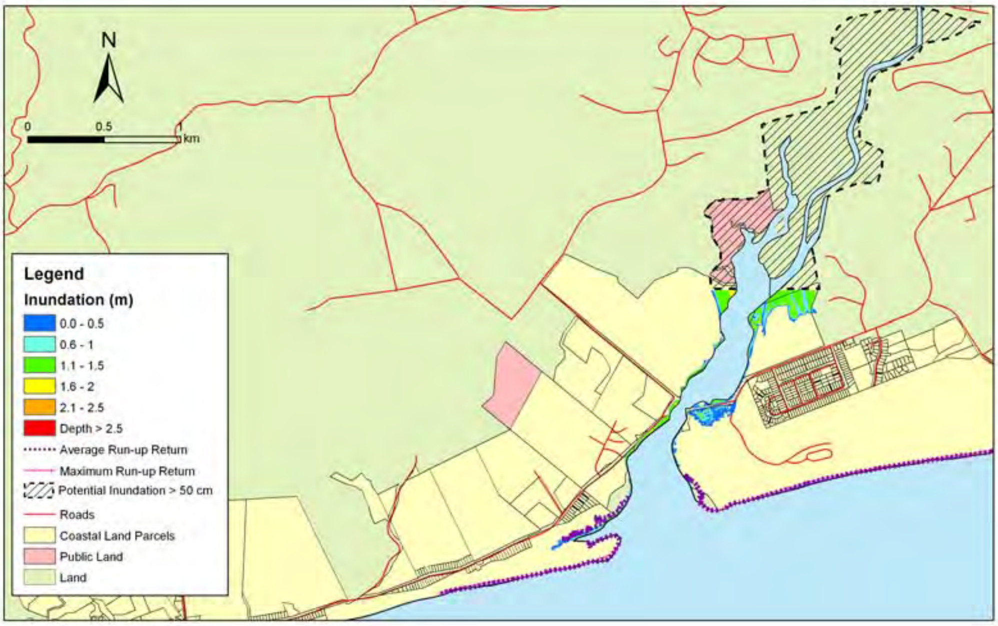

Figure 5.87: Kaikorai and Waldronville - 1:100 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

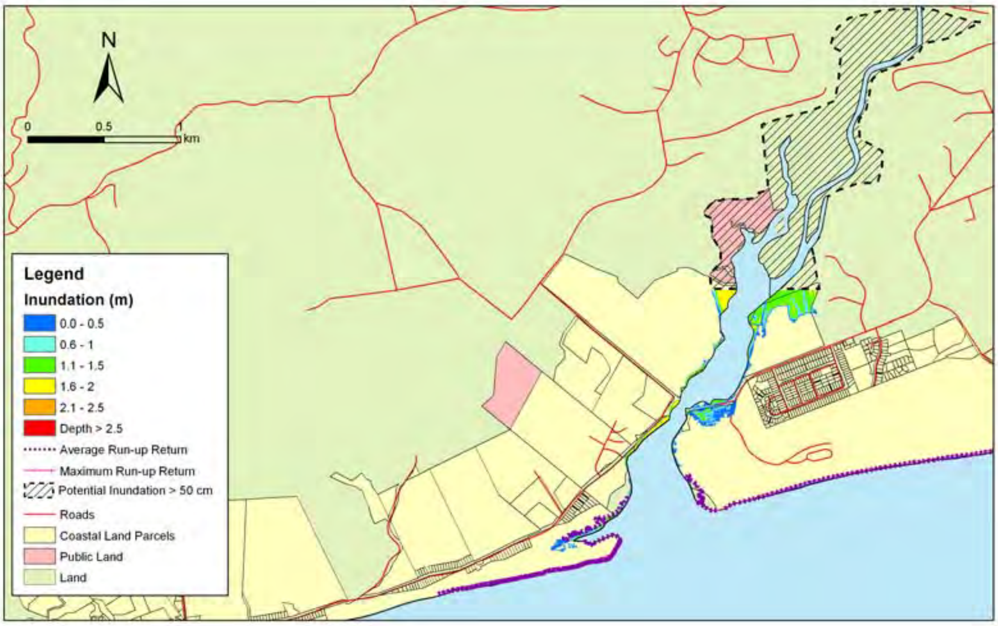

Figure 5.88: Kaikorai and Waldronville - 1:500 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

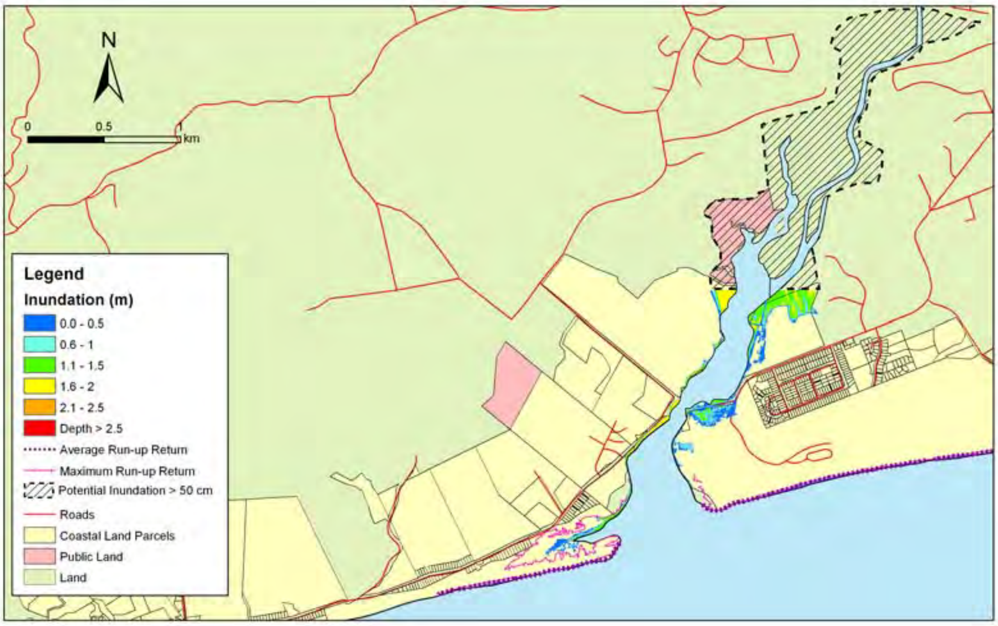

Figure 5.89: Kaikorai and Waldronville - 1:20 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

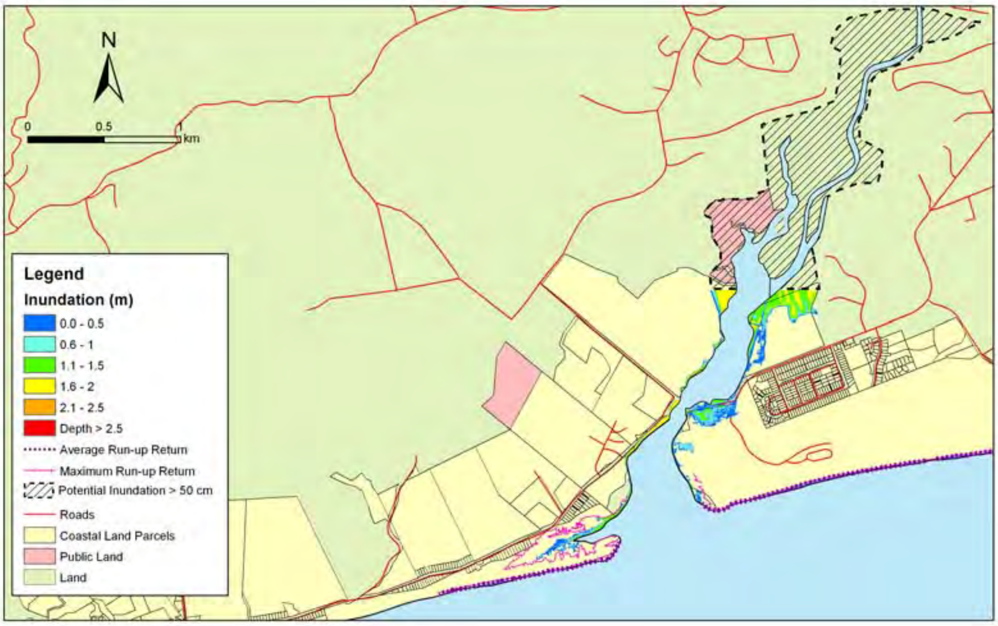

Figure 5.90: Kaikorai and Waldronville - 1:50 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

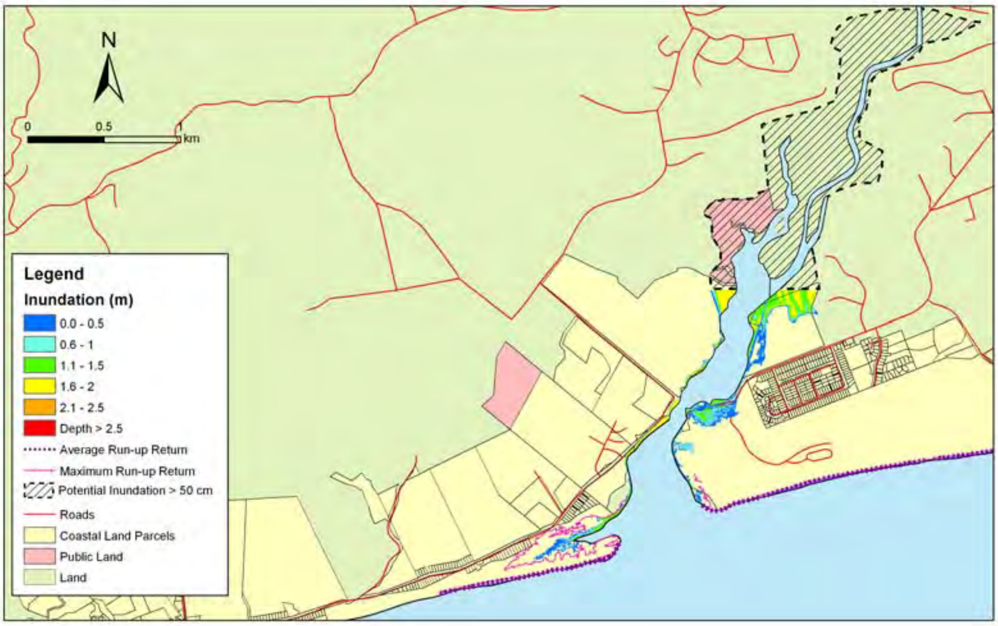

Figure 5.91: Kaikorai and Waldronville - 1:100 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

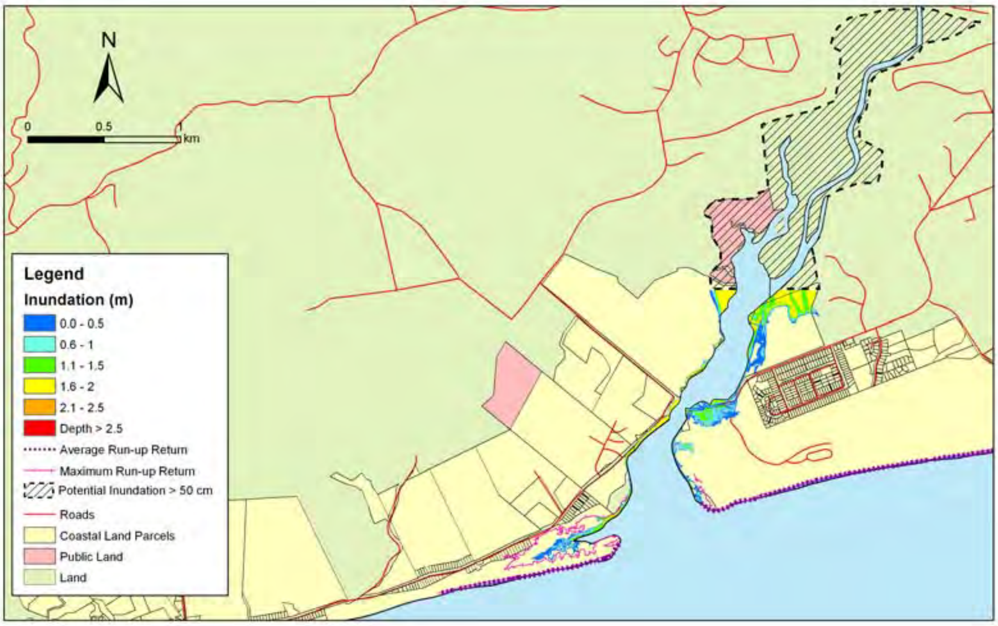

Figure 5.92: Kaikorai and Waldronville - 1:500 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

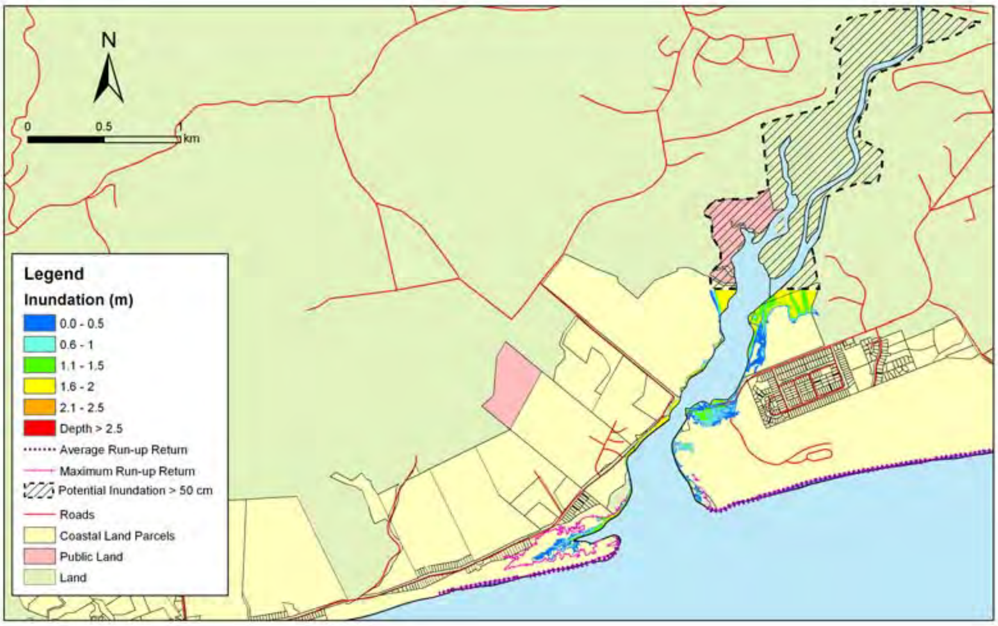

Figure 5.93: Kaikorai and Waldronville - 1:20 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

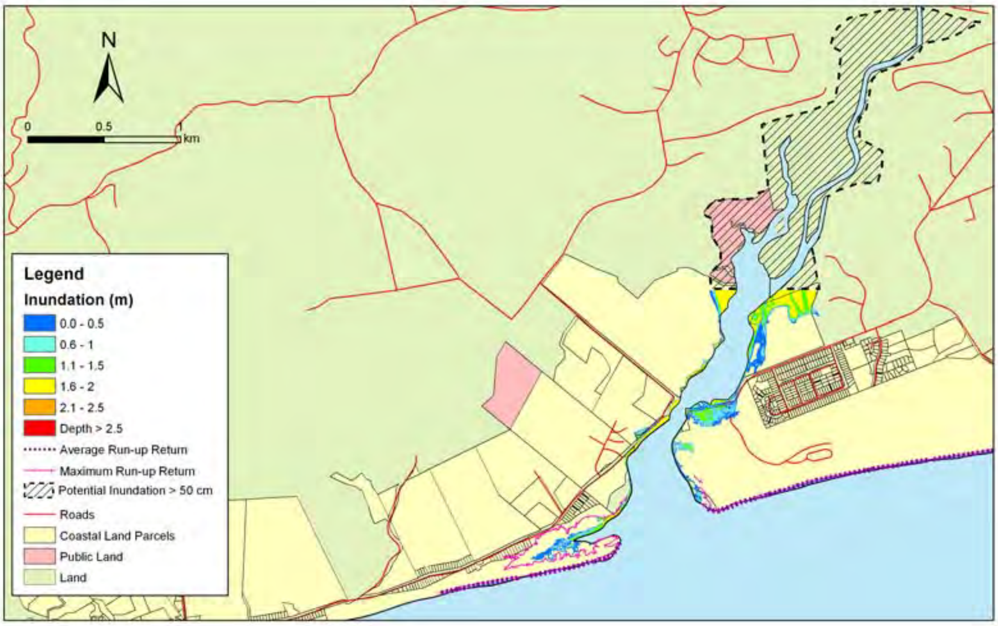

Figure 5.94: Kaikorai and Waldronville - 1:50 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

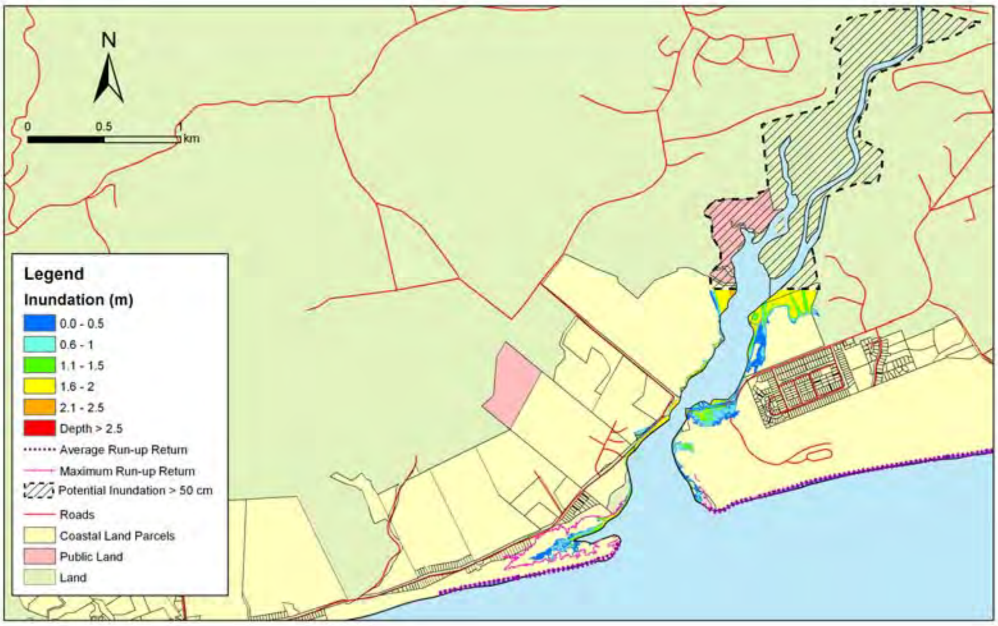

Figure 5.95: Kaikorai and Waldronville - 1:100 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

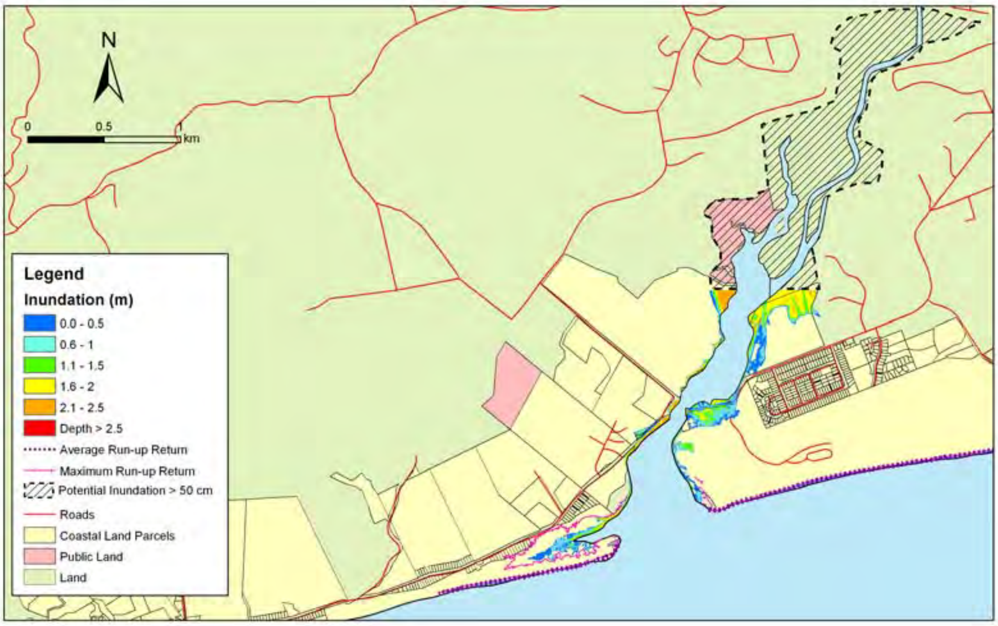

Figure 5.96: Kaikorai and Waldronville - 1:500 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up**.**

5.9 South Dunedin

Predicted inundation and wave run-up extent for present mean sea level are shown in Figures 5.97 – 5.100, for mean sea level + 0.3 m in Figure 5.101 – 5.104, and for mean sea level + 0.5 m in Figure 5.105 – 5.108. Erosion processes are not included in this modelling process, and therefore coastlines susceptible to erosion are represented as resilient features in the model due to the fixed topographic bed. It should be noted that the inundation scenarios for South Dunedin are based upon the 2004 LiDAR survey and therefore reflect the dune topography at that time. Dune systems such as those at South Dunedin are subject to change over time and caution should be observed in the interpretation of the inundation data.

- Maximum predicted sea level height: 2.05 m above MLOS (2.16 m above DVD-58).

- At present MLOS, predicted inundation is confined to the coastline. Predicted wave run-up is also limited to the coastline.

- Rising sea levels increase the depth of predicted inundation but do not noticeably increase the extent.

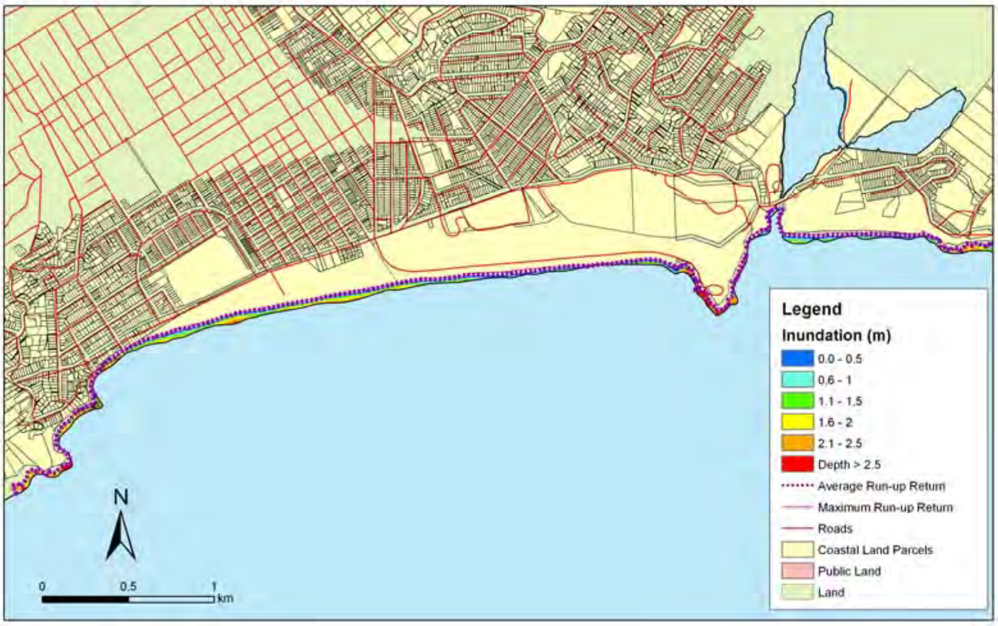

Figure 5.97: South Dunedin - 1:20 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

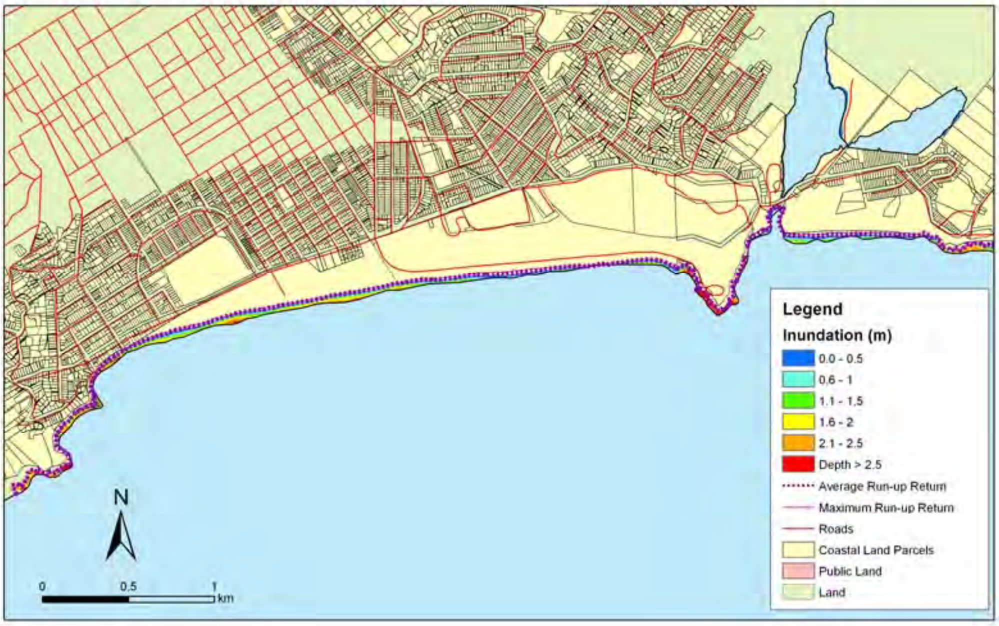

Figure 5.98: South Dunedin - 1:50 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

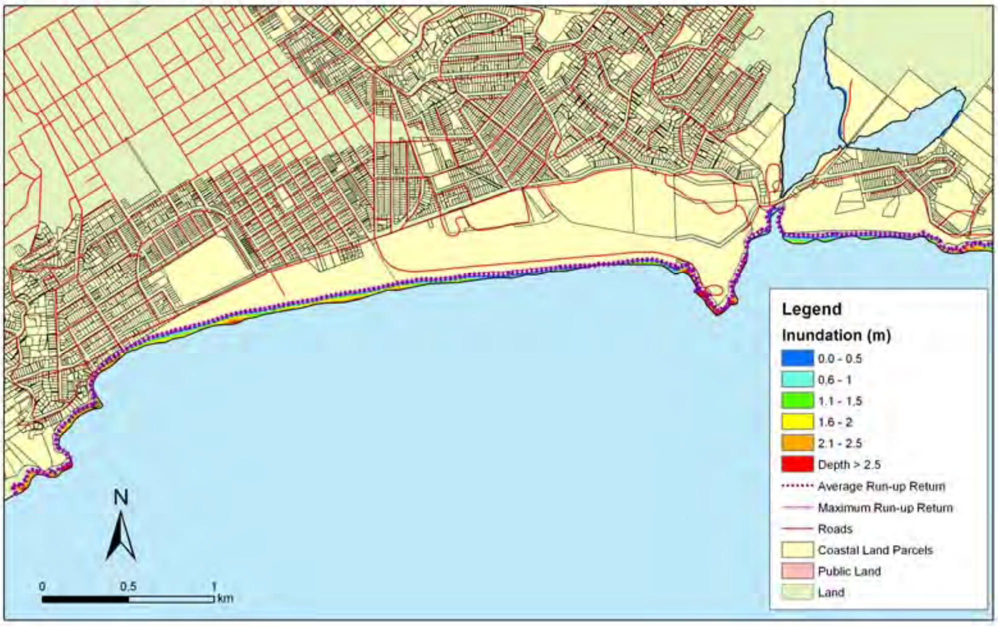

Figure 5.99: South Dunedin - 1:100 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.100: South Dunedin - 1:500 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.101: South Dunedin - 1:20 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.102: South Dunedin - 1:50 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up**.**

Figure 5.103: South Dunedin - 1:100 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.104: South Dunedin - 1:500 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.105: South Dunedin - 1:20 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.106: South Dunedin - 1:50 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.107: South Dunedin - 1:100 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

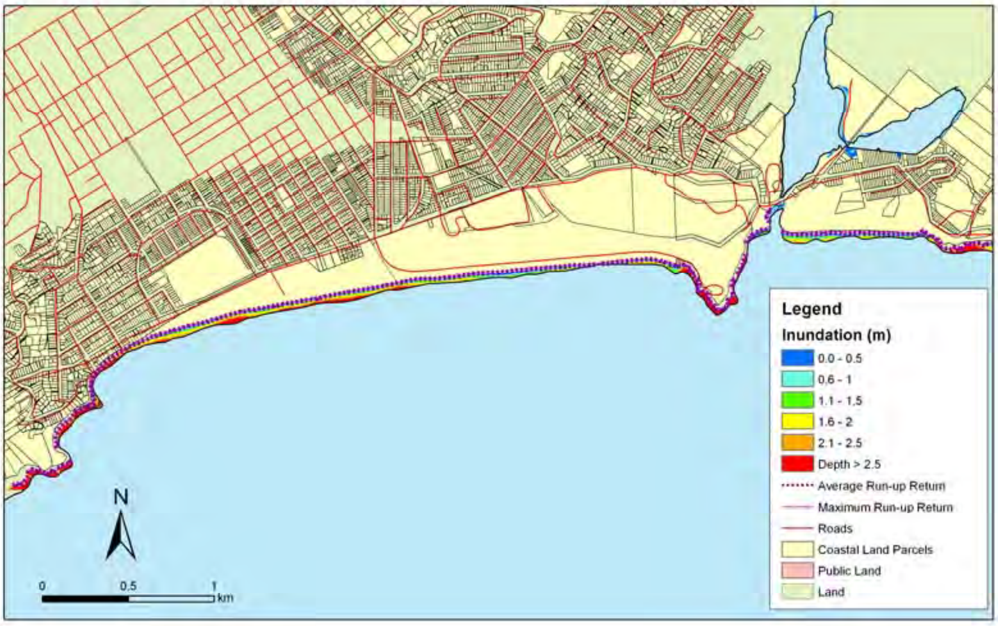

Figure 5.108: South Dunedin - 1:500 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up

5.10 Dunedin Harbour

Predicted inundation and wave run-up extent for present mean sea level are shown in Figures 5.109 – 5.112, for mean sea level + 0.3 m in Figure 5.113 – 5.116, and for mean sea level + 0.5 m in Figure 5.117 – 5.120.

- Maximum predicted sea level height: 1.91 m above MLOS (2.02 m above DVD-58).
- At present-day MLOS, inundation is predicted for a narrow strip of land around the edge of the harbour.
- Wave run-up bounds the area of inundation but does not significantly extend the impacted area.
- Rising sea levels have noticeable effects on the depth and extent of inundation around the harbour edge. The areas to the south-west and north of the harbour appear to be particularly susceptible to increased risk in future.

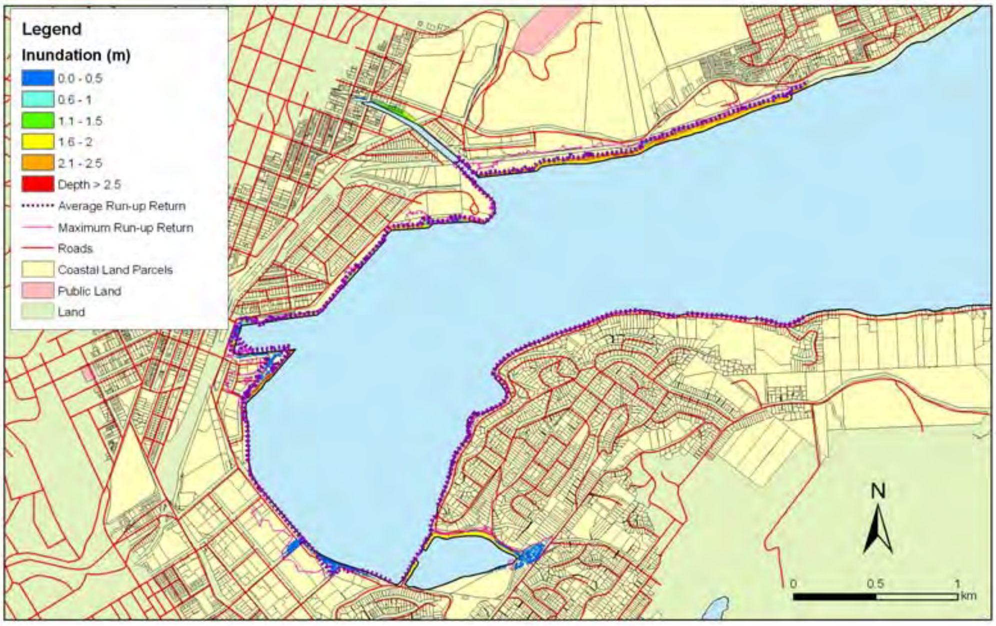

Figure 5.109: Dunedin harbour - 1:20 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

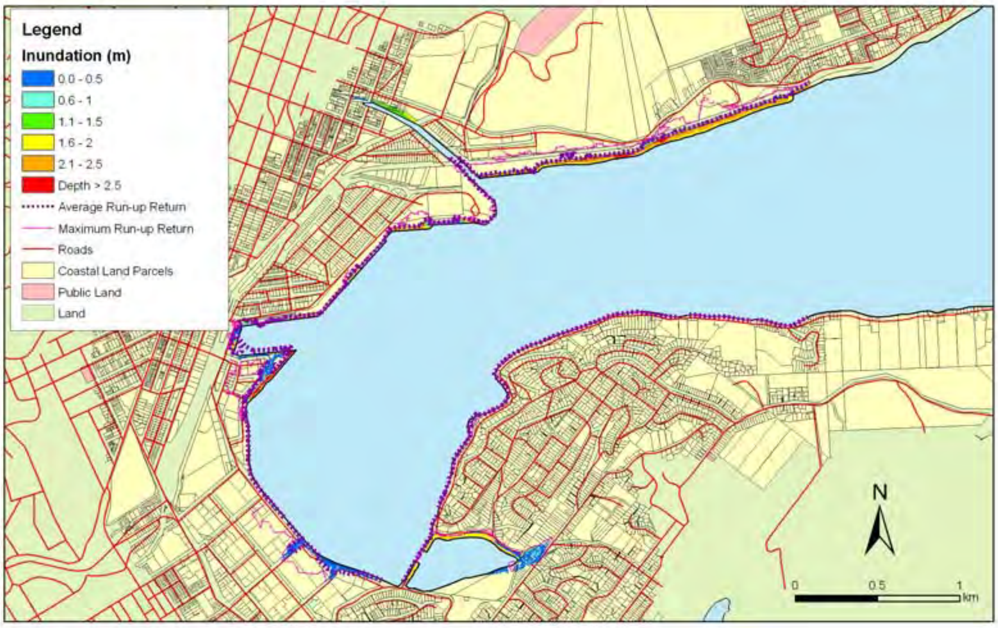

Figure 5.110. Dunedin harbour - 1:50 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

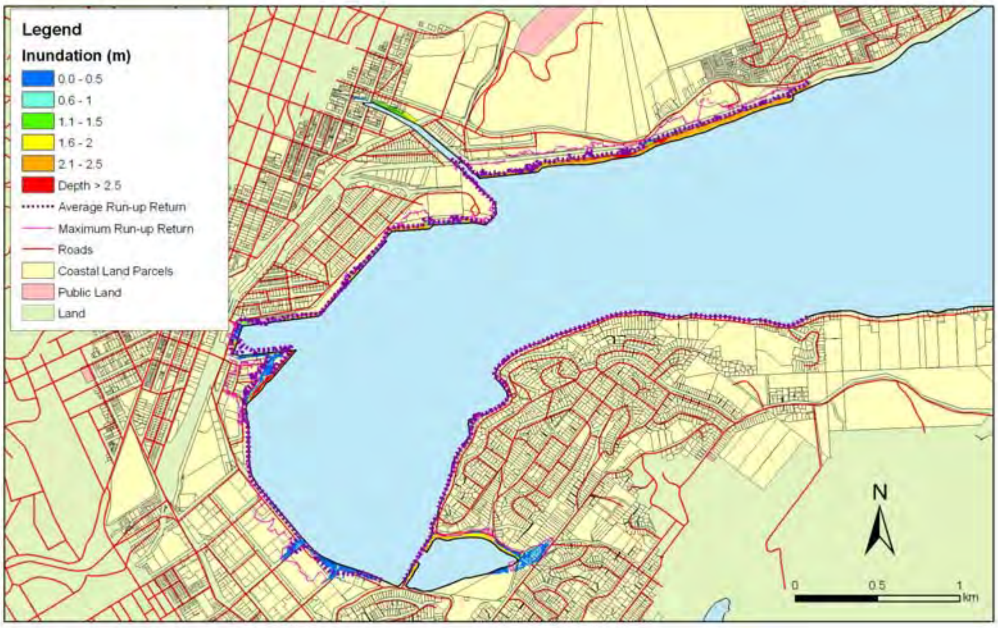

Figure 5.111: Dunedin harbour - 1:100 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

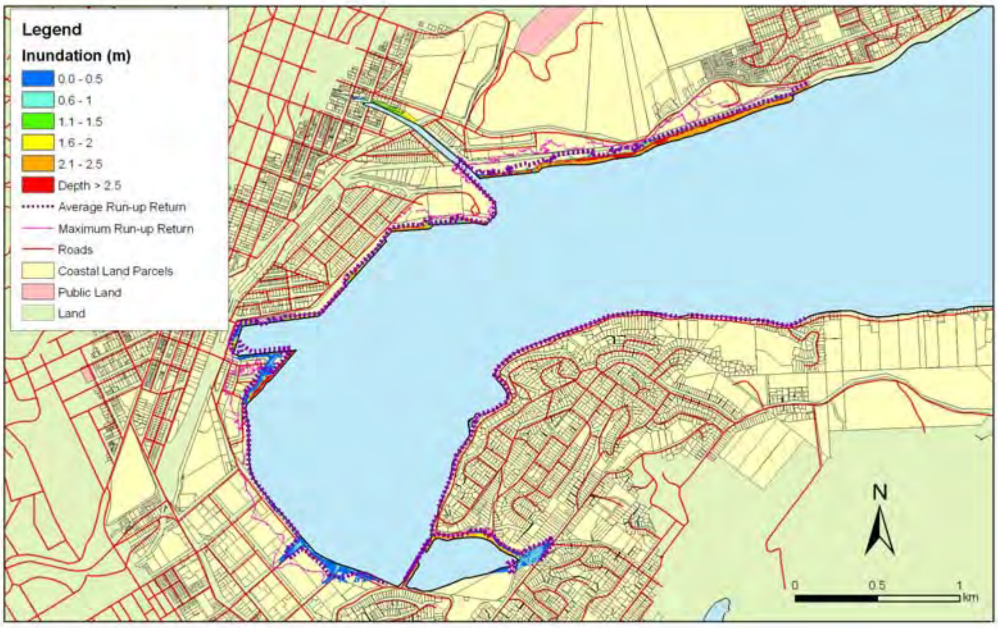

Figure 5.112: Dunedin harbour - 1:500 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

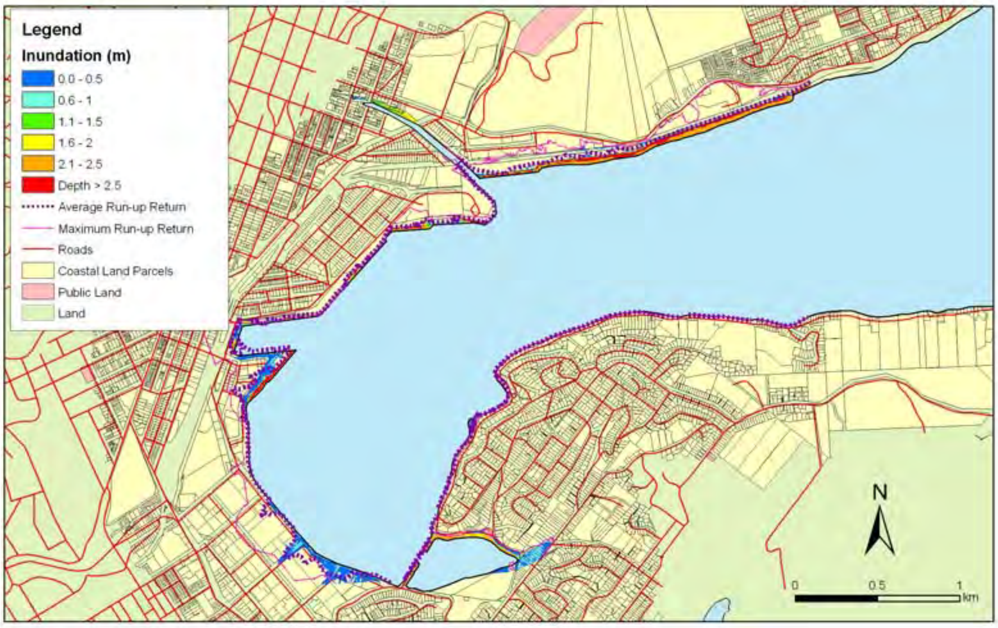

Figure 5.113: Dunedin Harbour - 1:20 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

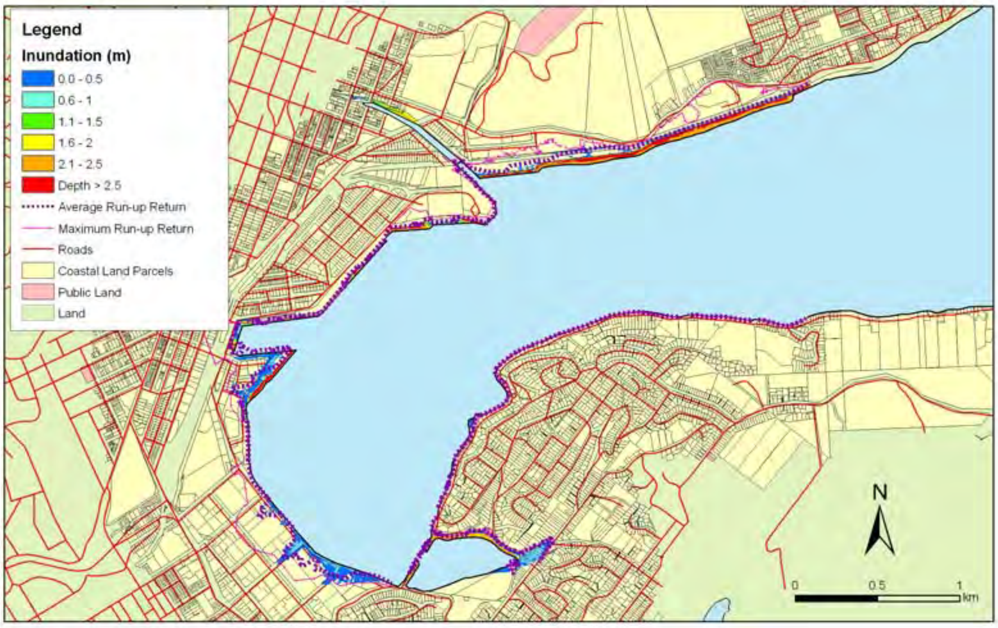

Figure 5.114: Dunedin Harbour - 1:50 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

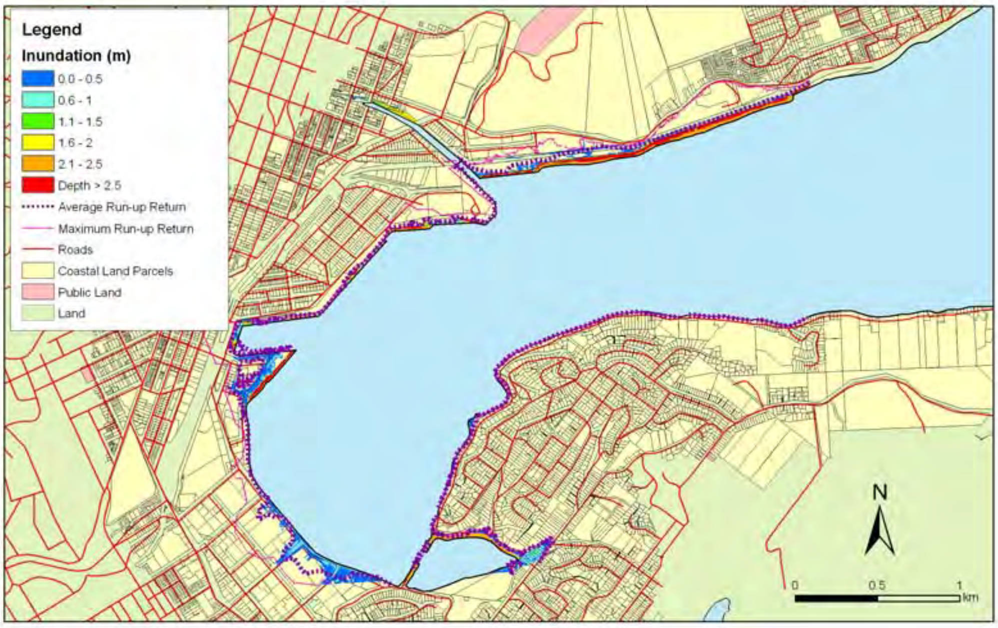

Figure 5.115: Dunedin Harbour - 1:100 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

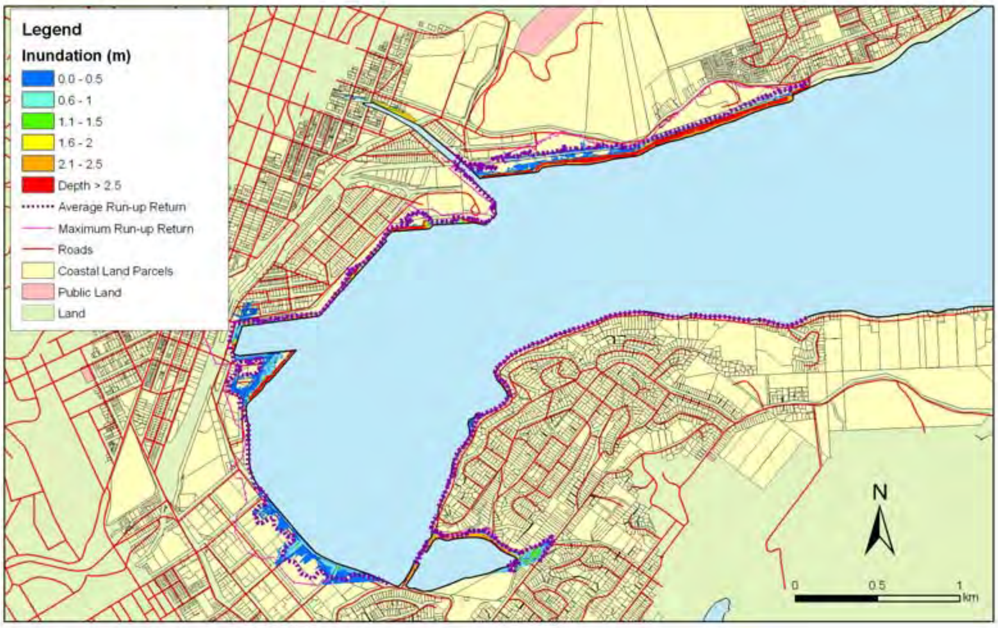

Figure 5.116. Dunedin Harbour - 1:500 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.117: Dunedin Harbour - 1:20 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up**.**

Figure 5.118: Dunedin Harbour - 1:50 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

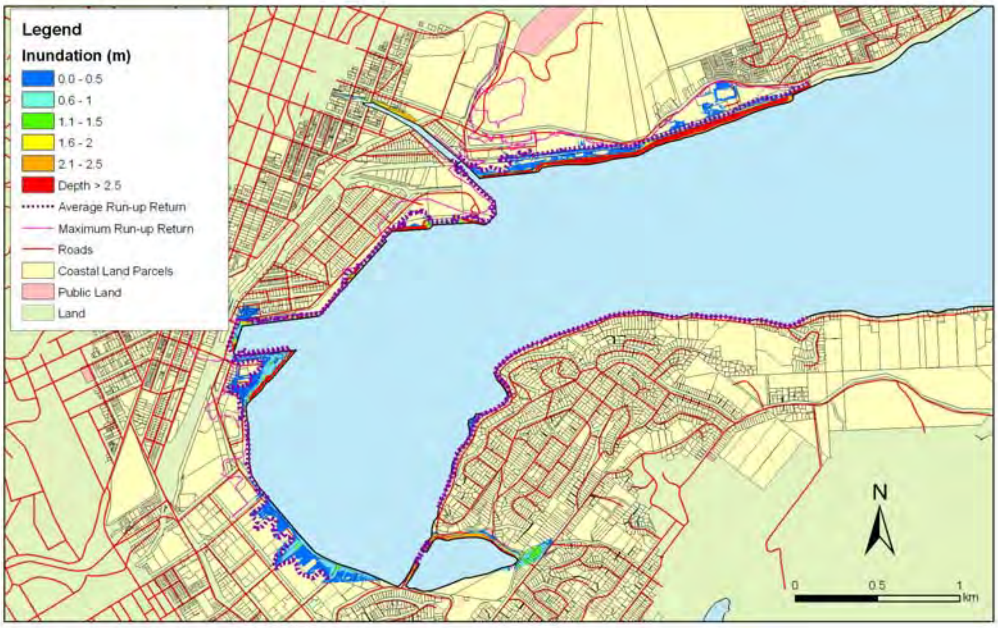

Figure 5.119: Dunedin Harbour - 1:100 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

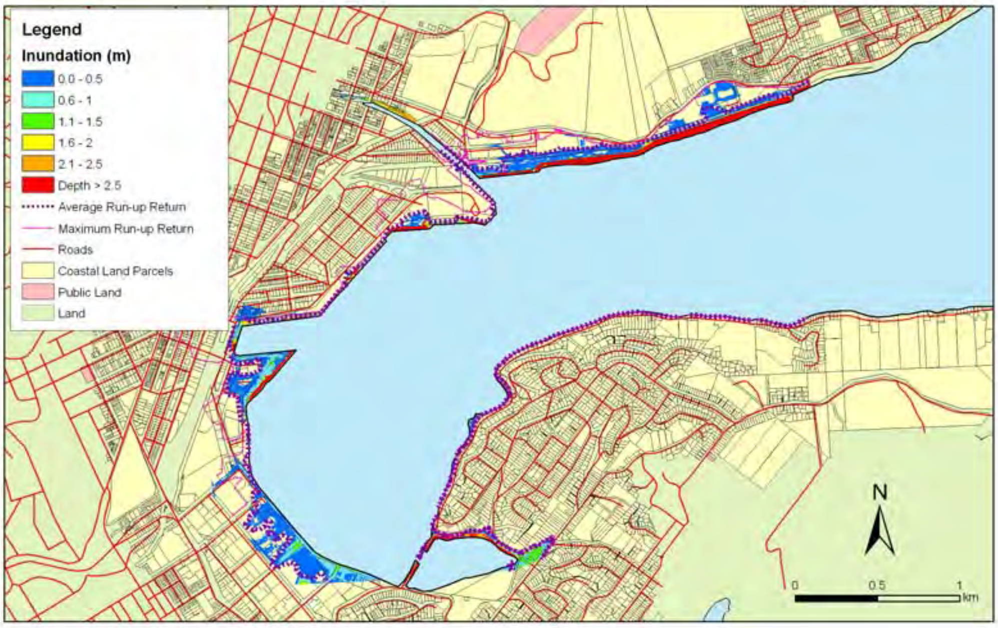

Figure 5.120: Dunedin Harbour - 1:500 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

5.11 Long Beach and Purakanui

Predicted inundation and wave run-up extent for present mean sea level are shown in Figures 5.121 – 5.124, for mean sea level + 0.3 m in Figure 5.125 – 5.128, and for mean sea level + 0.5 m in Figure 5.129– 5.132.

- Maximum predicted sea level height of 1.80 m above MLOS (1.91 m above DVD-58).

- At MLOS, inundation is predicted on the north side of Purakanui inlet and also inshore of Long Beach. The predicted inundation behind Long Beach occurs via a small stream that bisects the beach and provides a direct flood route to the low-lying land behind the village. Elsewhere, inundation is marginal.

- Wave run-up is confined to the coast at Long Beach. In Purakanui inlet, wave run-up extends a little distance inshore from the inundated area.

- Rising sea levels significantly increase the extent of inundation both inshore of Long Beach and to the north of Purakanui inlet.

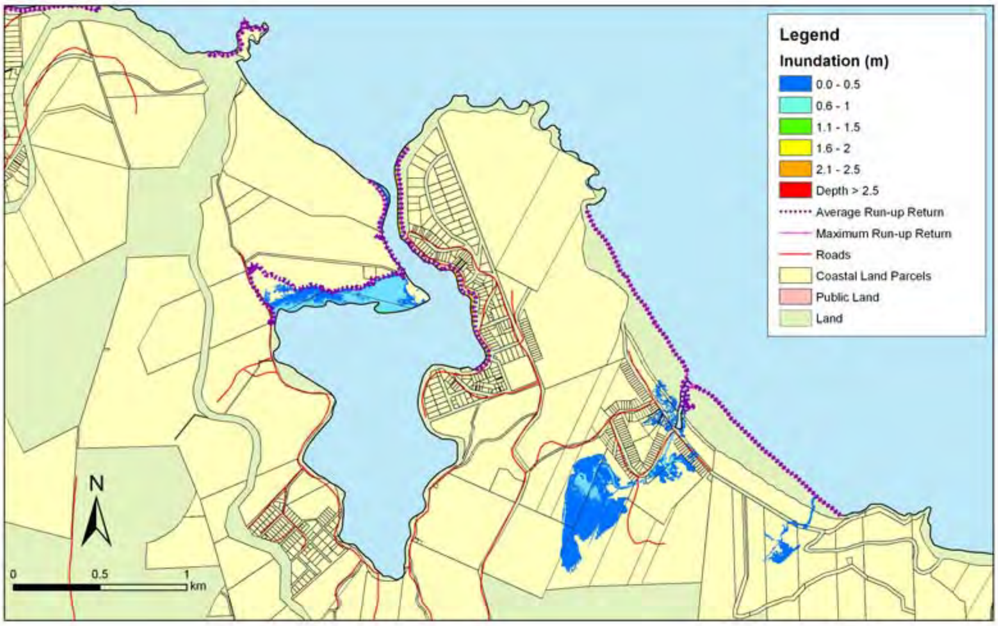

Figure 5.121: Long Beach and Purakanui - 1:20 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

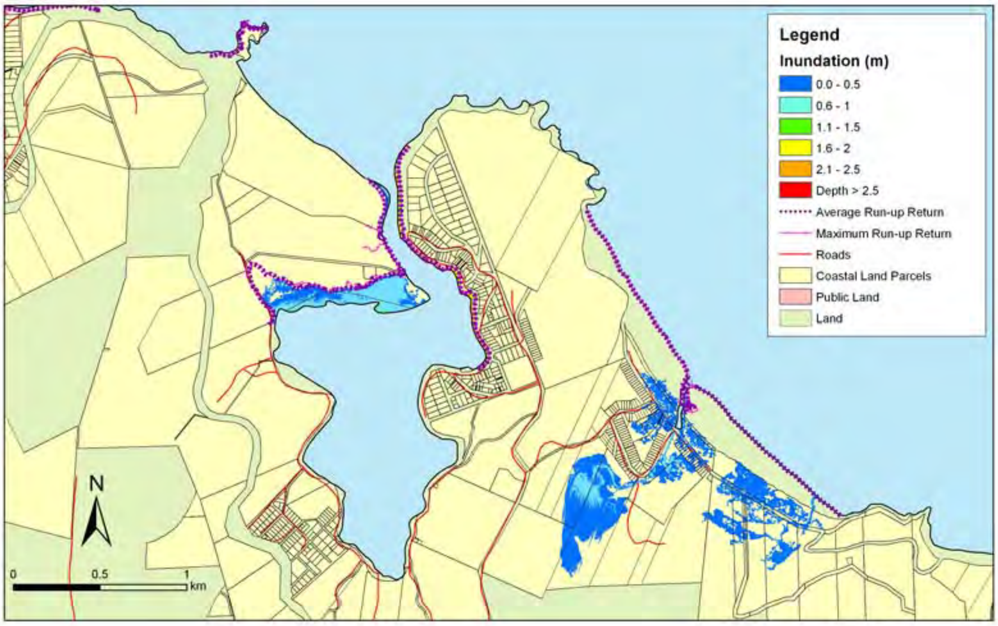

Figure 5.122: Long Beach and Purakanui - 1:50 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

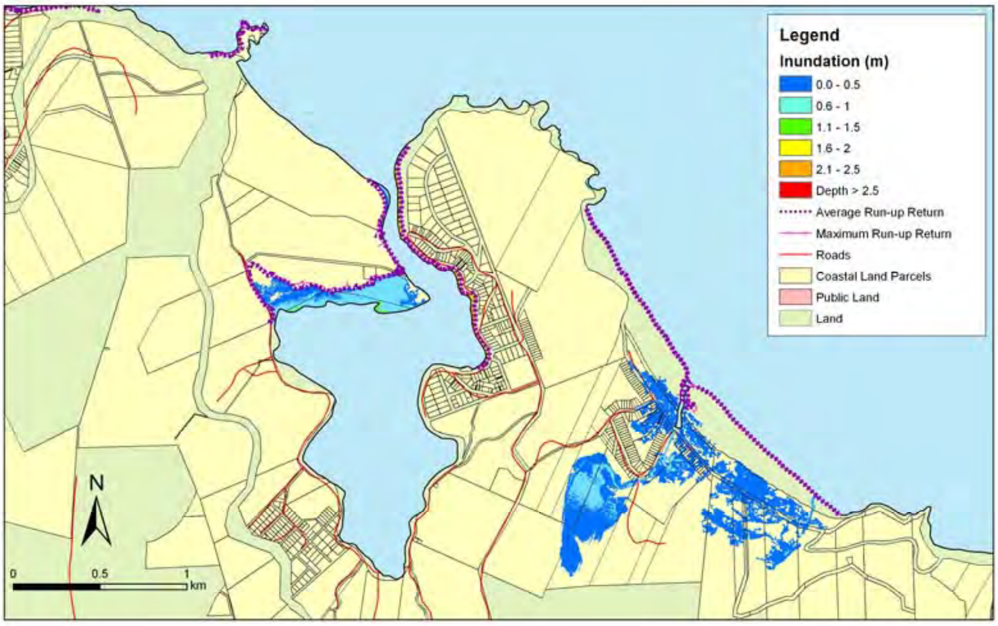

Figure 5.123: Long Beach and Purakanui - 1:100 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

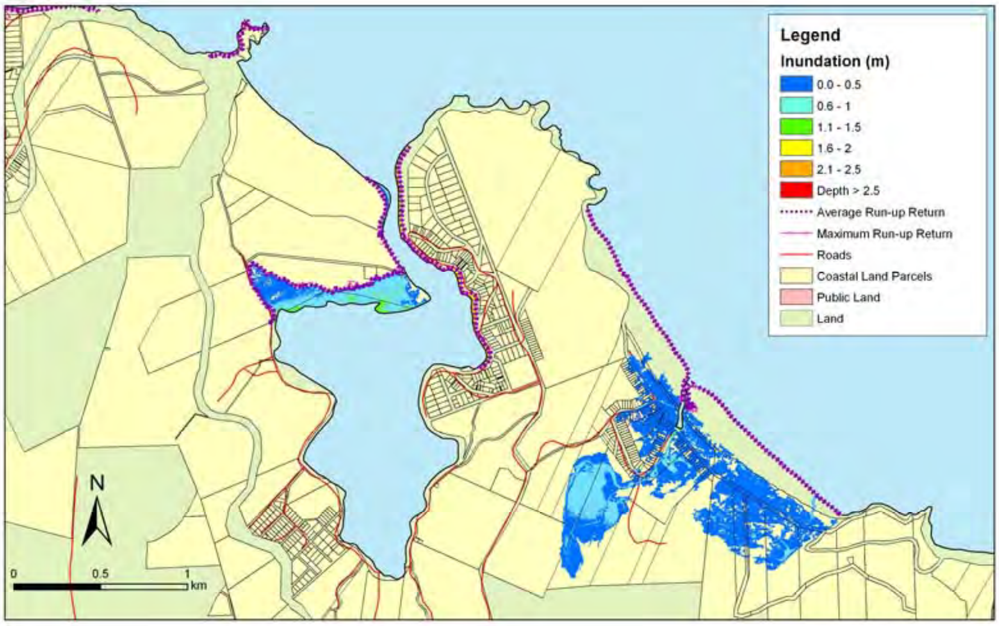

Figure 5.124: Long Beach and Purakanui - 1:500 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

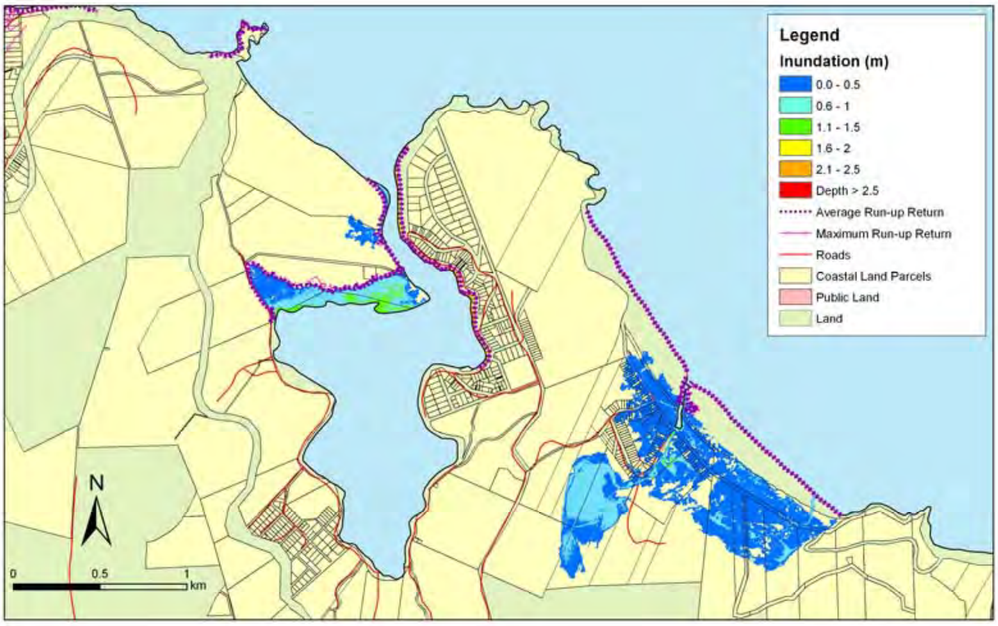

Figure 5.125: Long Beach and Purakanui - 1:20 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

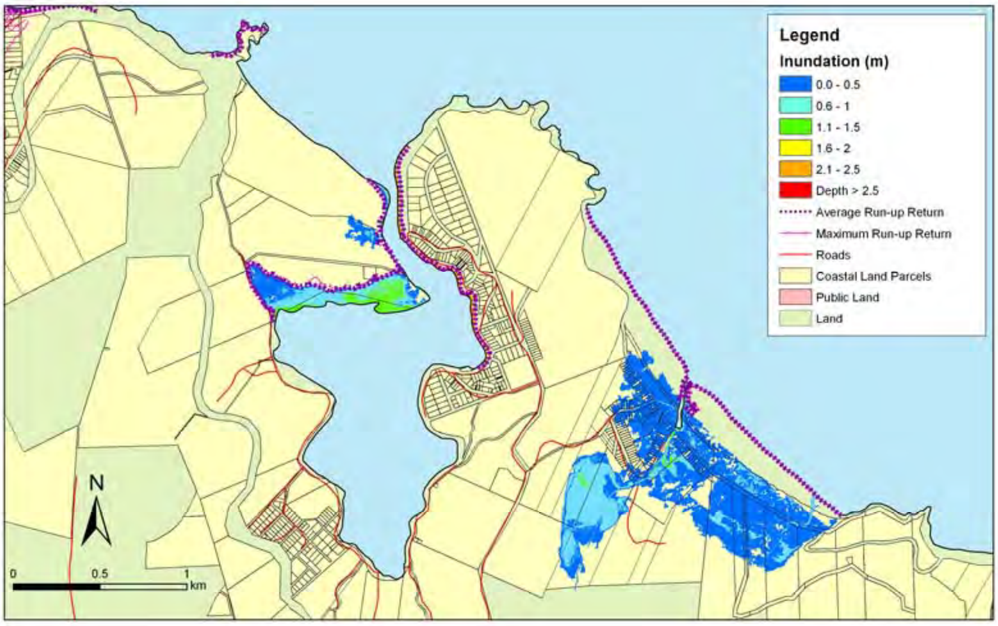

Figure 5.126: Long Beach and Purakanui - 1:50 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

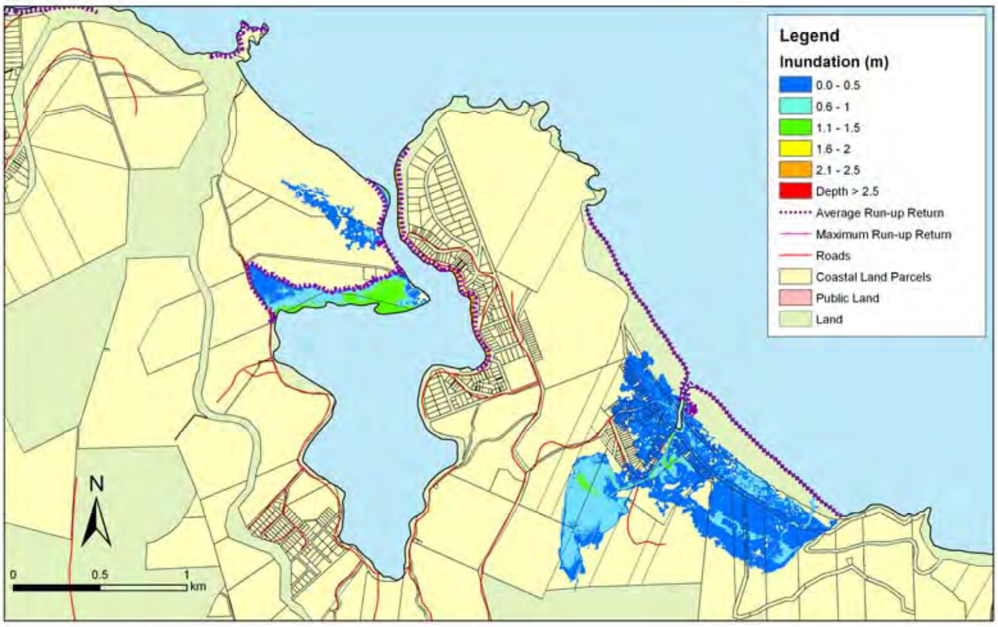

Figure 5.127: Long Beach and Purakanui - 1:100 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

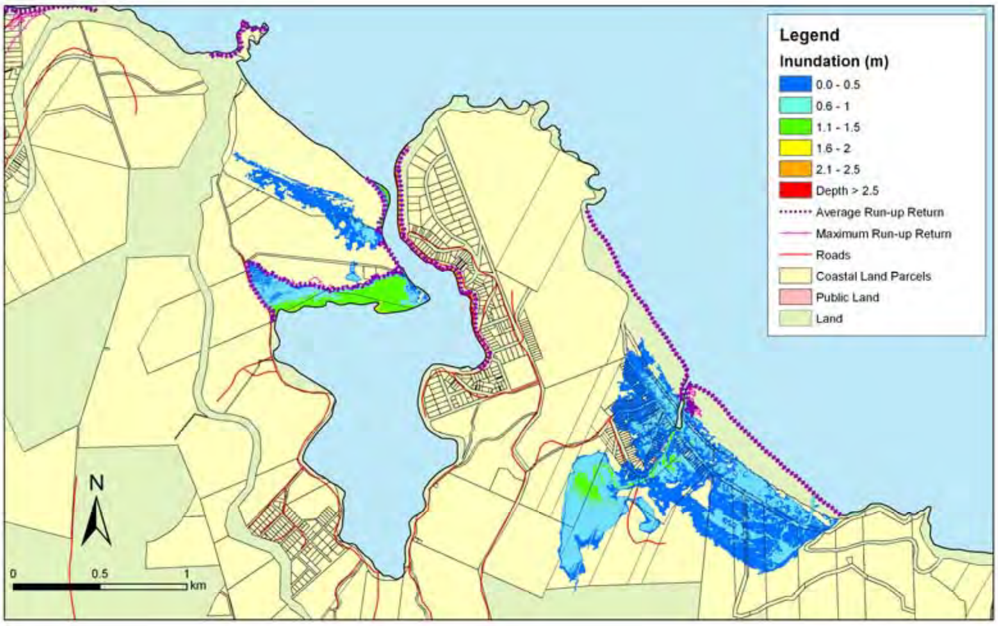

Figure 5.128: Long Beach and Purakanui - 1:500 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

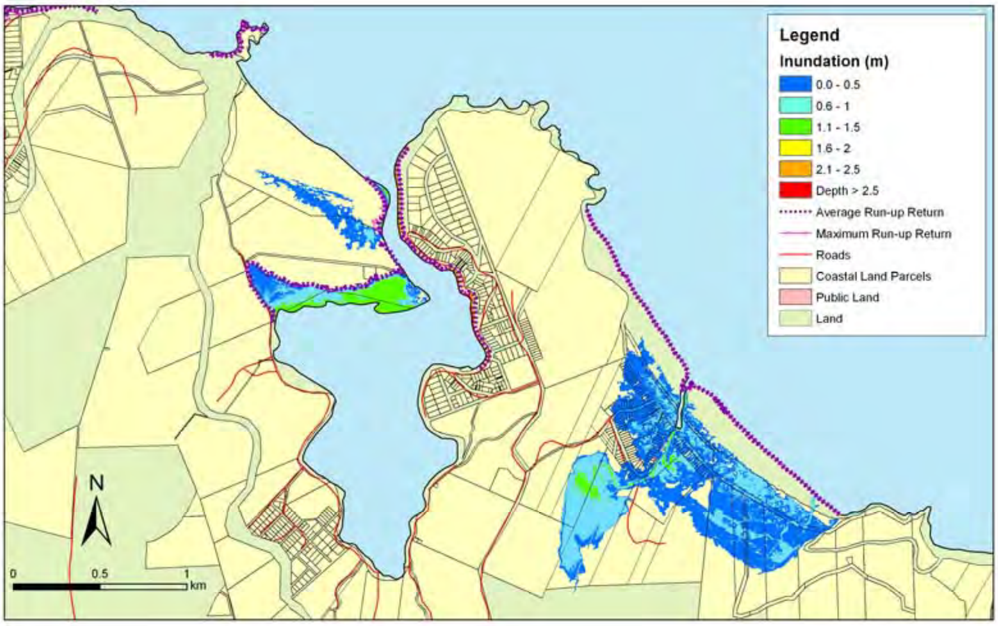

Figure 5.129: Long Beach and Purakanui - 1:20 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

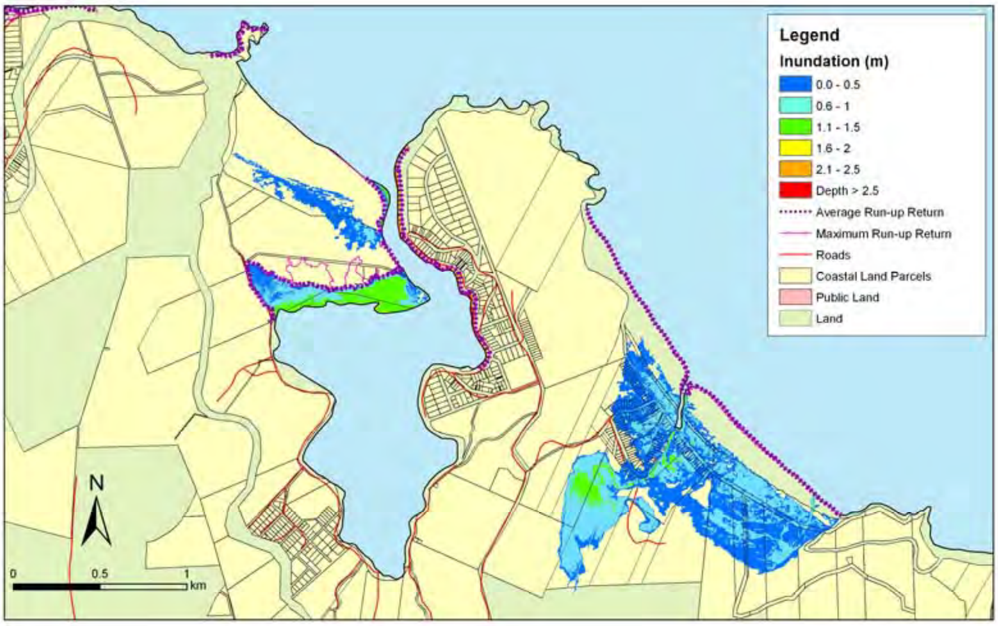

Figure 5.130: Long Beach and Purakanui - 1:50 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

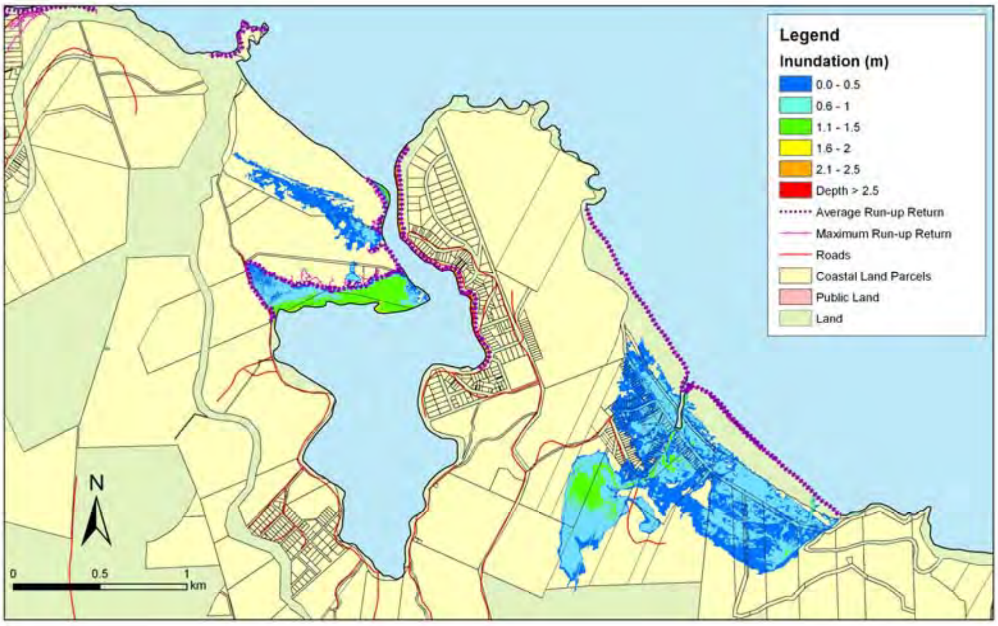

Figure 5.131: Long Beach and Purakanui - 1:100 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

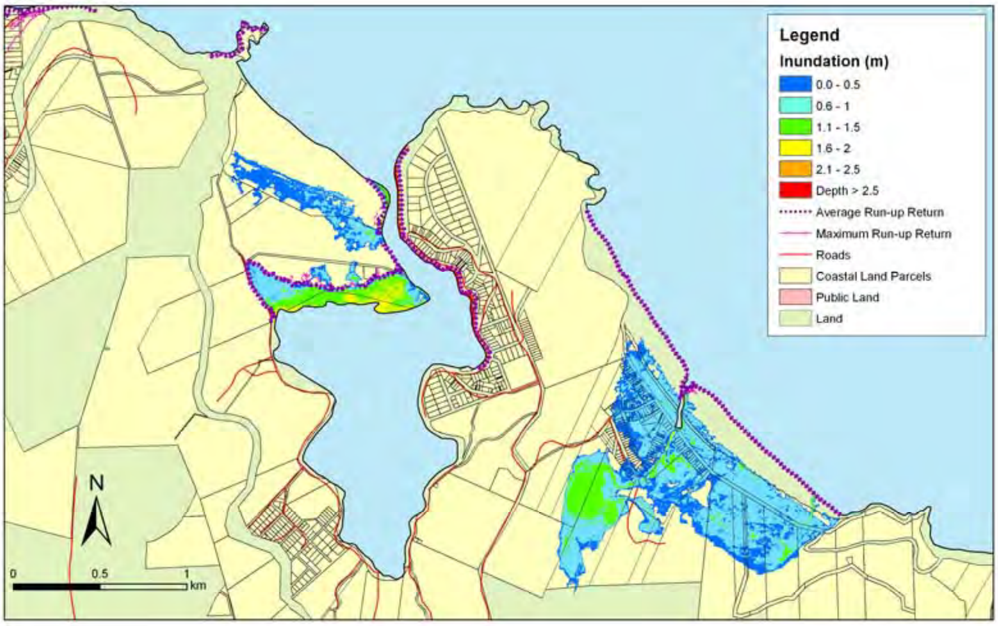

Figure 5.132: Long Beach and Purakanui - 1:500 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

5.12 Warrington and Blueskin Bay

Predicted inundation and wave run-up extent for present mean sea level are shown in Figures 5.133 – 5.136, for mean sea level + 0.3 m in Figure 5.137 – 5.140, and for mean sea level + 0.5 m in Figure 5.141 – 5.144.

- Maximum predicted sea level height of 1.78 m above MLOS (1.89 m above DVD-58).

- Inundation is predicted on the northern and southern shores of Blueskin Bay, affecting the townships of Evansdale and Waitati. The sand spit at the entrance to Blueskin Bay is also inundated. Inundation increases with increasing event return period.

- The sand spit at the entrance to the bay is overtopped by wave run-up in all but the 20-year return period scenarios. Elsewhere, run-up is confined to the coastline.

- Predicted inundation depth increases with rising sea levels, but there is relatively little increase in the extent of inundation around the bay.

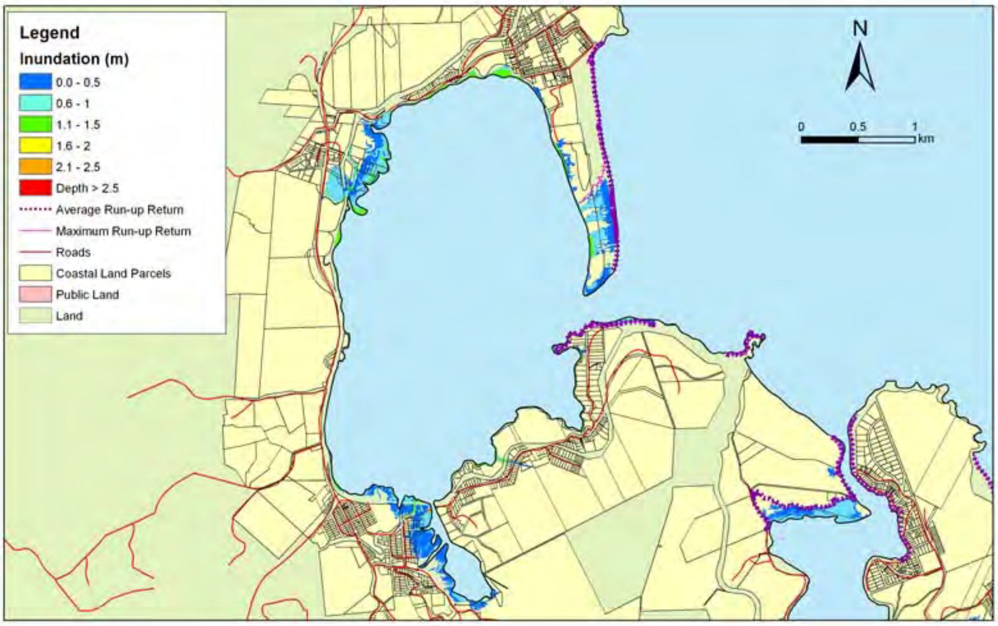

Figure 5.133: Warrington and Blueskin Bay - 1:20 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.134: Warrington and Blueskin Bay - 1:50 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.135: Warrington and Blueskin Bay - 1:100 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

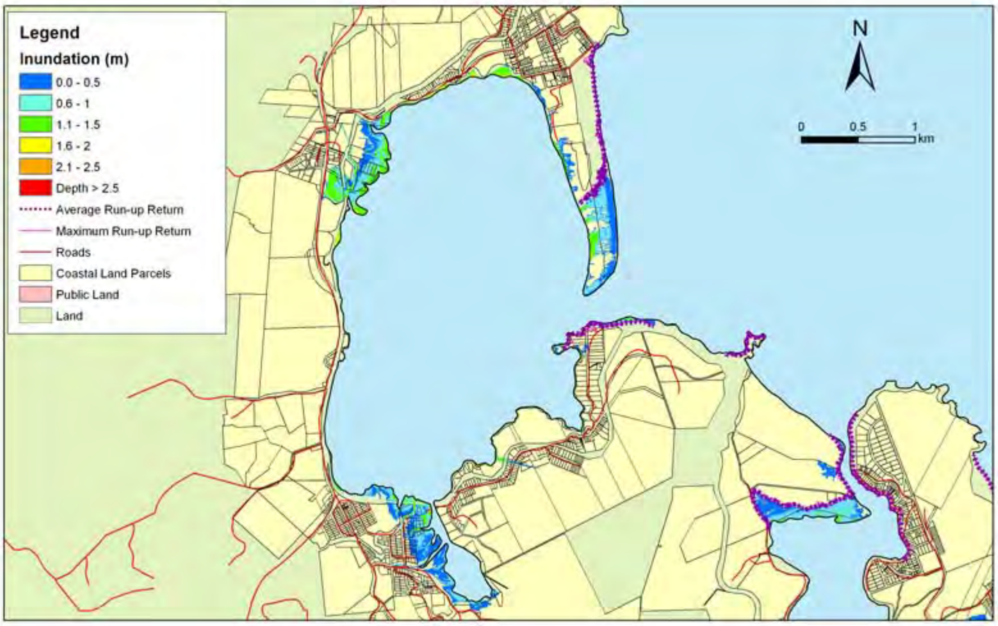

Figure 5.136: Warrington and Blueskin Bay - 1:500 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

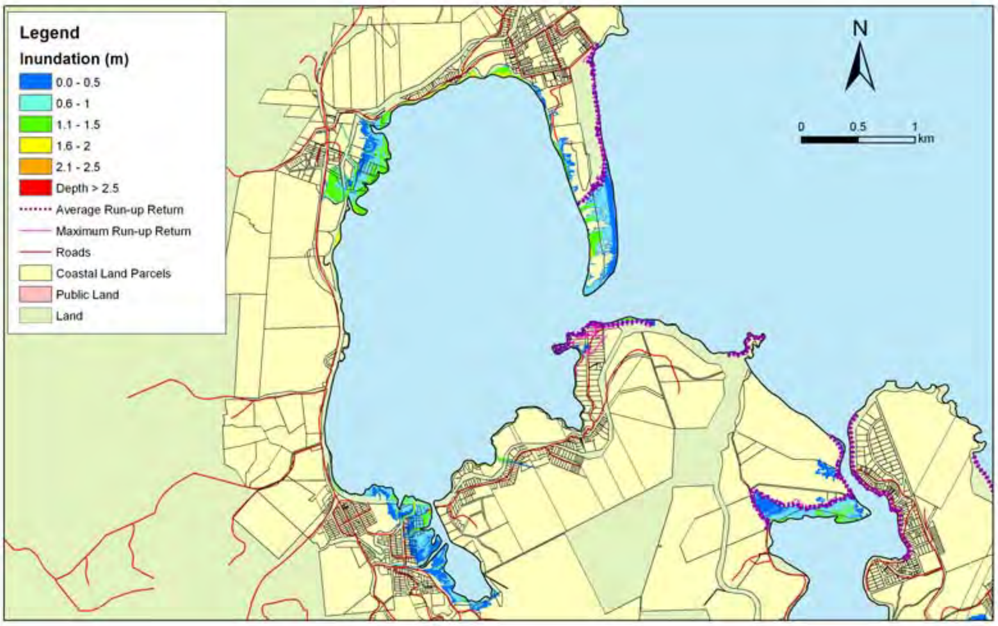

Figure 5.137: Warrington and Blueskin Bay - 1:20 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

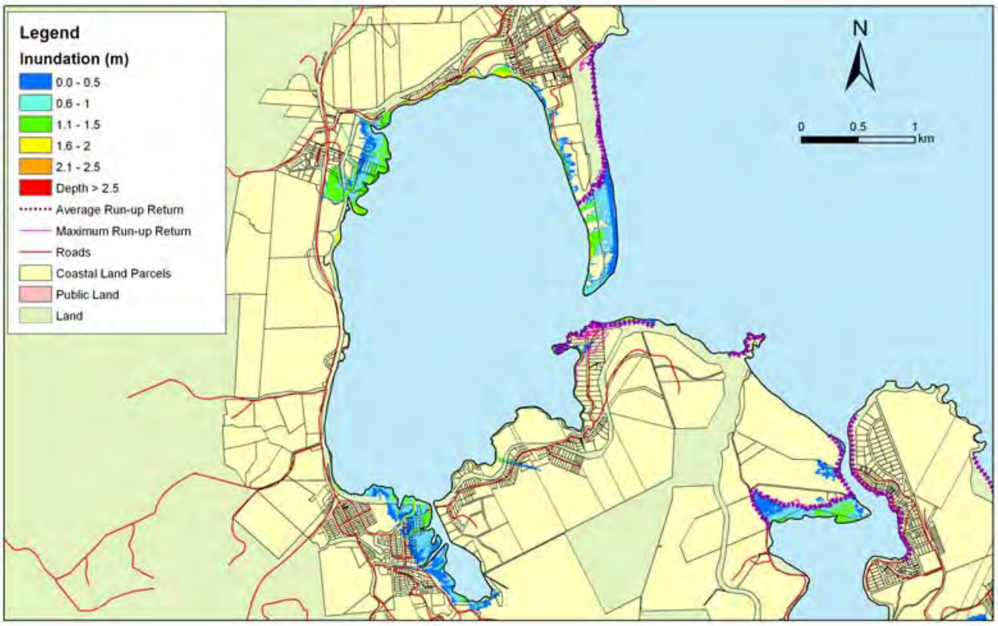

Figure 5.138: Warrington and Blueskin Bay - 1:50 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

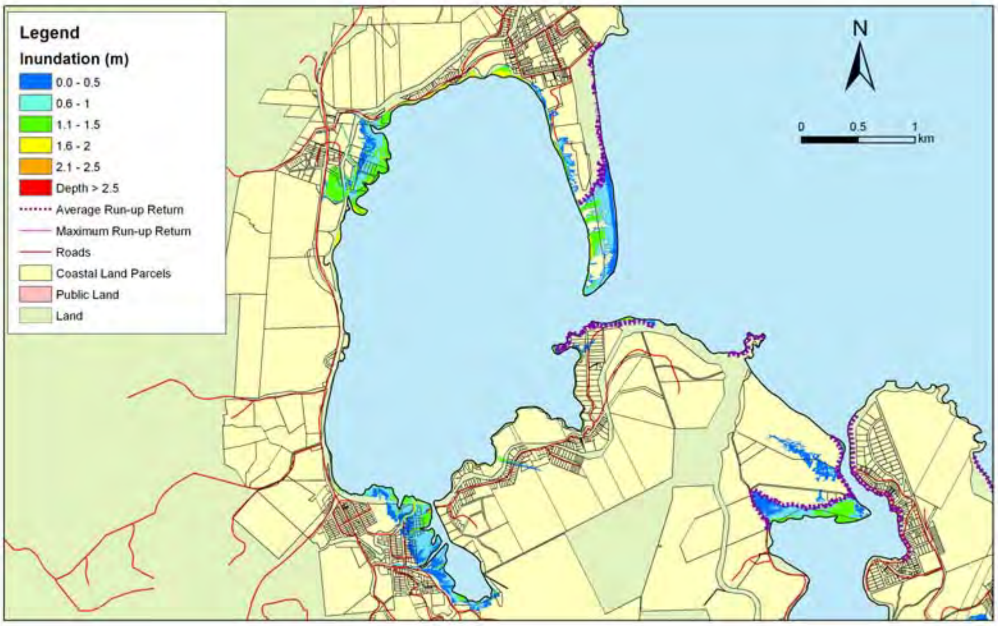

Figure 5.139: Warrington and Blueskin Bay - 1:100 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

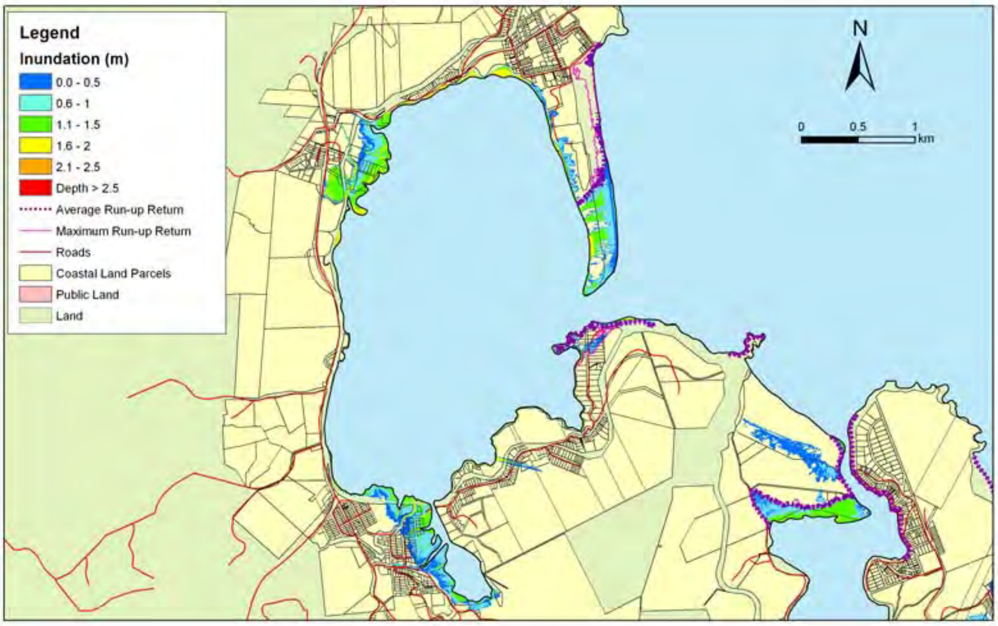

Figure 5.140: Warrington and Blueskin Bay - 1:500 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

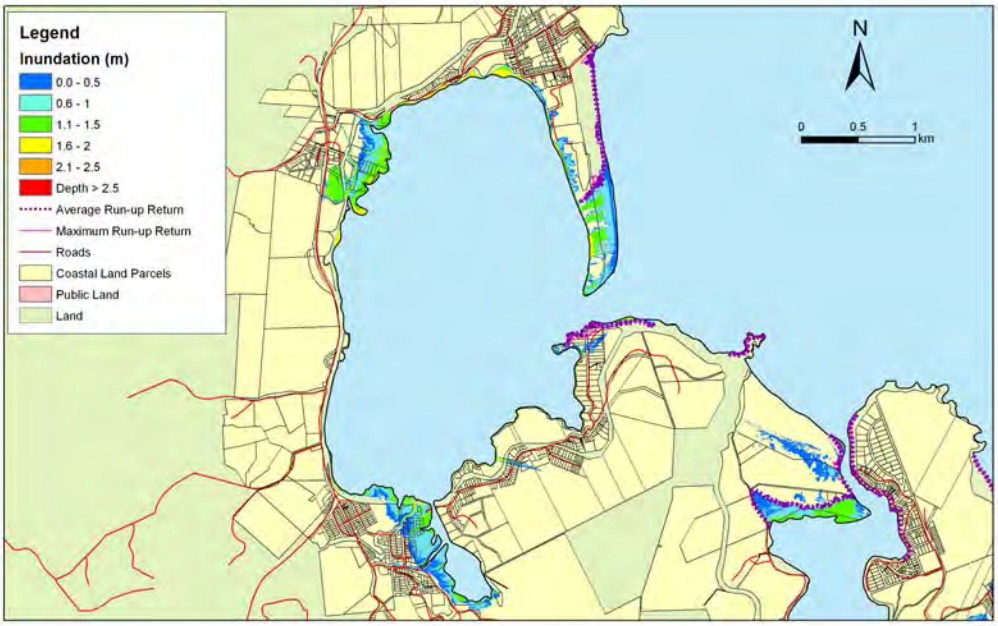

Figure 5.141: Warrington and Blueskin Bay - 1:20 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

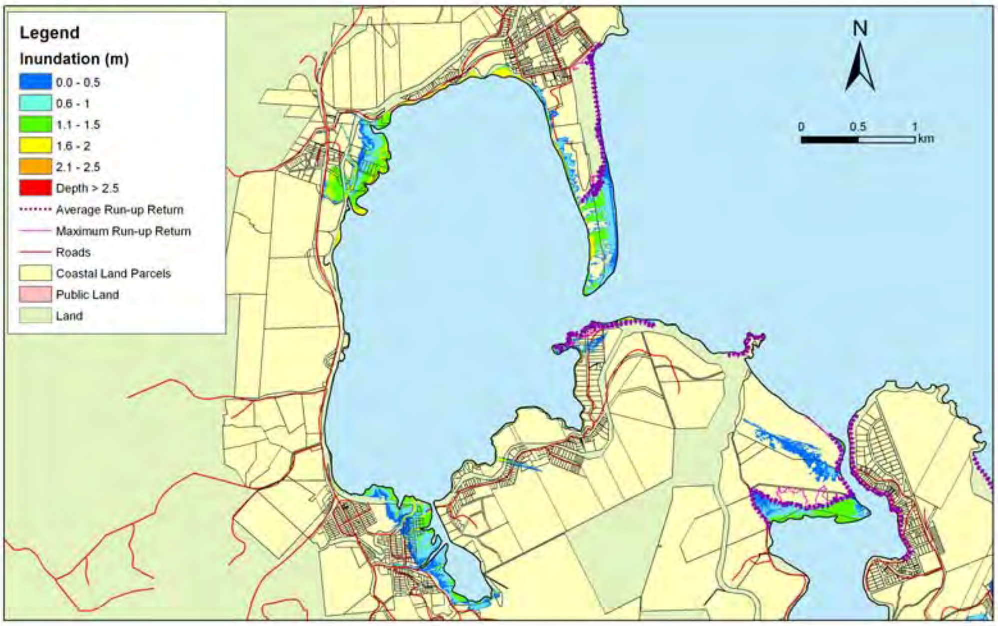

Figure 5.142: Warrington and Blueskin Bay - 1:50 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

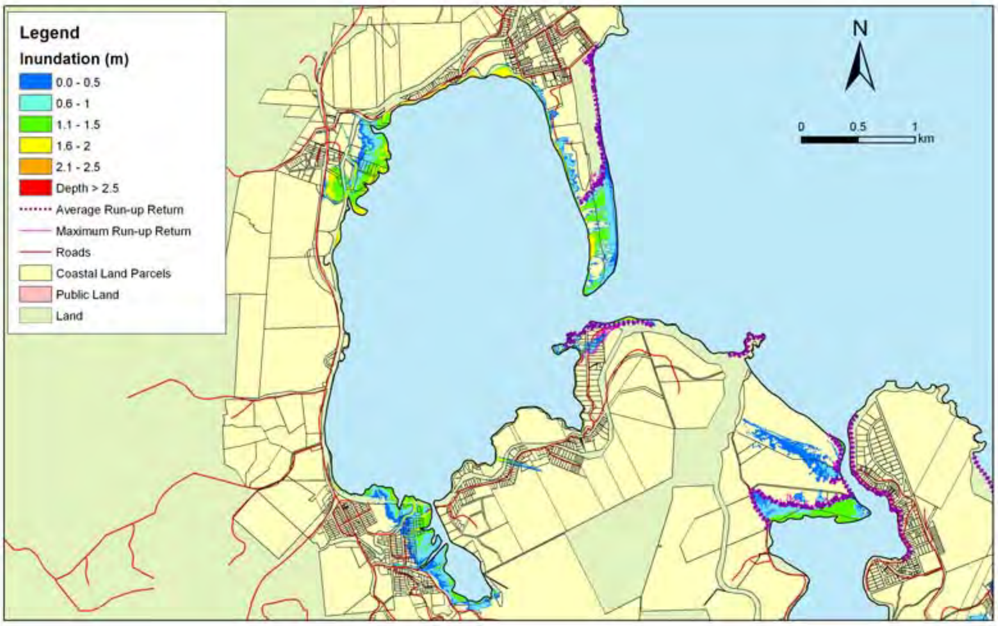

Figure 5.143: Warrington and Blueskin Bay - 1:100 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

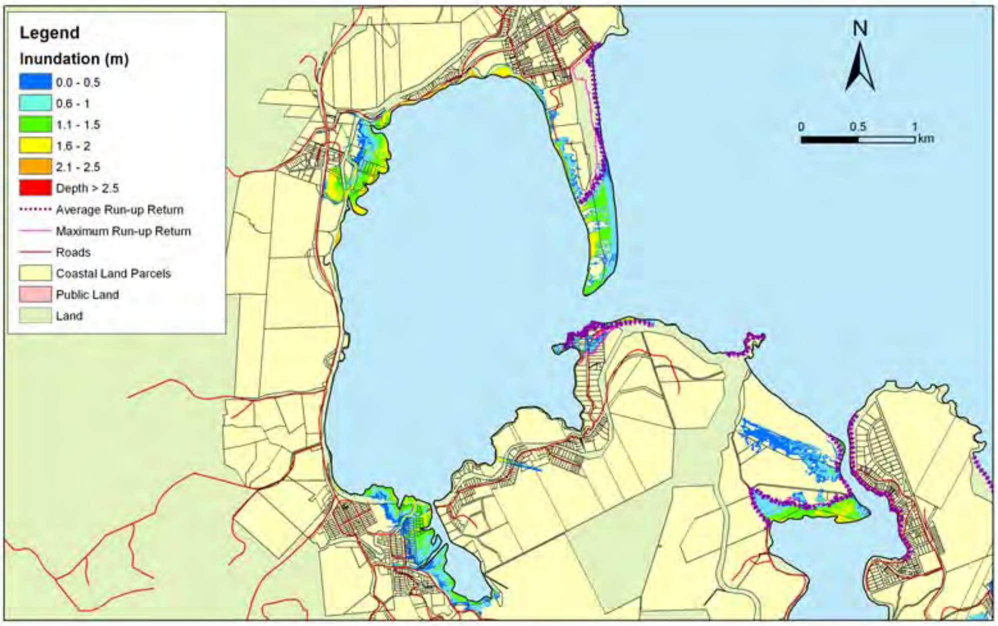

Figure 5.144: Warrington and Blueskin Bay - 1:500 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up

5.13 Karitane

Predicted inundation and wave run-up extent for present mean sea level are shown in Figures 5.145 – 5.148, for mean sea level + 0.3 m in Figure 5.149 – 5.152, and for mean sea level + 0.5 m in Figure 5.153 – 5.156.

- Maximum predicted sea level height of 1.86 m above MLOS (1.97 m above DVD-58).
- There is considerable inundation predicted along both sides of the Waikouaiti River for present MLOS. Karitane is inundated directly from the river and also from flooding that develops from further upstream. There is also inundation predicted along the shore of Hawksbury Lagoon.
- Wave run-up is not considered along the river or in Hawksbury Lagoon, and run-up effects are not significant along the coast.
- Rising sea levels increase the depths and extent of the predicted inundation.

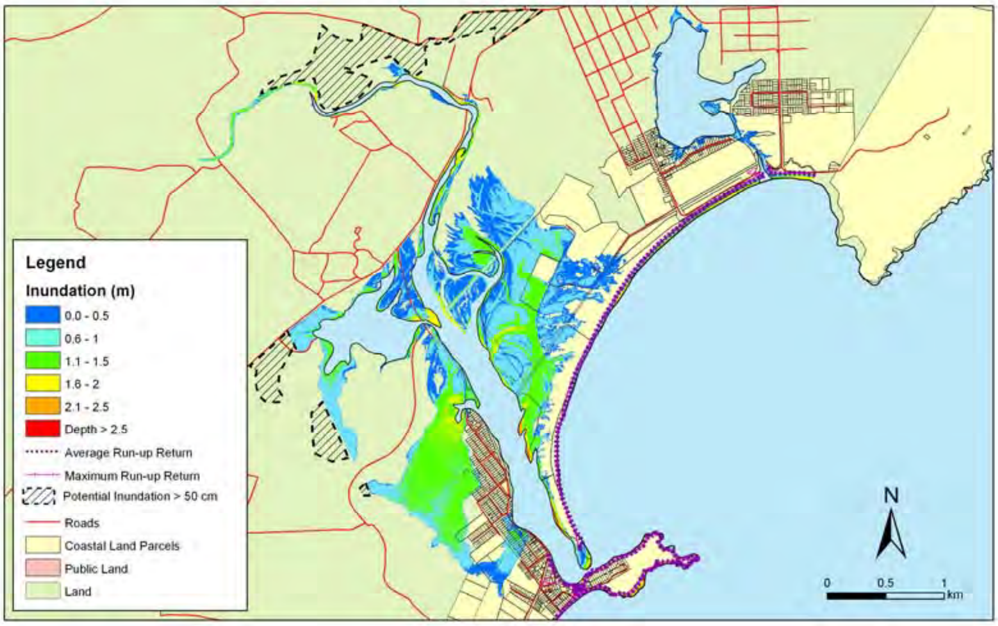

Figure 5.145: Karitane - 1:20 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

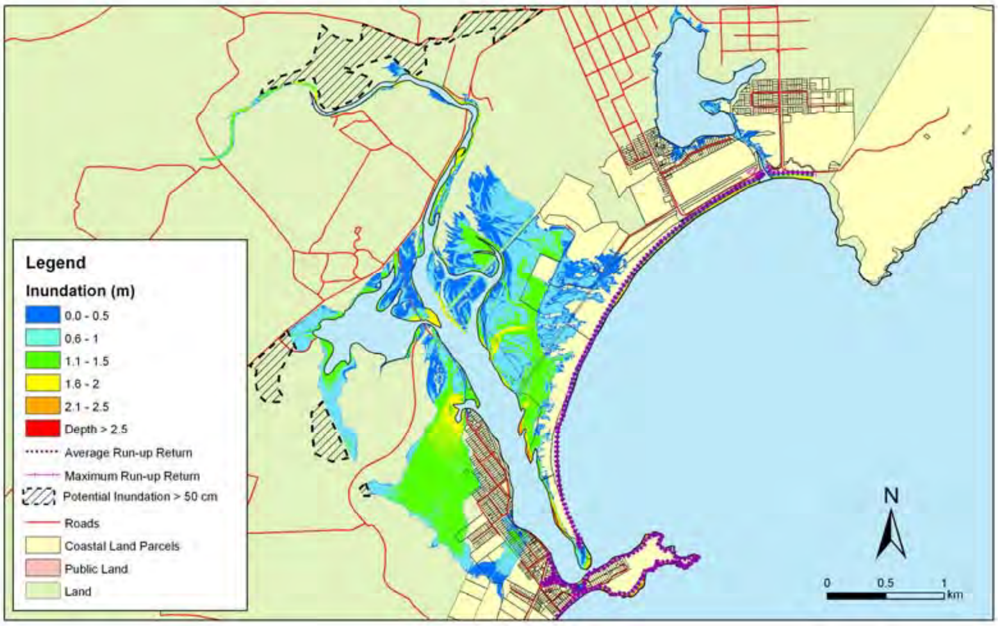

Figure 5.146: Karitane - 1:50 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

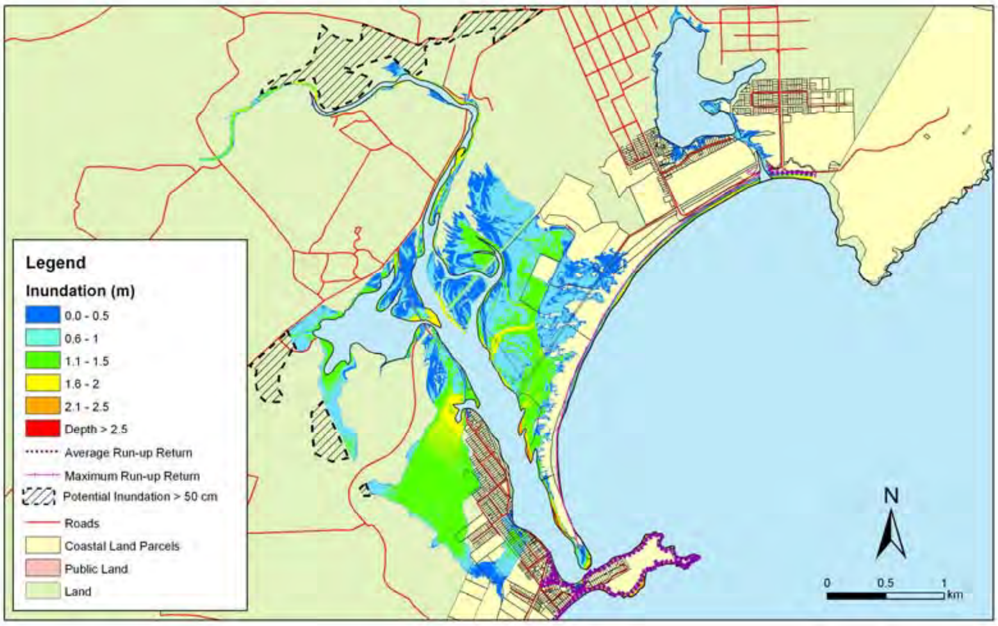

Figure 5.147: Karitane - 1:100 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

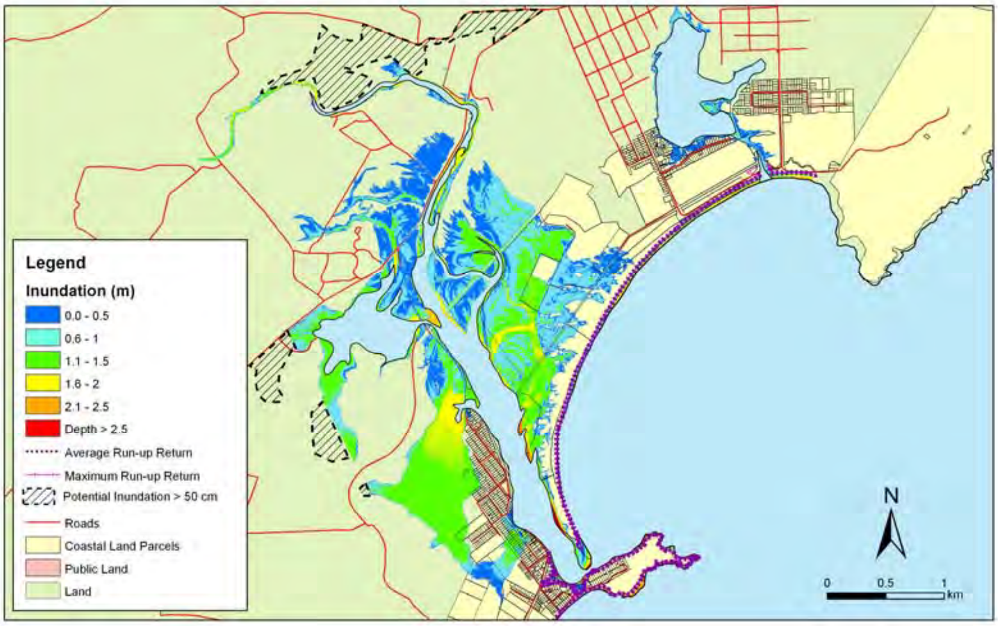

Figure 5.148: Karitane - 1:500 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

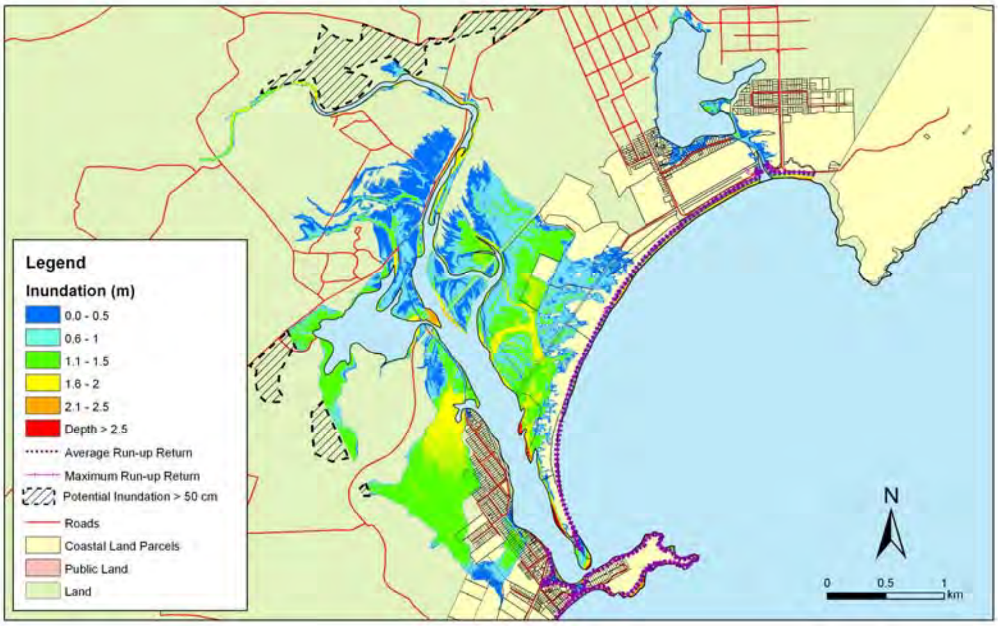

Figure 5.149: Karitane - 1:20 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

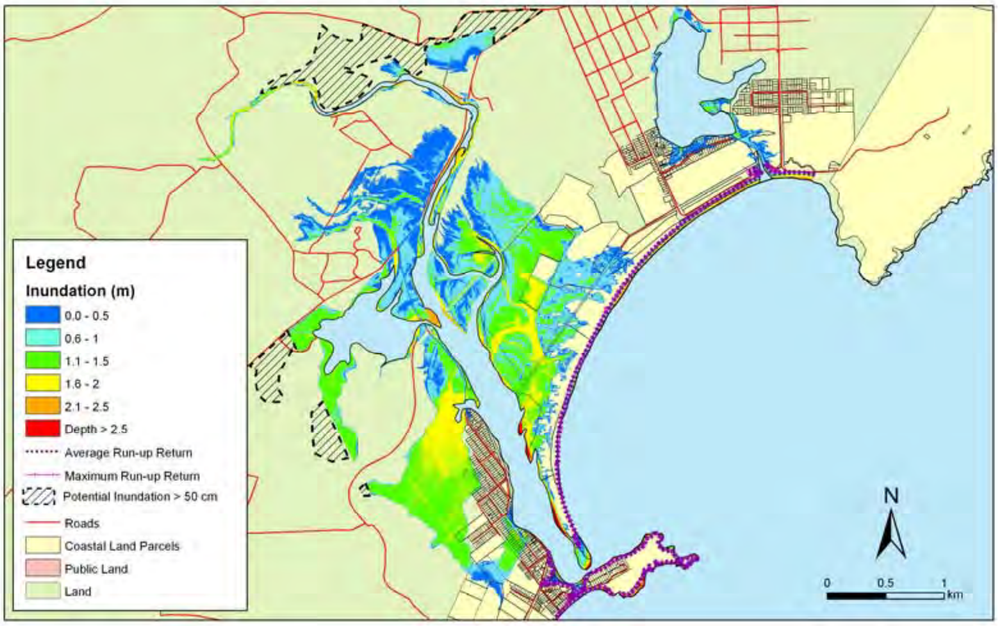

Figure 5.150: Karitane - 1:50 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

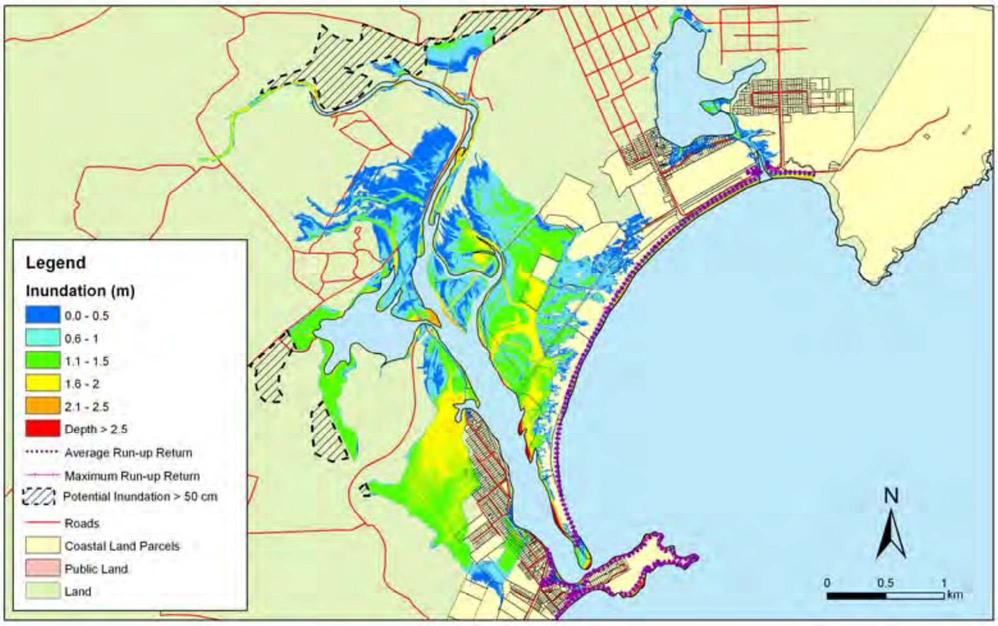

Figure 5.151: Karitane - 1:100 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

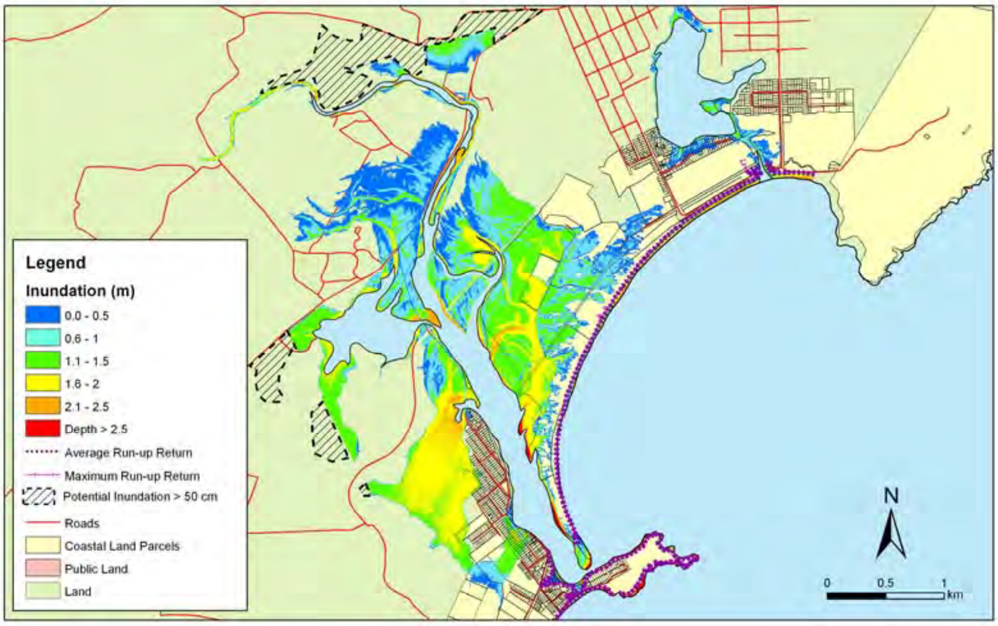

Figure 5.152: Karitane - 1:500 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

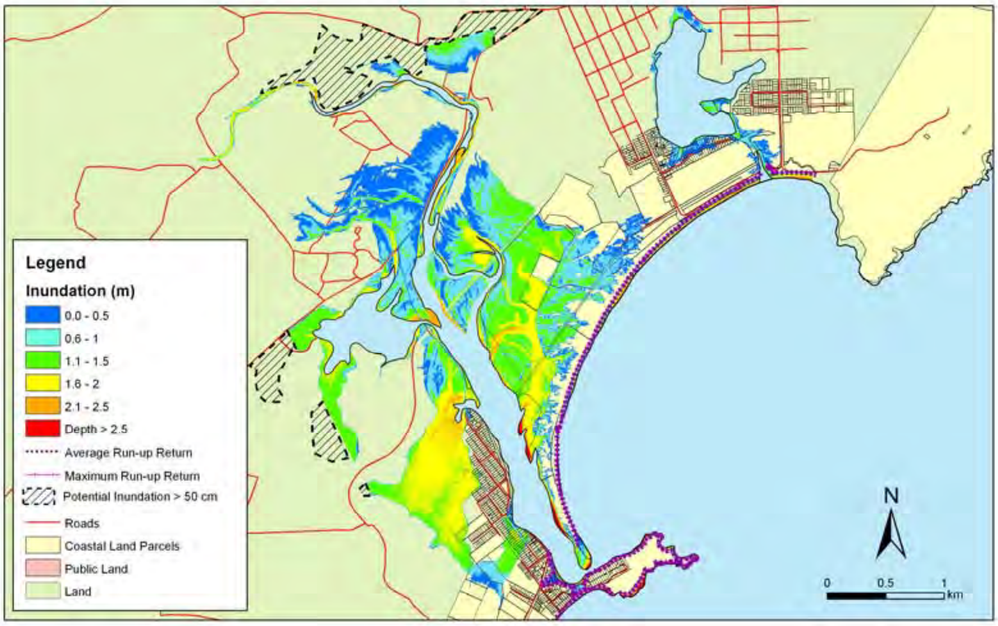

Figure 5.153: Karitane - 1:20 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up**.**

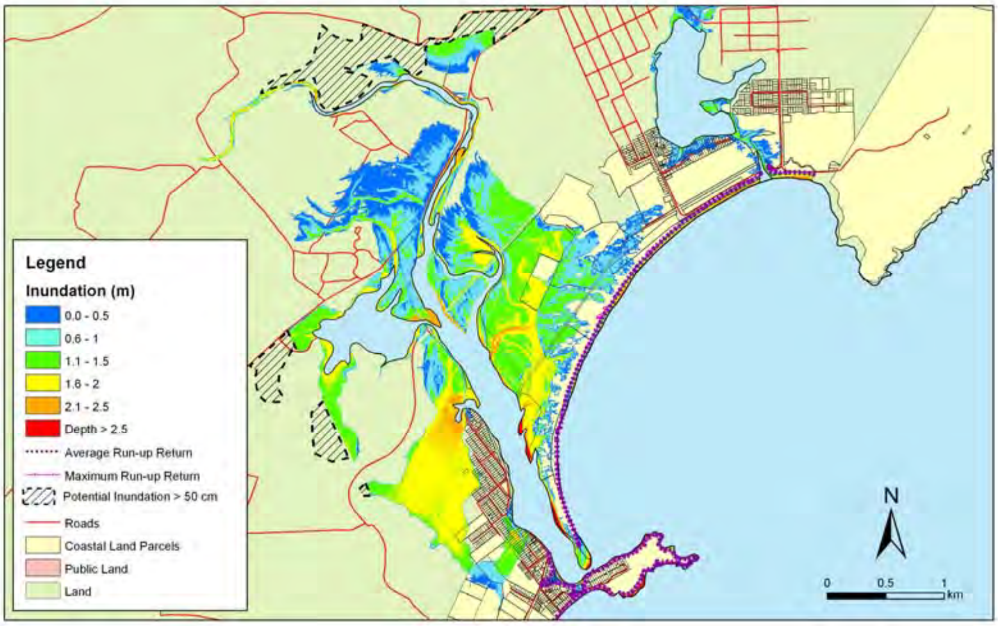

Figure 5.154: Karitane - 1:50 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

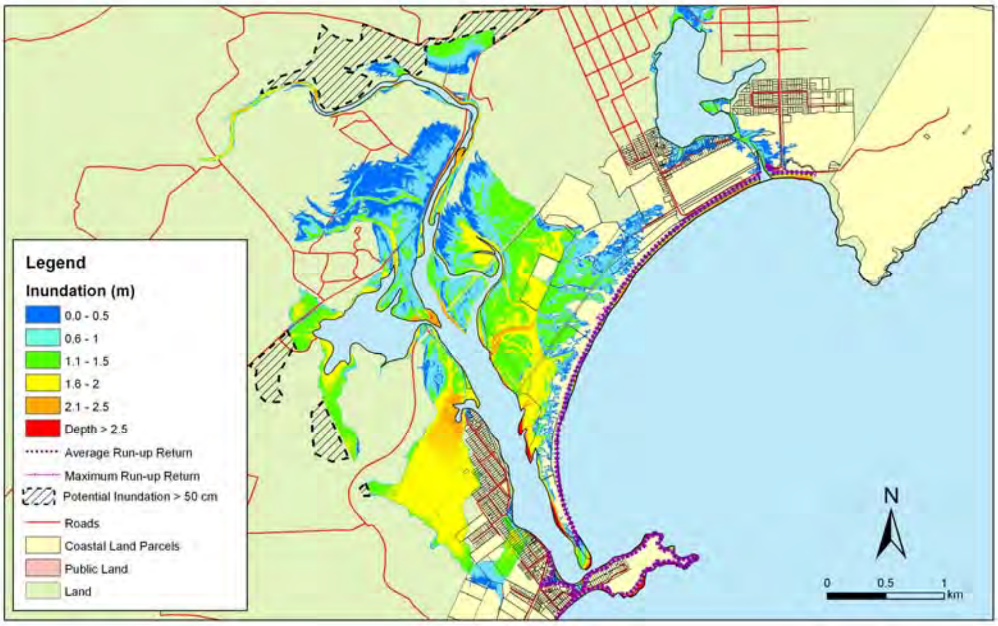

Figure 5.155: Karitane - 1:100 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

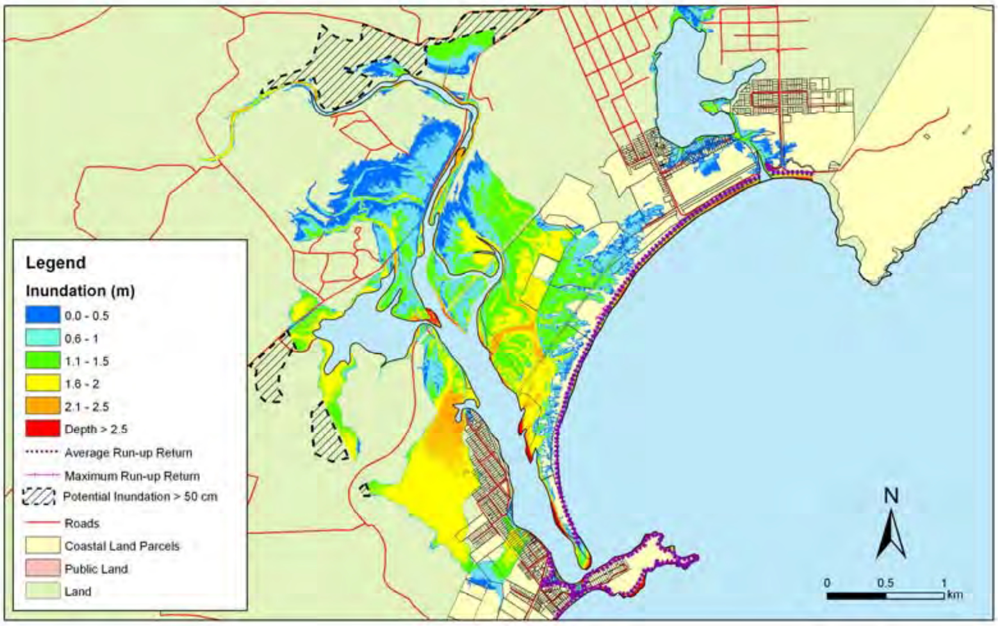

Figure 5.156: Karitane - 1:500 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up

5.14 Moeraki

Predicted inundation and wave run-up extent for present mean sea level are shown in Figures 5.157 – 5.160, for mean sea level + 0.3 m in Figure 5.161 – 5.164, and for mean sea level + 0.5 m in Figure 5.165 – 5.168.

- Maximum predicted sea level height of 1.83 m above MLOS (1.94 m above DVD-58).
- At MLOS, predicted inundation is confined to a narrow coastal strip.
- Wave run-up is confined to the coastline.
- Higher sea levels increase the depth of inundation but water does not penetrate inland.

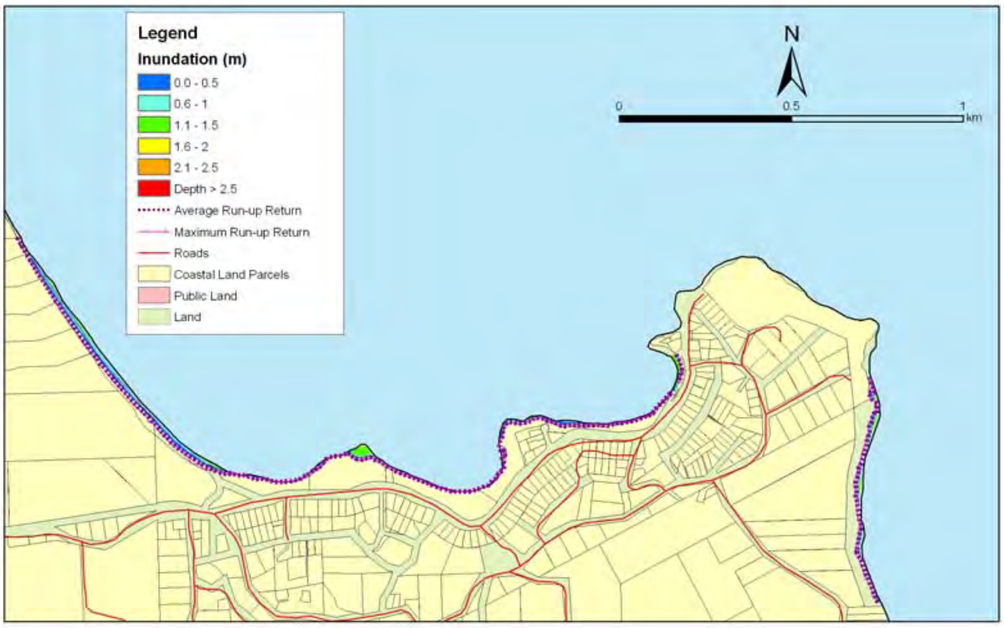

Figure 5.157: Moeraki - 1:20 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

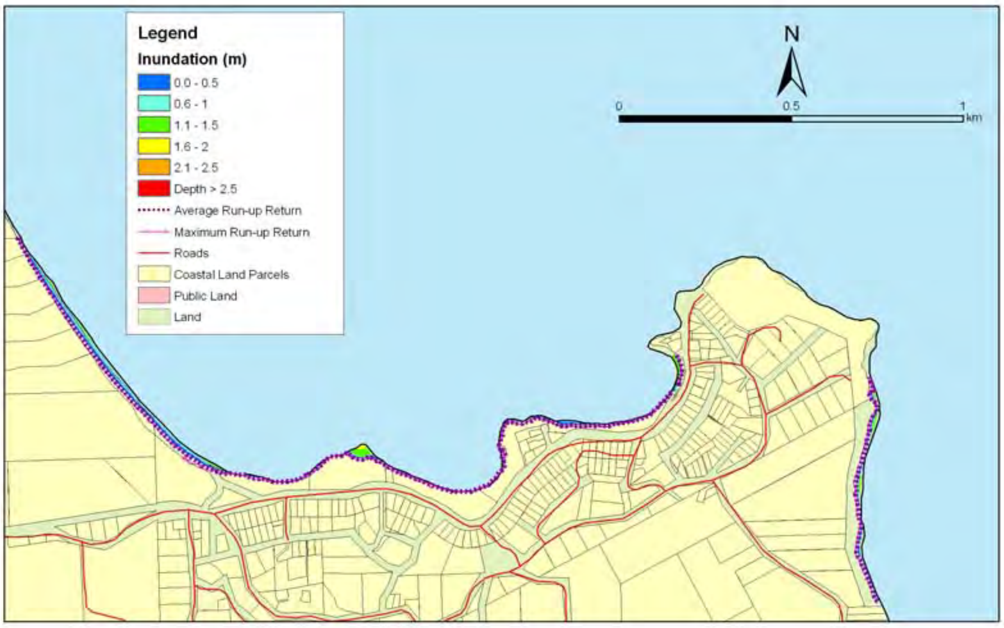

Figure 5.158: Moeraki - 1:50 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

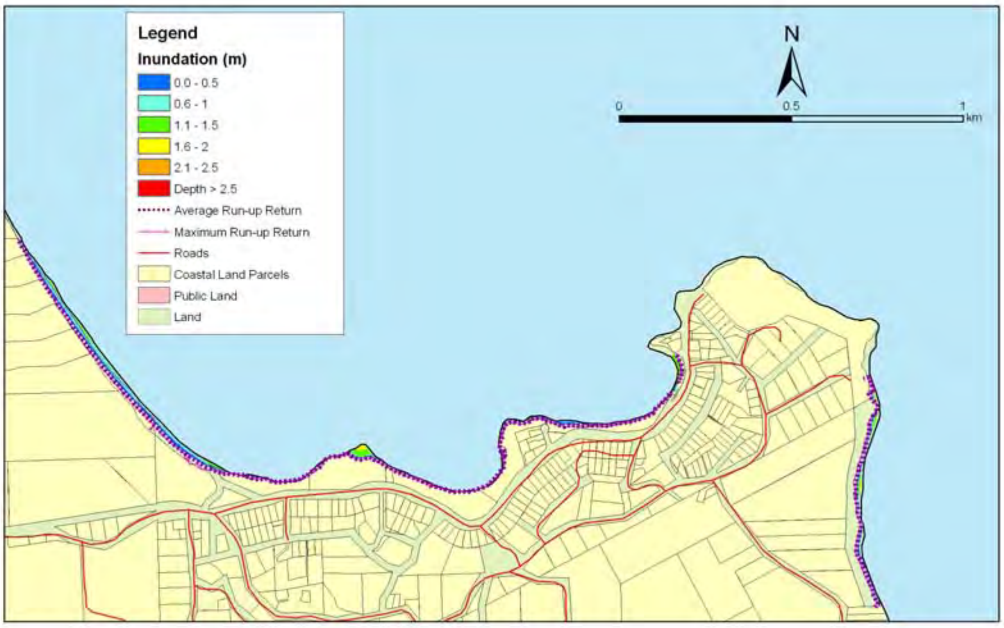

Figure 5.159: Moeraki - 1:100 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

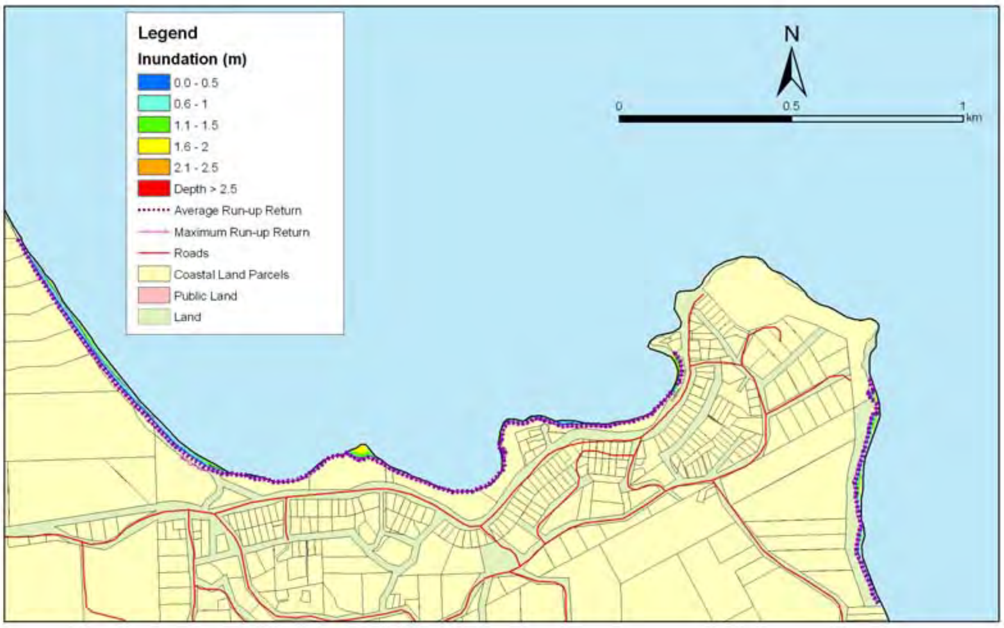

Figure 5.160: Moeraki - 1:500 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up**.**

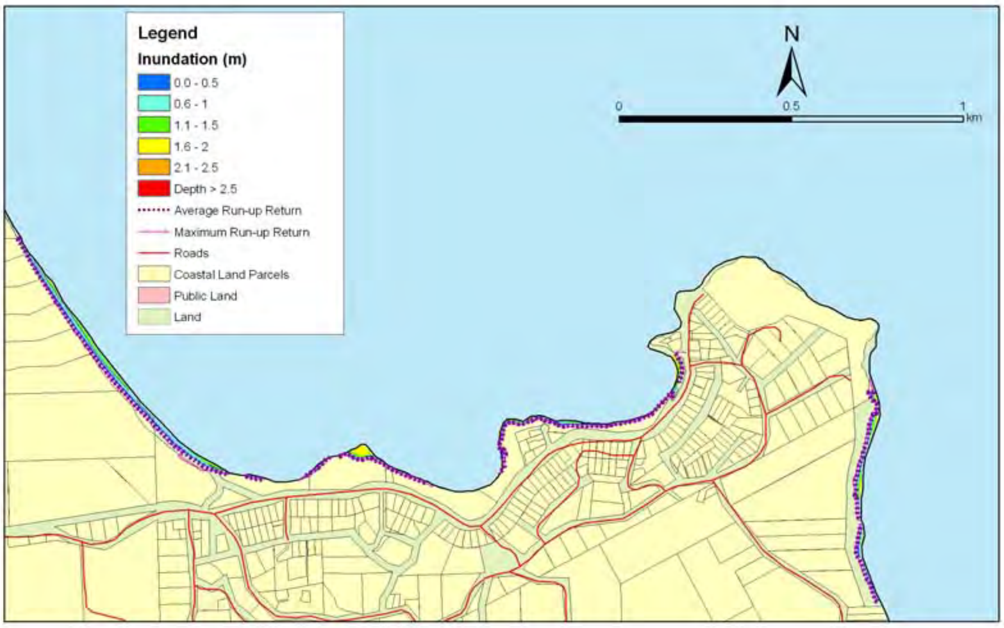

Figure 5.161: Moeraki - 1:20 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

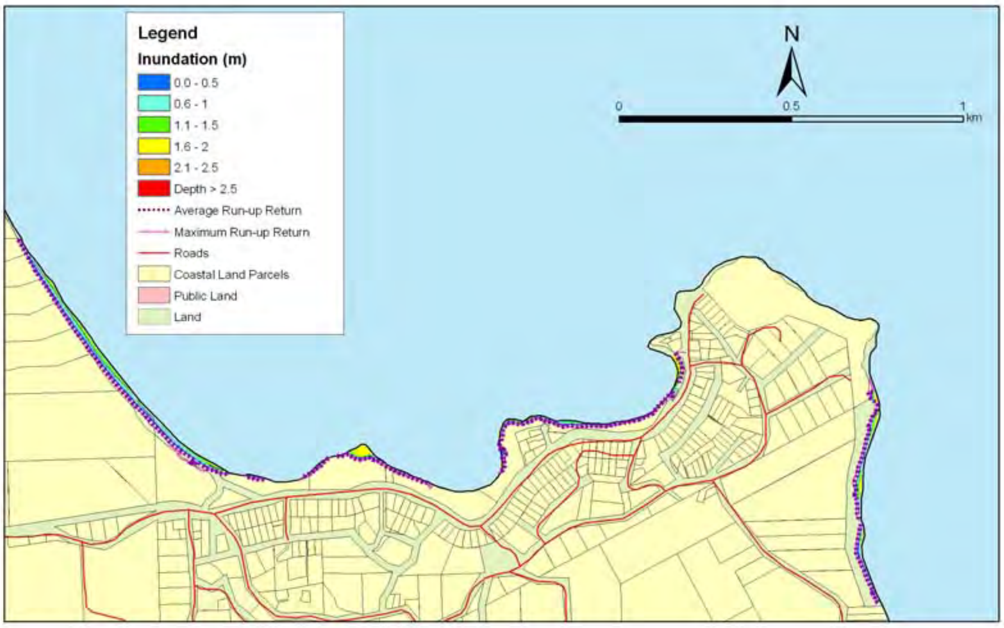

Figure 5.162: Moeraki - 1:50 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

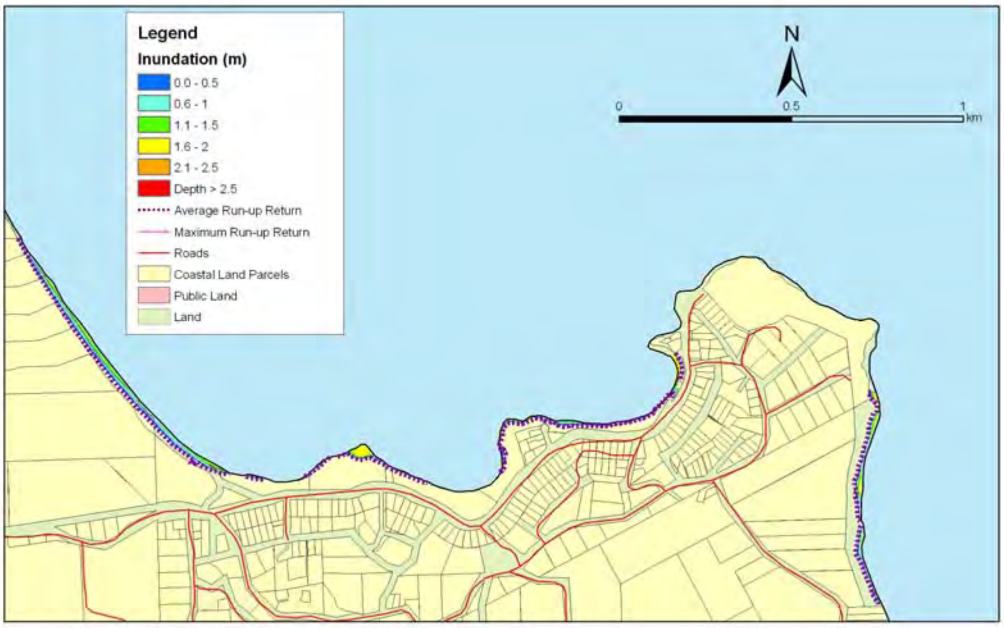

Figure 5.163: Moeraki - 1:100 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

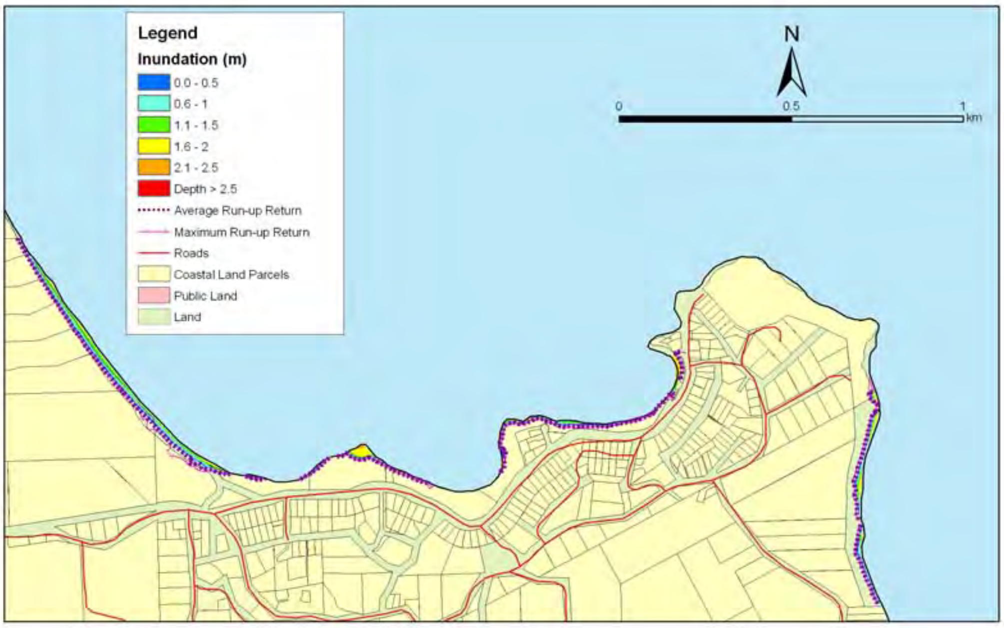

Figure 5.164: Moeraki - 1:500 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

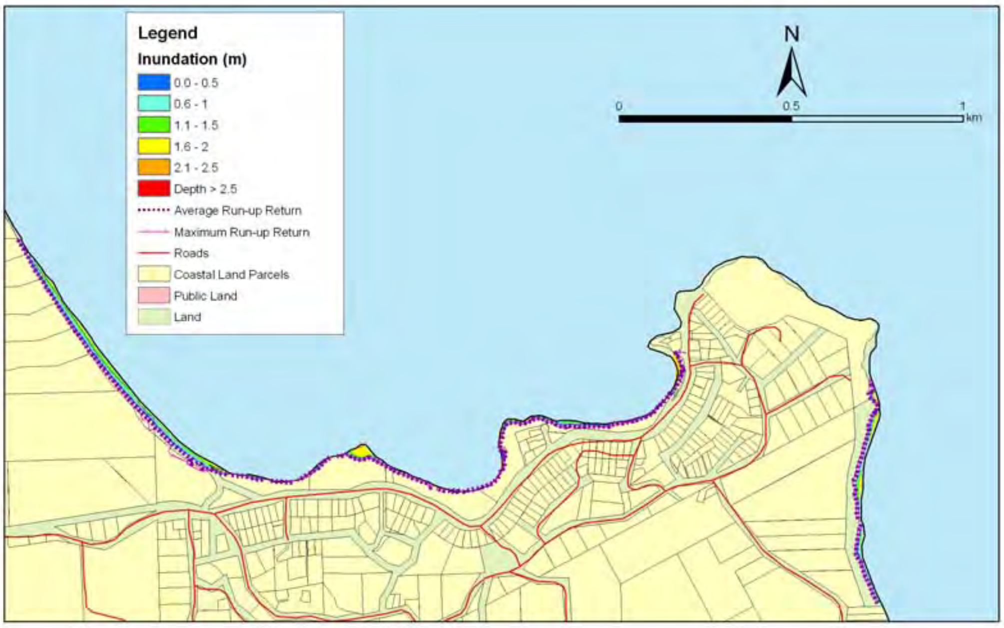

Figure 5.165: Moeraki - 1:20 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

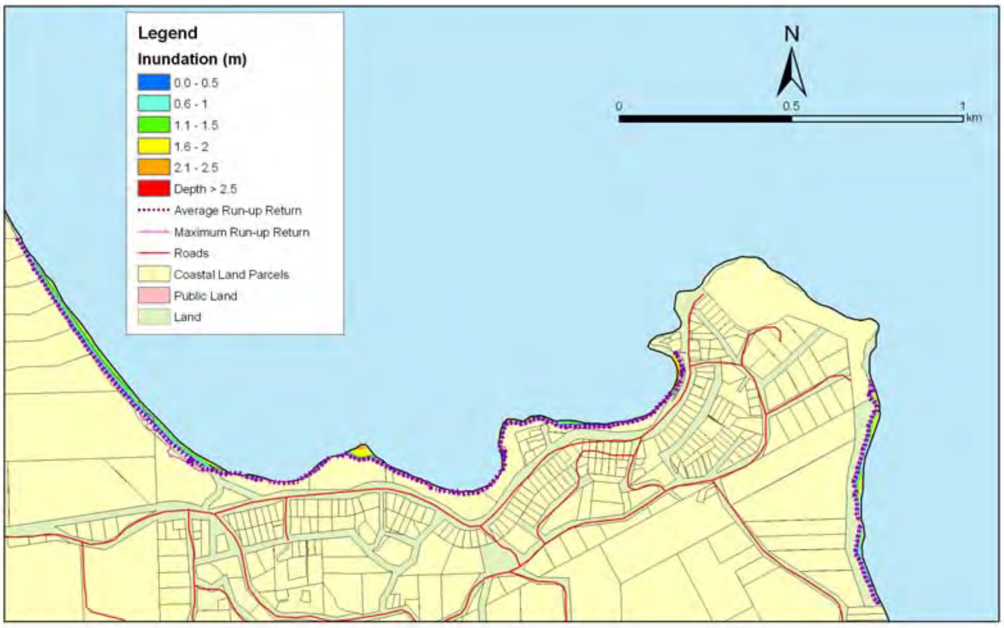

Figure 5.166: Moeraki - 1:50 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

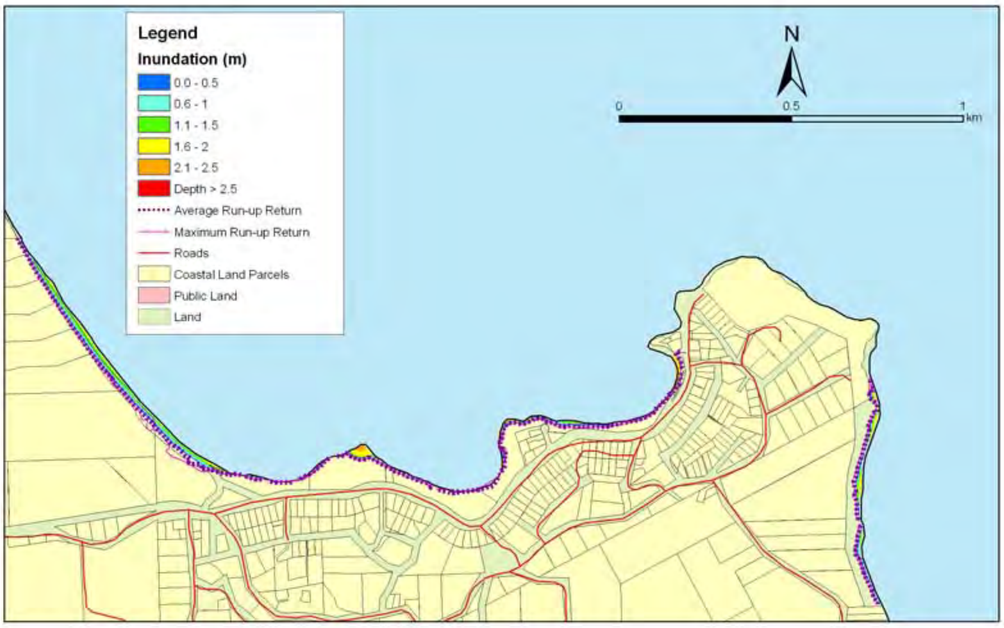

Figure 5.167: Moeraki - 1:100 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

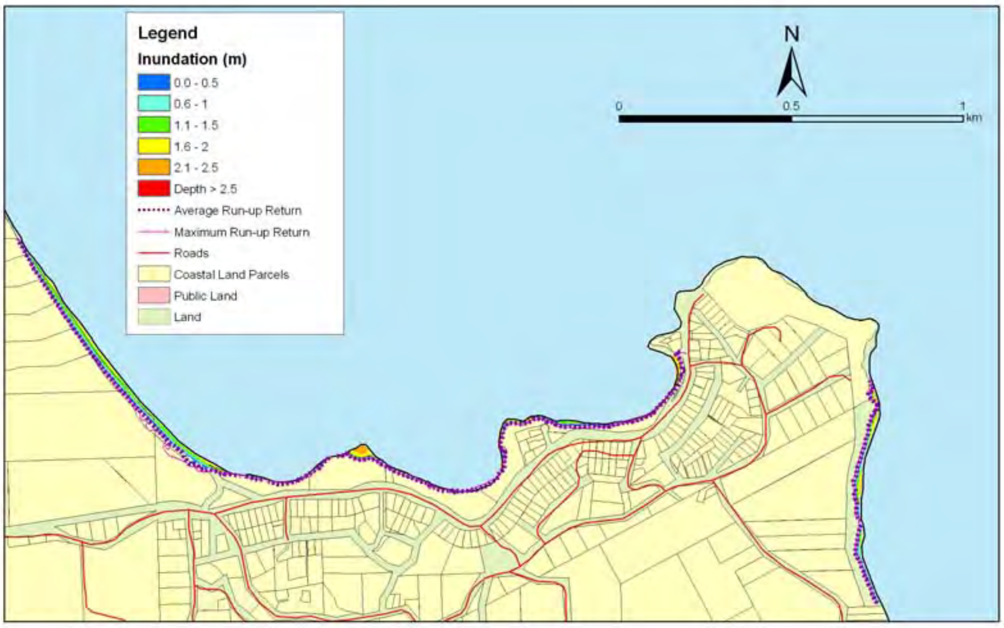

Figure 5.168: Moeraki - 1:500 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up

5.15 Hampden

Predicted inundation and wave run-up extent for present mean sea level are shown in Figures 5.169 – 5.172, for mean sea level + 0.3 m in Figure 5.173 – 5.176, and for mean sea level + 0.5 m in Figure 5.177 – 5.180.

- Maximum predicted sea level height of 2.07 m above MLOS (2.18 m above DVD-58).

- At present MLOS, predicted inundation is largely confined to the coastline, except for some minor flooding around the two streams that flow through the town.

- Some potential for wave run-up effects around the two streams is highlighted.

- Rising sea levels moderately increase the inundation and wave run-up predicted adjacent to the two streams.

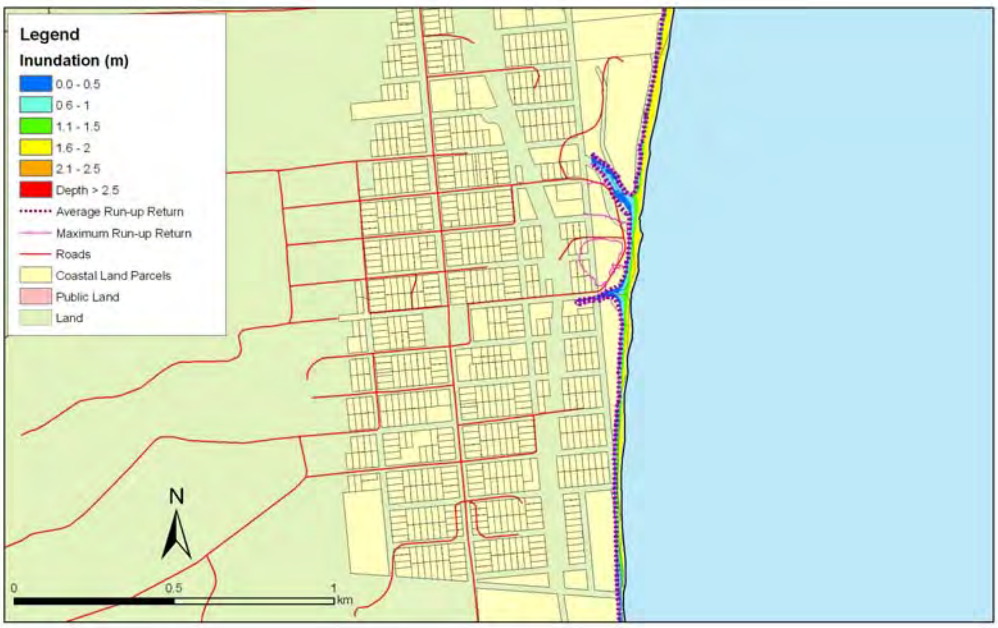

Figure 5.169: Hampden - 1:20 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.170: Hampden - 1:50 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

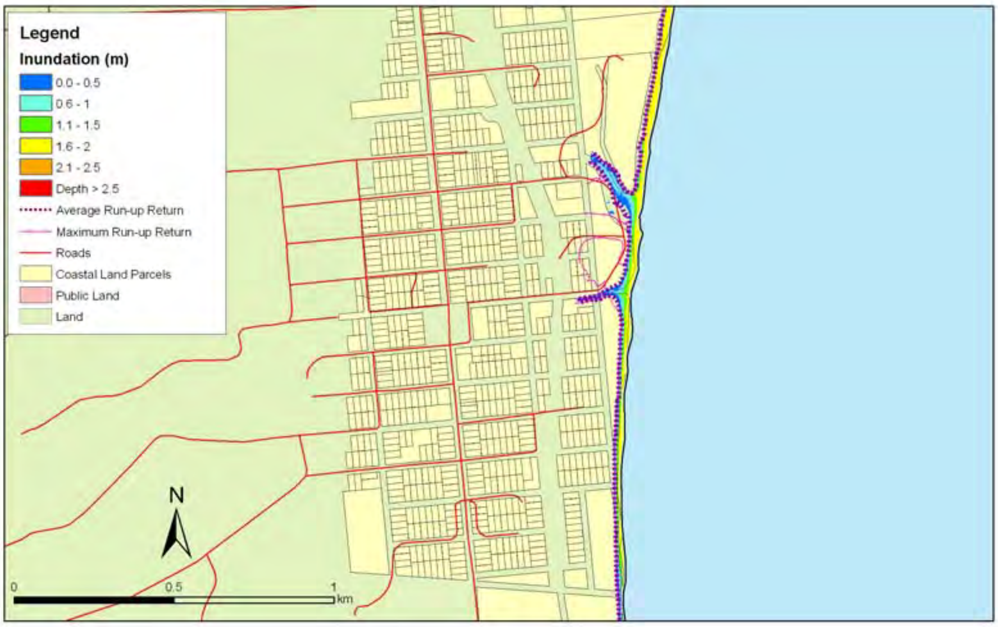

Figure 5.171: Hampden - 1:100 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.172: Hampden - 1:500 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.173: Hampden - 1:20 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.174: Hampden - 1:50 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.175: Hampden - 1:100 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.176: Hampden - 1:500 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.177: Hampden - 1:20 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.178: Hampden - 1:50 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

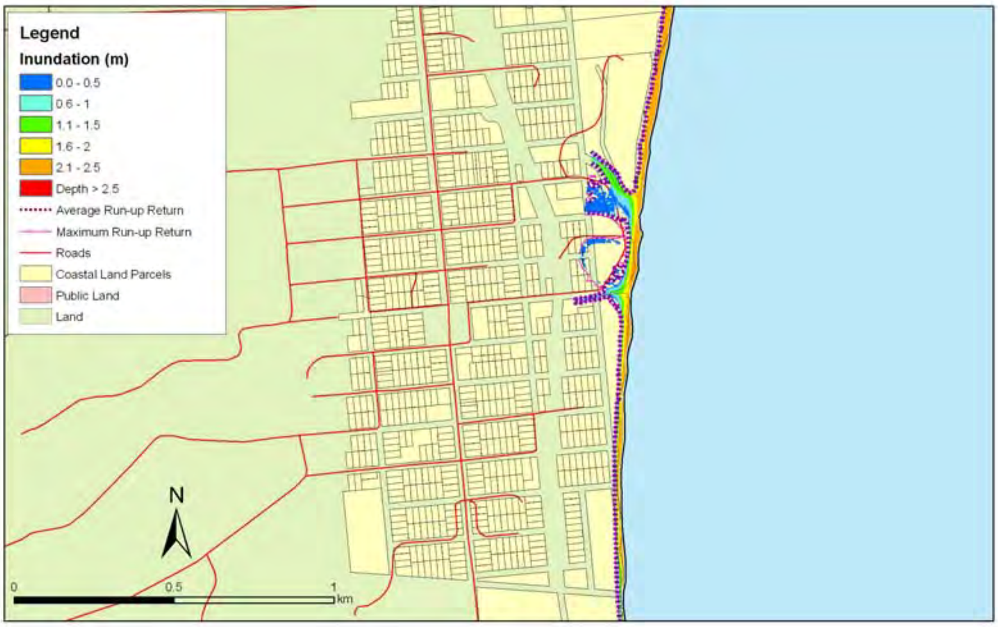

Figure 5.179: Hampden - 1:100 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

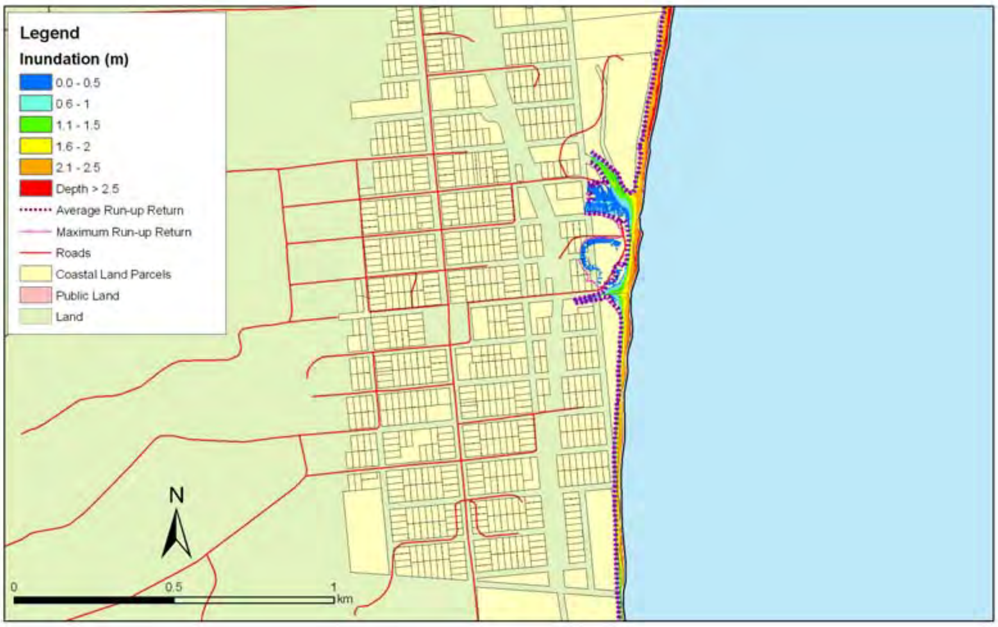

Figure 5.180: Hampden - 1:500 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up

5.16 Taranui and Kakanui

Predicted inundation and wave run-up extent for present mean sea level are shown in Figures 5.181 – 5.184, for mean sea level + 0.3 m in Figure 5.185 – 5.188, and for mean sea level + 0.5 m in Figure 5.189 – 5.192.

- Maximum predicted sea level height of 2.20 m above MLOS (2.31 m above DVD-58).

- At present MLOS, there is considerable predicted inundation on the north bank of the Kakanui River inside the mouth. There is also inudunation predicted along both banks further upstream. The spit at the river mouth is submerged. Elsewhere, inundation is confined to the coastline.

- Wave run-up is not considered within the sheltered waters of the Kakanui River. Elsewhere, it is confined to the coastline for the 1:20 and 1:50 year events, but extends inshore for the 1:100 and 1:500 year events.

- Rising sea levels increase the depth and extent of the inundation. Wave run-up extends inland for all return periods.

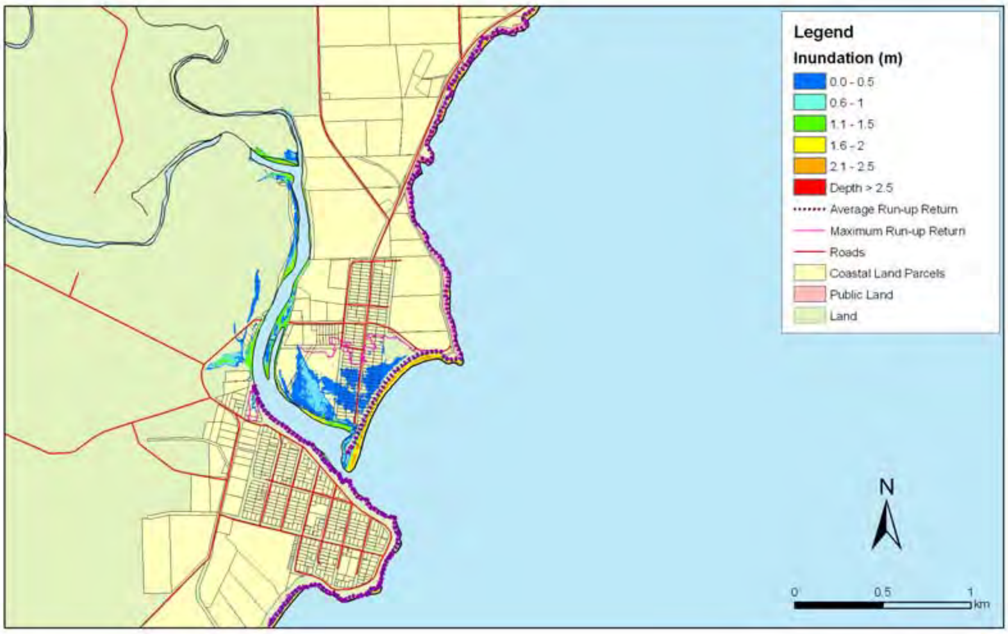

Figure 5.181: Taranui and Kakanui - 1:20 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

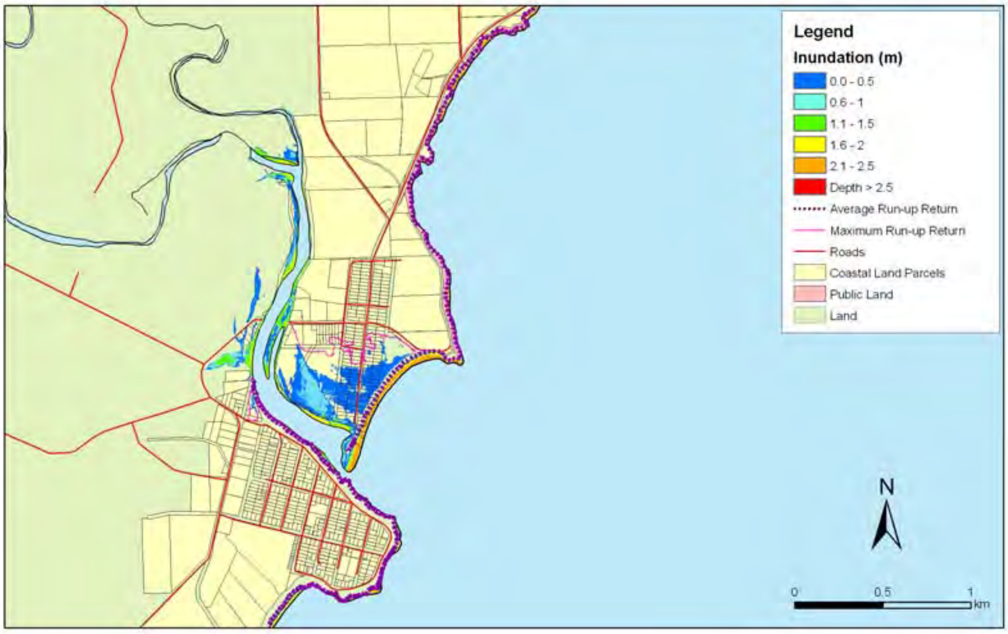

Figure 5.182: Taranui and Kakanui - 1:50 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

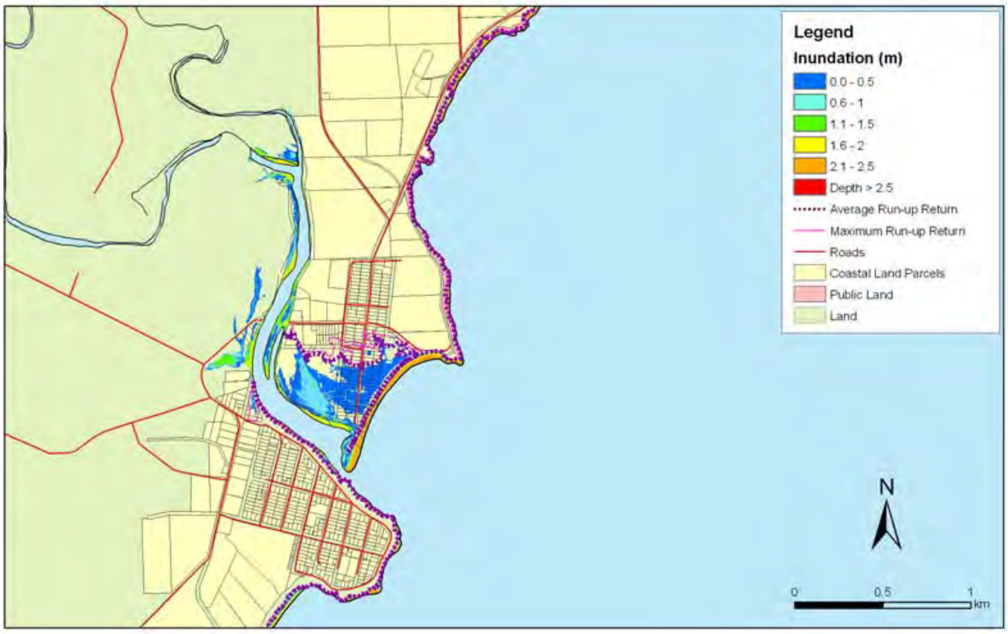

Figure 5.183: Taranui and Kakanui - 1:100 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up**.**

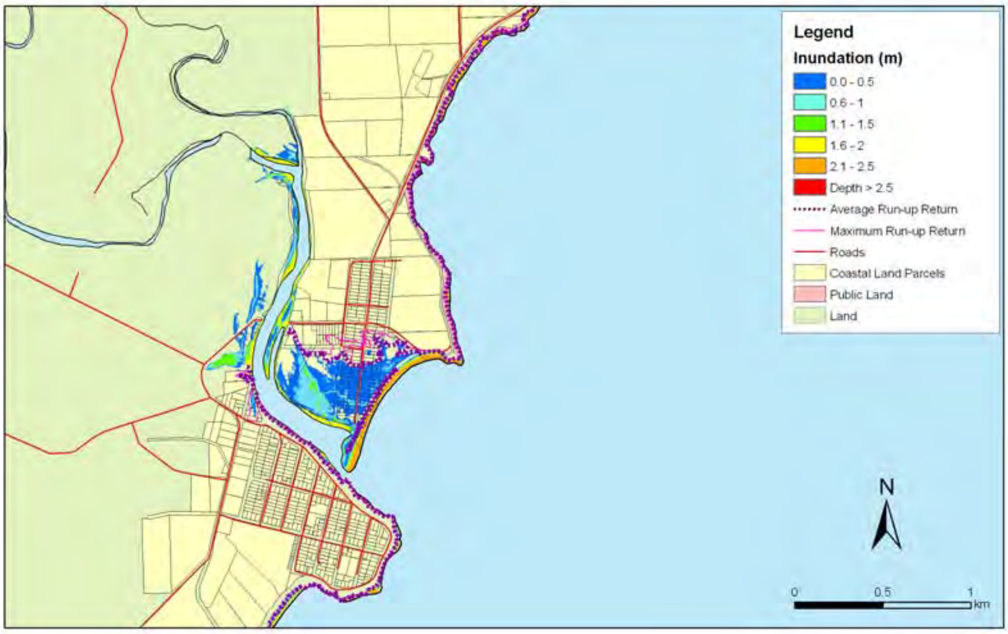

Figure 5.184: Taranui and Kakanui - 1:500 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

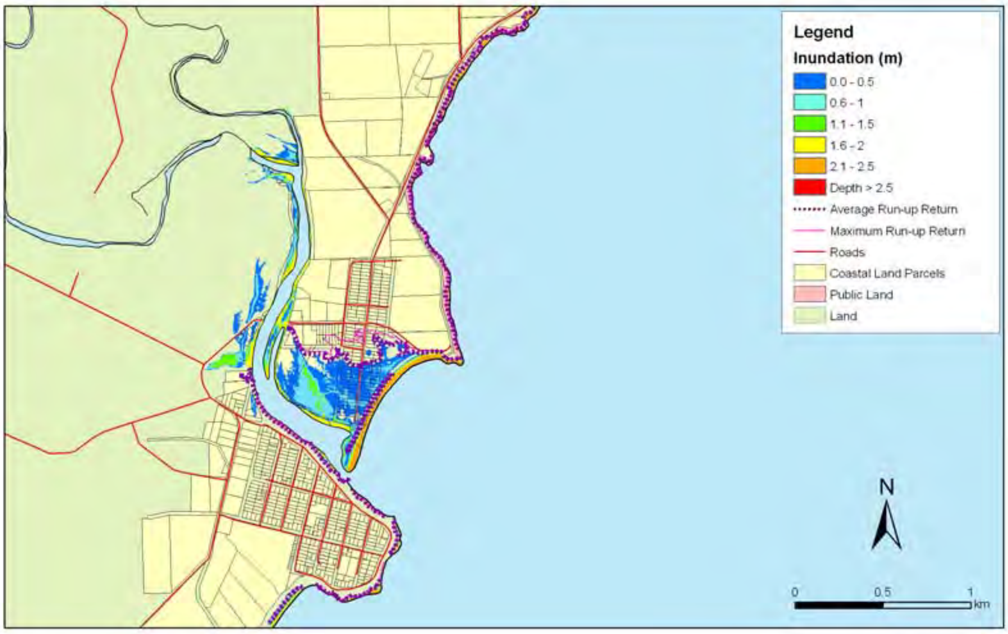

Figure 5.185: Taranui and Kakanui - 1:20 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

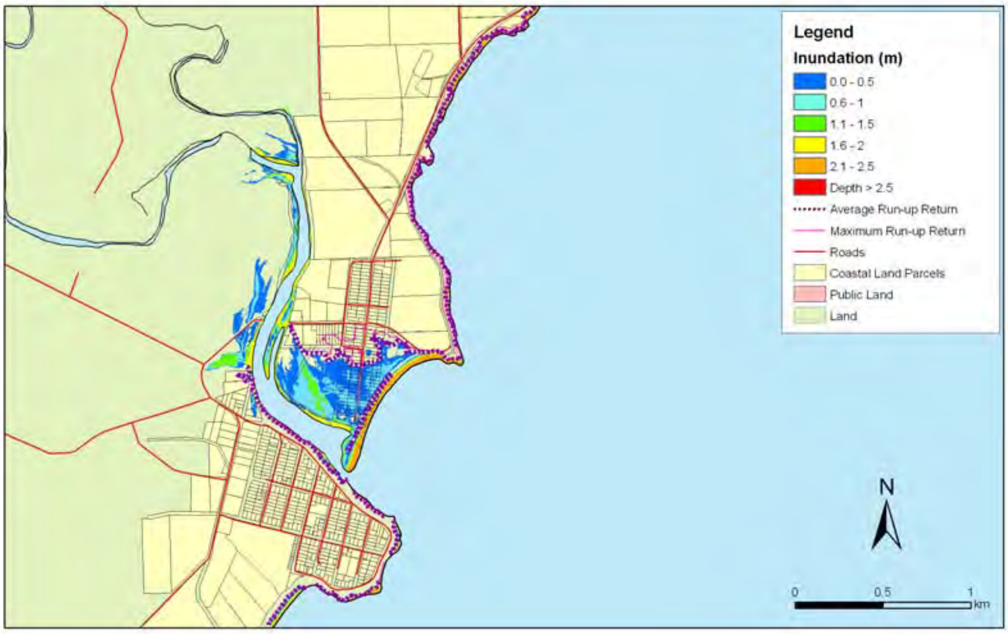

Figure 5.186: Taranui and Kakanui - 1:50 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

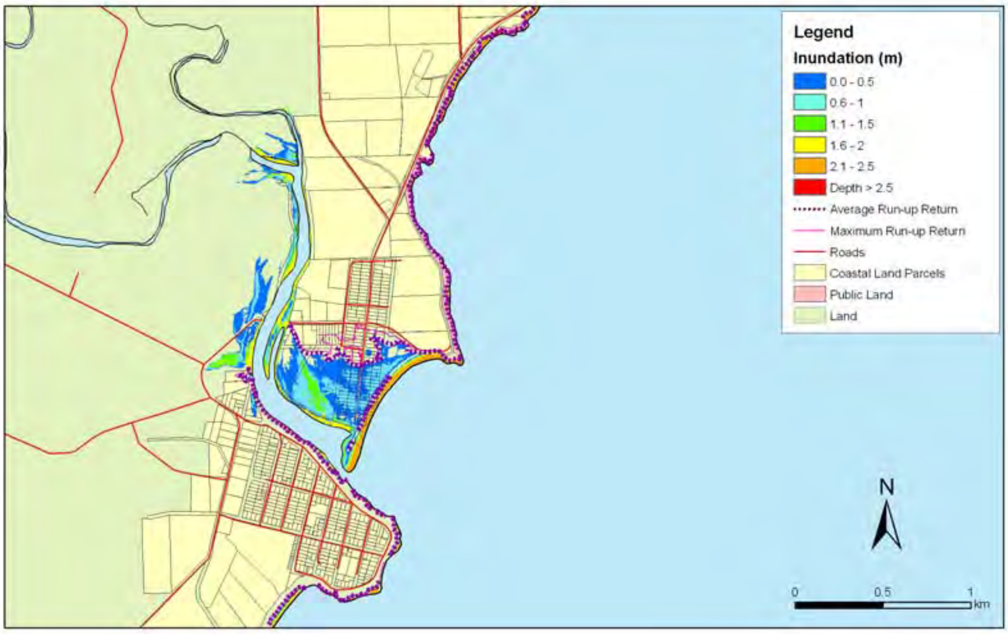

Figure 5.187: Taranui and Kakanui - 1:100 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

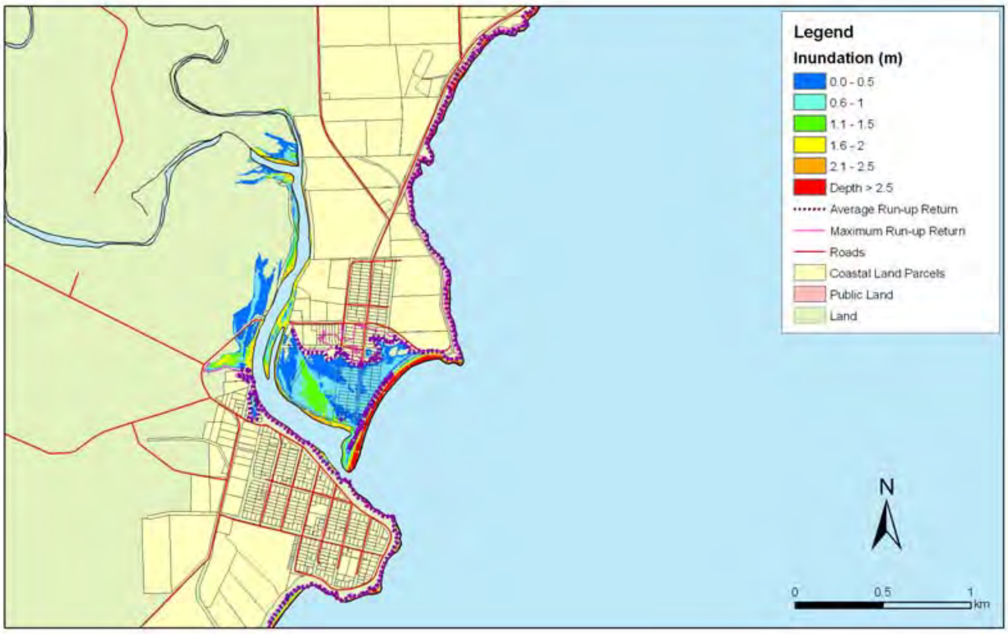

Figure 5.188: Taranui and Kakanui - 1:500 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

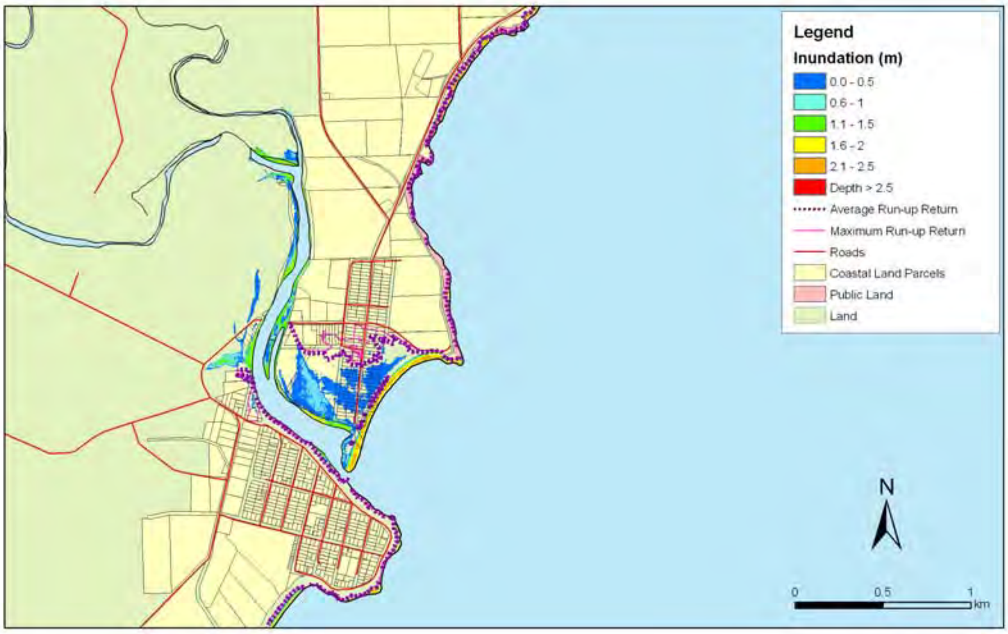

Figure 5.189: Taranui and Kakanui - 1:20 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

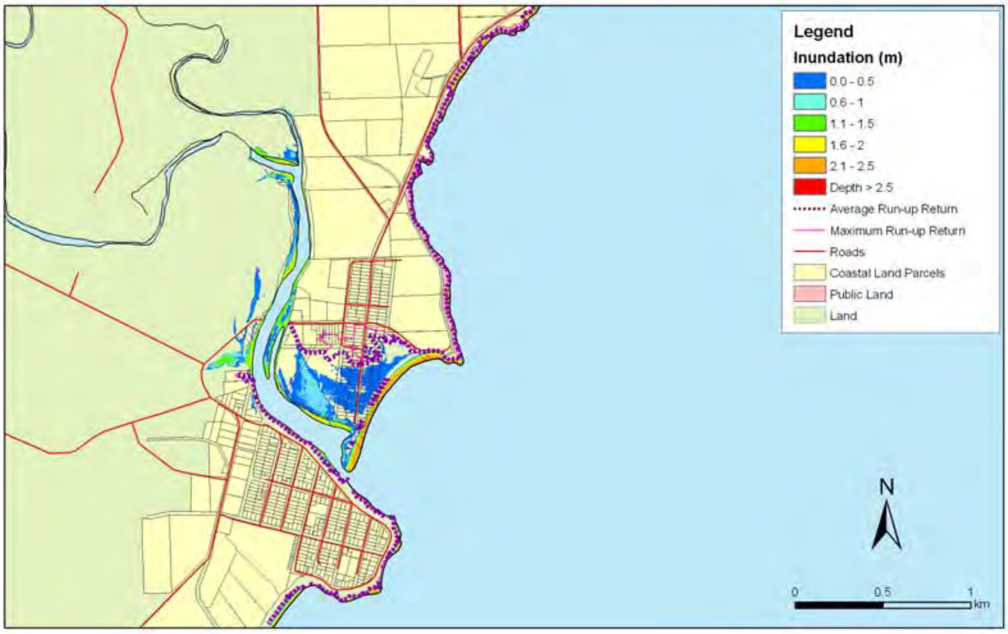

Figure 5.190: Taranui and Kakanui - 1:50 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

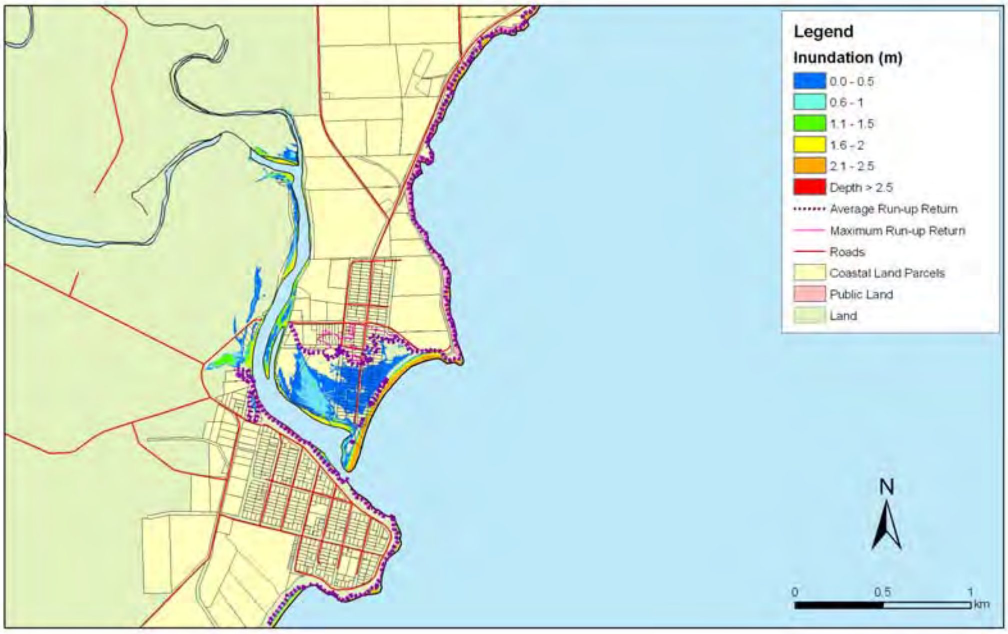

Figure 5.191: Taranui and Kakanui - 1:100 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

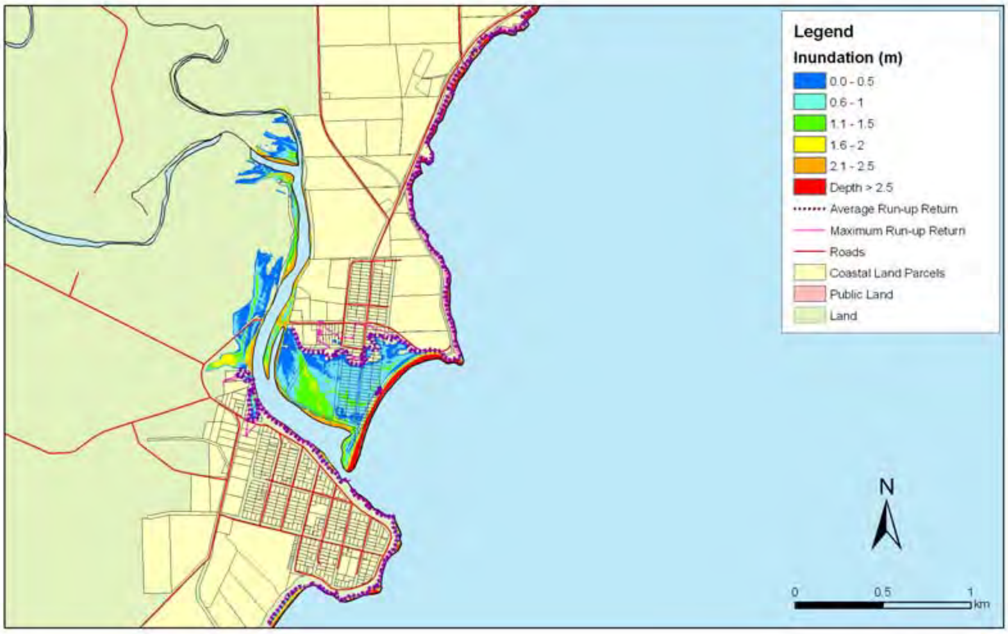

Figure 5.192: Taranui and Kakanui - 1:500 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up

5.17 Oamaru

Predicted inundation and wave run-up extent for present mean sea level are shown in Figures 5.193 – 5.196, for mean sea level + 0.3 m in Figure 5.197 – 5.200, and for mean sea level + 0.5 m in Figure 5.201 – 5.204. Note that coastal erosion is not included in the modelling process, and dynamic coastlines are represented as resilient, permanent, features.

- Maximum predicted sea level height of 2.26 m above MLOS (2.37 m above DVD-58).

- Predicted inundation at present MLOS is confined to the coastline. According to our calculations, when combined with the LiDAR data, the harbour breakwaters are not submerged by the increased water levels. Anecdotal evidence suggests that overtopping of the breakwaters has occurred in the past (Tonkin and Taylor, 1997), which is predicted here when wave run-up is considered.

- Wave run-up is also confined to the coastline. Some overtopping of the harbour breakwater is predicted.

- Rising sea levels increase the depth of inundation along the coastline but do not affect the extent. The harbour breakwaters are not submerged but are partially overtopped by waves.

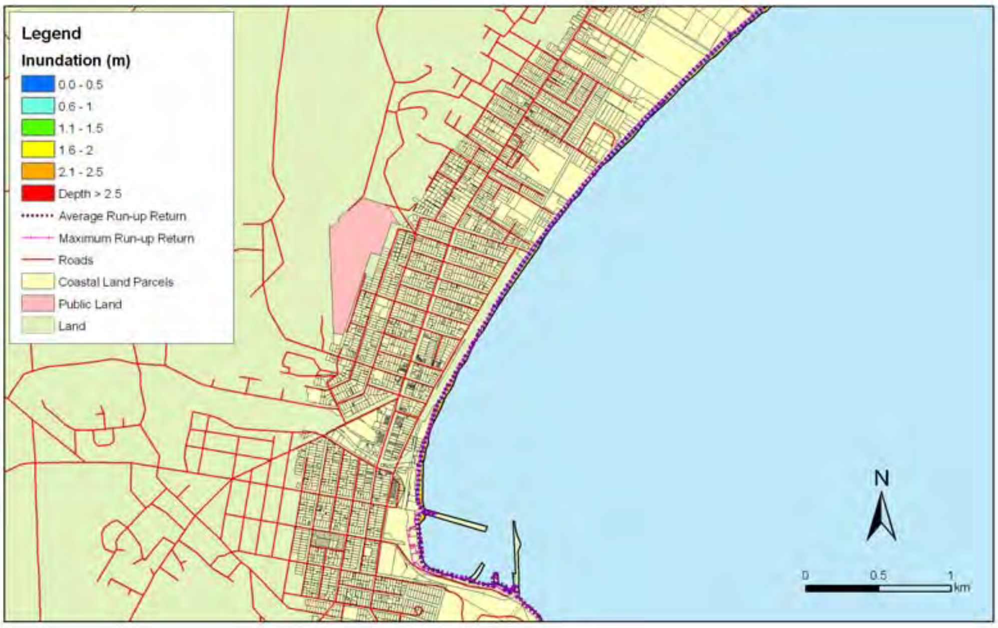

Figure 5.193: Oamaru - 1:20 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

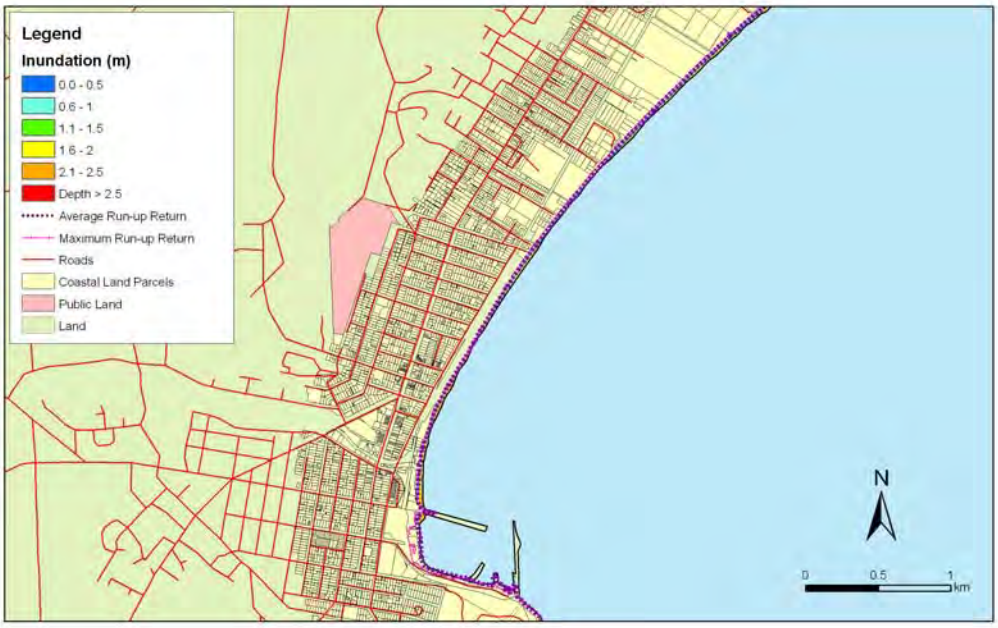

Figure 5.194: Oamaru - 1:50 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up**.**

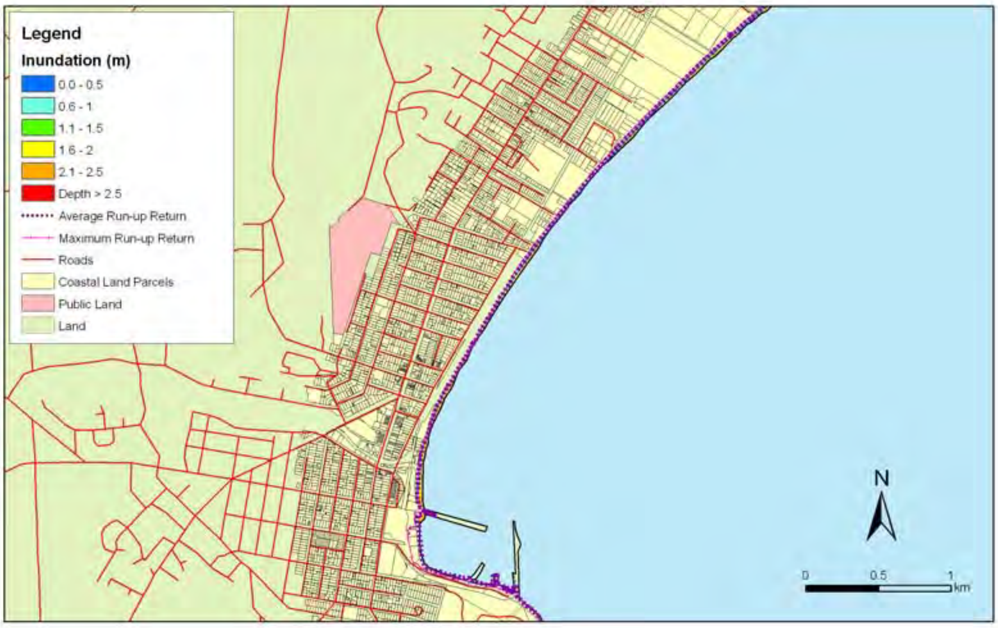

Figure 5.195: Oamaru - 1:100 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.196: Oamaru - 1:500 year sea level event at present MLOS: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.197: Oamaru - 1:20 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.198: Oamaru - 1:50 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.199: Oamaru - 1:100 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.200: Oamaru - 1:500 year sea level event at MLOS + 0.3m: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.201: Oamaru - 1:20 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

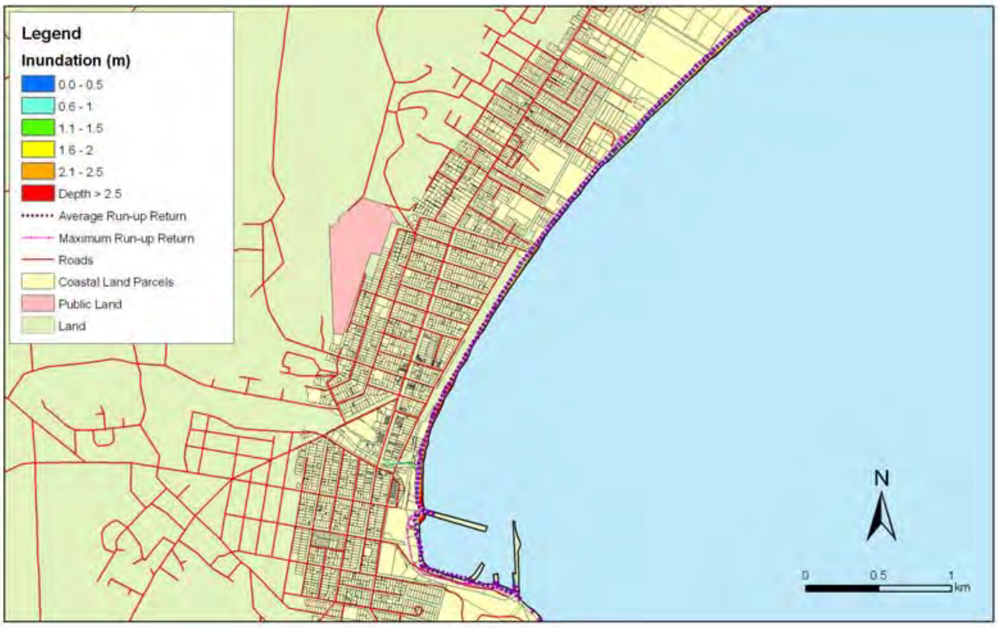

Figure 5.202: Oamaru - 1:50 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.203: Oamaru - 1:100 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up.

Figure 5.204: Oamaru - 1:500 year sea level event at MLOS + 0.5m: Maximum water depth for inundated land and the mean and maximum wave run-up

6. Discussion

The results presented here suggest that extreme storm surge and wave events in the Otago region may in future temporarily raise sea level by up to 2.63 m above present MLOS. This compares with typical present-day MHWS sea levels (with no storm surge or wave set-up) of about 1 m. The predicted levels vary greatly, both with return period (the maximum value given above has a return period of 500 years) and with location. Clearly, the higher sea levels occur with longer return periods, but the difference between a 20-year event and a 500-year event is typically only of the order of 20-30 cm. In contrast, the predicted levels vary between locations by up to 85 cm. There is no obvious north-south gradient in the predicted extreme values: the largest predicted values occur at Oamaru in the north and Clutha and Toko Mouth in the south. Wave set-up clearly makes a significant contribution to the sea level values, and is strongly dependent on local beach slope. Tidal heights and storm surge conditions vary relatively little spatially, and so wave set-up dominates the spatial variability.

Wave run-up increases the area of impact during surge events by creating a "splash zone" into which breaking waves may extend. Like wave set-up, run-up is strongly dependent on local beach slope and predicted values vary considerably between sites. Northward-facing sites (e.g. Purakanui, Long Beach, Moeraki) are also protected from the largest waves (which tend to come from the south) and therefore exhibit lower run-up values. Thus the predicted values are strongly dependent on site-specific conditions and management strategies need to consider these local factors.

The values presented here are slightly higher than those presented in an earlier study of extreme sea levels in Otago region (Wild et al., 2005). As well as the different methodologies used in the two reports, the earlier report did not include the effects of wave set-up. The magnitude of wave set-up is entirely sufficient to account for the difference between the two reports and demonstrates that the process should not be neglected when planning for future extreme events.

As mentioned earlier, the components of tide, storm surge and wave set-up may combine in a multitude of combinations to result in the predicted extreme sea level with a given return period. To demonstrate this we present in the table below examples for three locations (Clutha, Dunedin Harbour and Oamaru) of how different combinations may provide the same net result (i.e. extreme sea level). Tide is an essential contributor to extreme sea level events, and so high water must be assumed; here we present examples at MHWS and Perigean high water. For each return period extreme sea level and two tidal heights, we present two different combinations of storm surge and wave set-up that combine to create the total sea level. The individual components may have return periods less than or greater than the return period for the total sea level event and these values are provided also. For example, the first four rows in the table produce a sea level of 2.01 m, which has a return period of 20 years. The top two rows give scenarios whereby storm surge and wave set-up combine with MHWS to provide the sea level. The third and fourth rows provide scenarios whereby storm surge and wave setup combine with the larger perigean tide to produce the extreme sea level. The scenarios are then repeated successively for the other return periods and the other sites.

From Table 6.1, it can be seen that longer return-period storm surge and wave set-up events are required for extreme sea levels to occur at MHWS tides than at Perigean tides, as the latter are considerably larger. At Oamaru, given the limitations on wave set-up and surge heights, it appears that extreme sea level events with 100 year and 500 year return periods are only likely to occur if the surge and wave set-up coincides with Perigean tides, since MHWS is not high enough to support the predicted sea levels without extremely unlikely surge and wave set-up events (i.e. > 500 year return periods).

The examples given in Table 6.1 are only a sample of the possible combinations that could produce the predicted sea level. However, as the return period and height of the sea level event increases, the number of possible combinations decreases as the probability of each component reaching the necessary height also decreases.

Table 6.1: Potential scenarios leading to extreme sea levels. (Note: Return periods of 1 year indicate heights below the threshold for independent events).

	Sea level		Tides		Scenario: Pressure + Wind		Scenario: Waves	
	Return period	Height	Type	Height	Return period	Height	Return period	Height
Clutha Mouth	20	2.01	MHWS	0.89	220	0.89	1	0.23
					1	0.29	7	0.83
			Perigean	1.22	1	0.39	1	0.39
					4	0.59	1	0.19
	50	2.08	MHWS	0.89	220	0.89	1	0.30
					1	0.29	18	0.90
			Perigean	1.22	1	0.39	1	0.46
					4	0.59	1	0.26
	100	2.14	MHWS	0.89	220	0.89	1	0.36
					1	0.29	42	0.96
			Perigean	1.22	1	0.39	1	0.52
					4	0.59	1	0.32
	500	2.25	MHWS	0.89	220	0.89	1	0.47
					1	0.29	208	1.07
			Perigean	1.22	1	0.40	1	0.63
					4	0.60	1	0.43
Dunedin Harbour	20	1.66	MHWS	0.91	10	0.70	1	0.05
					1	0.40	84	0.35

	Sea level		Tides		Scenario			
					Pressure + Wind		Waves	
	Return period	Height	Type	Height	Return period	Height	Return period	Height
			Perigean	1.28	1	0.33	1	0.05
					1	0.18	1	0.20
	50	1.73	MHWS	0.91	21	0.77	1	0.05
					1	0.47	84	0.35
			Perigean	1.28	1	0.40	1	0.05
					1	0.18	4	0.27
	100	1.79	MHWS	0.91	41	0.83	1	0.05
					2	0.53	84	0.35
			Perigean	1.28	1	0.46	1	0.05
					1	0.18	39	0.33
	500	1.91	MHWS	0.91	164	0.95	1	0.05
					6	0.65	84	0.35
			Perigean	1.28	3	0.58	1	0.05
					1	0.27	124	0.36
Oamaru	20	2.01	MHWS	0.82	220	0.89	3	0.20
					66	0.70	179	0.30
			Perigean	1.15	4	0.59	31	0.26
					15	0.69	1	0.16
	50	2.08	MHWS	0.82	430	0.94	434	0.32
					841	0.99	48	0.27
			Perigean	1.15	11	0.66	31	0.26
					39	0.76	1	0.16
	100	2.14	MHWS	0.82	841	0.99	675	0.33
					-	-	-	-
			Perigean	1.15	14	0.68	179	0.30
	500	2.26	MHWS	0.82	-	-	-	-
					-	-	-	-
			Perigean	1.15	51	0.78	434	0.32
					252	0.90	3	0.20

Other factors affecting coastal sea levels around New Zealand that are not considered in this report were summarised by Wild et al. (2005), and include seasonal heating of the water column, ENSO (El Nino Southern Oscillation), the IPO (Inter-decadal Pacific Oscillation) and long-term climate change and sea level rise. Over the next few decades, global sea levels are expected to rise significantly (IPCC, 2007). Clearly, sea level rises of several tens of centimetres will have significant effects on the predicted sea levels given here. For example, a sea level rise of 0.5 m over the next 100 years would increase the 100-year return period predictions by 20 – 30%.

In this report, we have considered the possible effects of sea level rise on potential inundation of Otago. The inundation maps demonstrate that some of the low-lying areas of Otago are at risk of future inundation. This is particularly exacerbated when potential sea level rise is taken into account. In particular, areas around Papatowai, the Catlins River, Taranui, Taieri Mouth, Long Beach, Purakanui, Karitane, Clutha delta and Toko Mouth appear to be susceptible to inundation. The extent of inundation clearly increases when longer-term events and long-term sea level rise are included in the calculations. Other relatively low-lying areas are not predicted to be inundated during future storm surge events. This apparent discrepancy may be explained by the absence of a direct linkage to the sea, in which case inundation cannot occur. Alternatively, some low-lying areas lie considerable distances upstream along rivers e.g. the mudflats on the Kaikorai river, and it is not clear, since the absolute elevation of the land is not precisely known, whether storm surge events will propagate so far upstream. Here the low-lying areas are marked as potential inundation areas. Unlike tsunami events (Lane et al., 2007), where the wave also carries significant momentum, storm surge events are much less dynamic and are not energetic enough to propagate far upstream beyond the elevation of sea level. Tsunamis of a given height will likely inundate further inland than an equivalent height storm surge event.

The study presented here takes measured time series of meteorological and atmospheric conditions and uses established engineering techniques to derive time series of storm surge and wave set-up. There are inherent uncertainties in these simplified approaches, including the relatively short length of data time series, the necessary approximations of seabed and beach slope required for each calculation and the neglect of complicated ocean dynamics. However, to obtain more accurate, dynamical, estimates of storm surge would require coastal hydrodynamic modelling, and that approach makes the prediction of future extreme events more difficult. The estimates of extreme sea levels given here are considered robust, and compare well with those from an earlier study (Wild et al., 2005).

The process of converting predicted sea levels into maps of potential inundation also contains inherent uncertainties. First, there is error attached to the topography derived from LiDAR surveys. Second, the mapped inundation is not a dynamic process, whereby seawater indundates gradually inland from the coastline, but a static one where the predicted sea level is overlain on the digital DEM. Distinguishing likely inundation from unlikely inundation requires some interpretation and introduces an element of subjectivity. Nevertheless, the predictions of potential inundation given here feature direct connections to the sea and are considered to be essentially robust, and should provide good guidance toward identifying coastal areas that are potentially at risk in future

7. Conclusions

This study has investigated potential extreme sea level events for the Otago region that are predicted to occur with return periods of 20, 50, 100 and 500 years. Time series of tidal heights, storm surge and wave set-up have been derived from observed time series of sea level, atmospheric pressure and wind speed and direction. Established statistical techniques were applied to predict the probability if future extreme sea level events. Areas potentially affected by wave run-up were also determined.

Predicted peak sea levels varied with both location along the Otago coastline and with return period. The highest predicted sea level of 2.63 m above MLOS occurred at Toko Mouth with a 500-year return period. Conversely, the minimum predicted level of 1.55m above MLOS occurred at Warrington with a 20-year return period. Wave run-up increased the affected areas by up to 1.85 m (in vertical height). Wave set-up makes a significant contribution to the predicted sea levels and is mainly responsible for the variation between locations as it is strongly dependent on local beach slope.

Maps of land areas at risk from inundation by extreme sea level events were produced for 17 settlements in Otago for each return period. Inundation varied greatly between locations, depending on the local topography. A number of low-lying areas are at risk of extensive inundation from storm events. In particular, areas around Papatowai, the Catlins River, Taranui, Taieri Mouth, Long Beach, Purakanui, Karitane, Clutha delta and Toko Mouth appear to be susceptible. The predicted future rise in sea levels increases the depth and extent of inundation in several localities.

This work represents a best estimate of the inundation of the Otago coastline caused by extreme sea levels due to combinations of high tides, storm surge and wave set-up. While every effort has been made to ensure accurate results, using rigorous statistical methods, these are based upon our current state of knowledge.

8. References

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