A methodology to assess the impacts of climate change on flood risk in New Zealand

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Executive Summary

Global climate change is predicted to increase the temperature of the atmosphere between 1.4 °C and 5.8 °C by the end of the century if no action is taken to reduce greenhouse gas emissions. This will have an impact on flooding, as the warmer air holds more moisture, and this moisture can produce not only more rain but more intense weather systems.

The New Zealand Climate Change Office of the Ministry for the Environment has produced a series of guidance materials to help local government assess the impacts of climate change. These materials provide information on climate change impacts as well as a generic risk assessment framework that can apply to flood risk as well as to other weather-related natural hazards.

This report provides more specific guidance for councils on how to handle the possible impact of climate change when assessing flood risk. Firstly, a simple screening test is recommended to assess whether climate change is likely to significantly affect flooding in a region. If so, it is recommended that a further, more detailed analysis be carried out for each catchment of interest.

More accurate projections of expected future flood risk will provide local government with a better basis for community consultation and informed decision-making on necessary levels of flood protection works.

This report first outlines the application of the screening test, which will help councils identify whether changes in flood risk are likely to be significant. It then outlines a more detailed methodology to assess the impacts of climate change on flooding. The methodology involves using weather models to estimate the impact of expected temperature changes on future rainfall. The weather models generate estimates of the future rainfall. Hydrological modelling is then used to convert future rainfall to future river flows, including peak flow levels. Finally, inundation models can be used to convert that peak flow to the area, depth, and flow speed of flood waters. Many councils are already using hydrological and inundation modelling when assessing current flood risk for their communities. The methodology described here to assess the impacts of climate change fits well into this more general framework.

The detailed methodology outlined in this report, as well as the application of the simple screening test, make a number of assumptions and carry a range of uncertainties. The report discusses these assumptions and uncertainties, and the extent to which the results obtained by this methodology can be a robust tool for decision-making.

1. Introduction

One of the impacts expected from global climate change is an increase in the impacts of flooding.

The Ministry for the Environment (MfE) has developed guidance for local government on best practice in assessing the impact of climate change in a region. For flood risk, the first stage of this is to assess both qualitatively and quantitatively whether climate change is likely to be an issue. To achieve this MfE guidelines suggest using a simple screening test to tell councils whether or not they need to conduct a full risk assessment using more complex scenarios. This report both explains the application of this screening test, and outlines a more complex but more accurate risk assessment method using detailed and catchment-specific weather models, rainfall, river flow, and resulting inundation.

As the details of the impacts on flooding of climate change will be catchment dependent, the specific results from one catchment are unlikely to be indicative for any other catchment. An individual assessment is therefore necessary for each catchment where councils wish to determine the likely impacts of climate change on flood risk. The methodology is designed to be applicable to most catchments larger than an area of 40 by 40 km (1600 km^2). It is also designed for a mainly rural setting.

2. Planning and decision-making context

The management of flood risk in New Zealand is governed by a number of different laws and regulations. It is primarily undertaken by regional councils in conjunction within territorial authorities. Flood risk management is currently under review by the Government under the lead of the Ministry for the Environment.

At present, the Building Act requires that the risk of flooding to a specific building be no more than a 2% probability in any given year (a 2% Annual Exceedance Probability, AEP). Some regional councils stipulate higher levels of protection in their Regional Policy Statements, with a required AEP of 1%.

Since climate change is likely to change flood risk in most regions, expected risk from flooding should be taken into account when existing flood defence systems are reviewed and/or upgraded, so that the same level of protection is provided over the lifetime of the system in question. This is also consistent with the recent amendment to the Resource Management Act, which requires that all persons exercising powers and duties under the Act have particular regard to the effects of climate change (Resource Management (Energy Efficiency and Climate Change) Amendment Act 2004).

A key objective of this report is to outline a cost-effective, credible methodology for councils to assess the likely changes in current 2% and 1% AEP flood risks for their communities.

3. Methodology

3.1. Overview

The methodology described in this report enables councils to establish how much the current flood risk could alter under climate change, based on the expected changes in rainfall intensity during storm events.

The methodology follows a staged approach of increasing complexity.

The essential foundation for this approach is knowledge of the flood risk under the current climate conditions, based on some representative past storm events. An increasing number of councils already use rainfall information rather than river gauge data to determine flood risk and inundation levels associated with any given AEP. This underpinning information on actual rainfall in the catchment, and how this translates into river flows and inundation levels, is required to allow robust estimates to be made on the future effects of climate change on flood risk.

The first step of the methodology is to undertake a simple screening test. This involves the uniform scaling of the amount of rain falling during a storm event within the catchment over the peak rainfall period, where the scaling factor is proportional to the assumed increase in temperature caused by climate change.

If the above screening analysis shows a potential significant change in flood risk for the area in question, councils should proceed to the second step. This is a more detailed modelling of the likely changes in rainfall for the specific catchment under a warmer climate. This can be done by using a Regional Atmospheric Modelling System (RAMS), which is sensitive to specific catchment characteristics.

The increased rainfall from either the simple screening test or the more complex weather modelling approach can then be translated via run-off and river flow models into the peak flow and risk of inundation at areas of interest. The models used to translate the increased rainfall into river flows and inundation levels are the same as would be used in a sophisticated flood risk analysis for the current climate. This approach, for the current climate at least, is increasingly being adopted by councils.

It should be recognised that rainfall is not the only parameter that is likely to change in future and that could influence flood risk. Other factors include climate variability, land-use change, sea-level and storm surge for coastal locations, and the level of development and hence protection needed. Some of these factors rely on a number of assumptions and uncertainties. The report will briefly comment on how and the extent to which these factors can be taken into account, and as a consequence how robust the results of the methodology outlined here are likely to be.

3.2. Establishing the base case (current climate) flooding event

In order to assess the likely changes in flood risk under climate change, the council will need to choose a storm or storms under current climate conditions with which changes can be compared. It is often best to choose real examples of past storms, where their impact on flooding is known. These storms should span the range of storms likely to impact on the catchment being considered. They need not be the biggest storms experienced, but ones that could be regarded as being representative of the weather situations likely to be experienced. Choosing such storms enables weather and rainfall-to-river flow models to reproduce the current conditions. This should give councils a good idea of how well the models replicate the weather and its effects on flood risk for the catchment.

Current extreme rainfall rates for particular locations, durations and average recurrence intervals can be obtained from an analysis of historical rainfall data sets from monitored sites, or from the High Intensity Rainfall Design System (HIRDS) CD-Rom, available from NIWA.

For coastal settlements, councils may wish to consider the current flooding risk posed by a combination of heavy rain with high tides and storm surges.

3.3. Which climate change scenarios?

It is impossible to predict the precise amount by which the Earth will warm over the next century, and how much the different regions of New Zealand will warm, as this depends on future greenhouse gas emissions. In addition, although all climate models show a general warming trend, they give slightly different answers with regard to the exact amount of warming. We recommend councils consider at least two temperature change scenarios covering the expected lifetime of infrastructure and other major developments. For example, mid-low and mid-high scenarios for both 2030 and 2080 could be suitable choices.

It is generally recommended that more than one mid-range scenario be used, since a narrow focus on the mid-range may underestimate the uncertainties associated with climate change projections. While some timescale needs to be chosen to establish the size of changes, it must also be recognised that climate change will not end at 2080, but will continue to have an increasing effect into the distant future.

There are a number of factors to consider when deciding which climate change scenarios are most appropriate, including;

- The duration of decisions to be made
- The nature and value of the assets which may be at risk
- The extent of the assets which may be at risk

The projected changes in average temperature for each region of New Zealand are summarised in Table 2 of *Preparing for climate change* (see Further Reading, below). More details can be found on pages 11 and 12 of *Climate Change Effects and Impacts Assessment*.

3.4. Rainfall: the simple screening test

One approach to determining how climate change will affect extreme rainfall in a community is to use a standard scaling factor as set out in Table 7 (shown below) of *Preparing for climate change* (see Further Reading, below). The table recommends percentage adjustments to apply to extreme rainfall for a range of average recurrence intervals. The increases in rainfall are per degree Celsius of warming. Take, for example, a 1-in-50-year event lasting 3 hours. For this example, the amount of rain expected to fall under today’s climate should be increased by 7.2% for every degree Celsius of projected increase in the annual mean temperature.

The scaling factors are mid-range estimates. They take into account the extra rainfall likely as a result of the extra moisture holding capacity of the air. They do not take account of local catchment characteristics, nor do they reflect that storms are likely to be more intense due to the heat released by this moisture and the increase in pole to equator temperature gradient in our region.

ARI (years) Duration	2	5	10	20	30	50	60	70	80	90	100
< 10 minutes	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
10 minutes	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
30 minutes	7.4	7.5	7.6	7.6	7.7	7.7	7.7	7.7	7.7	7.7	7.7
1 hour	7.1	7.2	7.4	7.4	7.5	7.5	7.5	7.5	7.5	7.5	7.5
2 hours	6.7	7.0	7.1	7.2	7.3	7.3	7.3	7.3	7.4	7.4	7.4
3 hours	6.5	6.8	7.0	7.1	7.1	**7.2**	7.2	7.2	7.2	7.2	7.2
6 hours	6.3	6.6	6.8	7.0	7.0	7.1	7.1	7.1	7.1	7.1	7.1
12 hours	5.8	6.2	6.5	6.6	6.7	6.8	6.8	6.8	6.9	6.9	6.9
24 hours	5.4	5.9	6.2	6.4	6.5	6.6	6.6	6.6	6.7	6.7	6.7
48 hours	4.6	4.9	5.1	5.2	5.3	5.4	5.4	5.4	5.4	5.5	5.5
72 hours	4.3	4.6	4.8	5.0	5.1	5.2	5.2	5.2	5.3	5.3	5.3

Based on the estimates of increased rainfall from the above table, a screening assessment of the likely change in flood risk is possible. For example, the table above suggests that for a 1°C warming, 3-hour rainfalls with 50 year ARI are likely to increase by 7.2%. This figure can be used to increase the rainfall from past storms and the effects modelled. Hydrological models can be used to estimate the river flow expected from these bigger storms, and inundation modelling can be used to assess the likely increased areas and depths of flooding. These steps are outlined in sections 3.7 and 3.8. An increasing number of councils are already using such more sophisticated models to assess their current flood risk. An example of this approach is outlined in the appendix.

The simple screening test described in this section allows a preliminary and relatively low-cost assessment of whether climate change could significantly alter the flood risk for a particular location. However, a number of simplifying assumptions have been made in deriving the figures in the table, and no recognition has been given for particular catchment characteristics that could modify the preliminary findings. A more detailed assessment, as described below, is often warranted and necessary.

3.5. Rainfall: take a detailed look

If the simple screening test indicates that climate change could significantly affect an important or large-scale council function or service, we recommend a more complex approach using weather and flooding models. This will provide a truer and more detailed picture of the increased intensity of rainfall. For instance, the models may show that extremely heavy rain is concentrated more in particular locations, while nearby areas get lighter rain than would be expected under the current climate. The characteristics that make up the catchment could also be considered. This will influence both the weather and rainfall-to-river flow models.

Any weather model chosen for this work needs to be capable of reproducing the weather on scales that are relevant to the catchment. For example, in order to account for the effect of the Southern Alps, the model needs a grid spacing of around 5 km to correctly calculate the uplift of the air over the steep hills. Modern weather models are capable of replicating New Zealand weather systems in sufficient detail. For example, NIWA has used the Regional Atmospheric Modelling System (RAMS) to replicate the rainfall over the country, including the Southern Alps and Bay of Plenty.

High-resolution weather models often take their starting conditions from models of global weather. The global weather models start with observations of the weather and compute the movement of air, heat, and moisture, using physical principles, in order to simulate and forecast the weather. They form the basis of all modern weather forecasting.

Weather models are run operationally in many centres to produce forecasts of rainfall. NIWA has pioneered the use of this forecast rainfall as input into rainfall-to-river flow models for New Zealand. The results of pilot studies show that useful information on forecast river flows can be produced for many areas. For example, the flows for the Bay of Plenty flood event in July 2004 were well forecast by such a system.

The high-resolution weather model should first be tested to check it can replicate historical storms under the current climate. Then the model’s starting conditions can be changed to reflect future environments of the storms. For example, the temperature of the air and sea can be raised to reflect the environment expected in say 2050. This will provide a better estimate of likely changes in heavy rainfall than the simple screening analysis undertaken in the previous section.

The results from the weather model can then be fed through a rainfall-to-river flow model which delivers inundation levels for any given rainfall event. The modelling steps required to achieve this are outlined in sections 3.7 and 3.8. It should be noted that those steps, and the models required to provide quantitative information, are not specific to climate change, but are in increasingly common use around the country to model the flood risk under current climate conditions based on rainfall data.

3.6. What else could change?

Factors such as a rise in mean sea level, change in risk of storm surge, or change in river run-off caused by possible future change in land use, may heighten the risks of flooding even more. The additional factors which need to be considered depend on the specific catchment and likely future developments. It is outside the scope of this report to provide information on how to model changes in flood risk due to land-use change, or increasing development.

For coastal regions, an inundation model should include storm surge and projected sea level rises. The guidance manual, *Coastal Hazards and Climate Change,* recommends that in developing scenarios, councils use at least the most likely mid-range scenario for sea-level rise. It recommends staff use a figure of 0.2 m by 2050 and 0.5 m by 2100 when considering sea-level rise in projects or plans.

3.7. From rainfall to river flow

Having designed a suitable weather event, and applied the likely effect of climate change to the rainfall, this information should be run through a suitable rainfall-to-river flow model. This section explains how that is done.

The changes we see in peak flow, as a result of the modelling outlined in this section, will produce a multiplication factor which can be applied to the inundation modelling of a 2% AEP event or other ‘design storm’. The inundation modelling is outlined in the following section 3.8.

Once rainfalls have been estimated for each climate change scenario, from the high-resolution weather modelling (section 3.5) or a simple screening assessment (section 3.4), they have to be turned into river flows to provide the amount and rate at which floodwaters will spill onto areas likely to be flooded. A rainfall-to-river flow model works out such things as how much of the rainfall seeps into the ground and how much rapidly runs off the land into river channel. The model can be checked (‘validated’) against measured flow data for existing conditions to ensure it accurately reflects reality.

Flood peaks are caused by the rainfall that does not seep into the ground and that moves quickly across the land to the river channels. The rate at which the water runs off the land depends on:

- The steepness of the land.
- The type of land surface present in the catchment, e.g., water runs off smooth surfaces, such as concrete or asphalt parking lots, much more quickly than off ploughed fields.
- How wet the ground surface is when the rainfall occurs.

- The ability of the land to store water on vegetation, in the soil and in depressions in the ground.

The water that seeps into the ground does not usually reach the river in time for it to add to a flood peak. However, it pre-conditions the ground so that a future rainfall event of the same size as one just experienced can cause much more runoff to the river channel. This is because ‘antecedent’ rainfall fills up the storage in the soil and if a second event occurs before the stored water has had chance to drain, the new rainfall must run off to the river channel. The response of the soil depends on:

- The type of the soil. Sandy soils drain quickly and so their ‘memory’ of previous events is soon lost. Clay-like soils drain more slowly and so a previous rainfall can have a marked effect on how much of a later event runs off and how much infiltrates.

- The condition of the soil. By this is meant whether the surface is compacted, as in a mob-stocked field, or open as a result of ploughing.

- The steepness of the slope on which the soil lies.

- The depth to any impervious layer beneath the soil since this will impede the downward movement of water and may force some of the seepage back towards the surface.

- The type of vegetation growing in the soil. Trees tend to have deeper rooting systems than grass and can accordingly extract more water from deeper layers of the soil and transpire it back to the atmosphere. Thus the same soil under tree-type vegetation tends to dry out more quickly following a rainfall than an equivalent grass covered area.

- The temperature. In some parts of New Zealand moisture in the surface layers can freeze during winter and then, if a rainfall event occurs, the surface becomes impervious and large amounts of the rainfall will quickly reach the river channels. This situation can be further complicated if there is snow lying on the ground, since incoming warm rainfall may melt the snow and effectively cause an event worse than the rainfall event on its own.

Thus calculation of how much rainfall reaches a river is a complex procedure and rainfall-to-river flow models seek to use available data to make due allowance for all the various factors that can affect it.

Once the water running off the ground into the river channels has been calculated, a further calculation is needed to work out how long it will take the water to find its way down the channel network. The time for the water to reach a downstream location such as the breakout point for inundation flooding depends on:

- The steepness of the various parts of the river channel network.
- The roughness of the channel bed. Smooth channels transmit water quickly, whereas rough and weed infested channels delay the flow of water.
- The density of the channel network. A catchment with many kilometres of channel per square kilometre of ground surface will respond differently to a catchment with only a few kilometres of channel per square kilometre of ground surface.
- The shape of the catchment. Roughly circular catchments will have different flow characteristics when compared to elongated catchments.
- The direction in which a storm moves relative to the catchment. In elongated catchments a storm that travels from the headwaters to the outlet will add more to a flood peak than a storm that moves up a catchment from its mouth.
- ‘Catchment resonance’ or the way several upstream tributaries may all deliver their peak runoff to a main channel at about the same time and so compound the flood flow arriving at a down stream breakout point.

To cope with all the above sources of variation, a rainfall-to-river flow model must be ‘spatially distributed’. What this means is that the model must be able to:

- Accept rainfall that varies in both space and time.
- Calculate the surface runoff from each sub-area that contributes runoff to a river channel, taking into account things like the steepness, soil, and vegetation characteristics, and antecedent wetness of the sub-area.
- Combine the flows from these sub-areas.

A model able to accommodate the above characteristics will also be able to take into account factors that change with climate. So, for example, if as a result of climate warming more forest is converted into pasture, then this information can be put into the model by changing the vegetation type in those sub-areas where conversion occurs. Similarly, if the rainfall patterns change (e.g., become more intense in some areas and less intense elsewhere), then this can also be taken into account. Likewise, a suitable model should also be able to incorporate possible changes to river vegetation, (e.g., more willows growing in the channel will effectively roughen the channel and slow the passage of a flood).

Ideally, rainfall-to-river flow models should take account of the potential effects of climate change on conditions in the catchment, such as land use changes. In some cases, however, the effects will be small compared to the overall uncertainities involved in such a complex prediction exercise.

Councils are increasingly beginning to use such sophisticated rainfall-to-river flow models to better understand and quantify the flood risk for their communities under the current climate, based on rainfall observations in relevant catchments. These models, where data are available and models have been tested and implemented, can therefore readily be used to estimate the effects of climate change at a modest additional cost.

3.8. From river flow to flooding

As inundation modelling is computationally slow and expensive, the approach suggested here is to apply the weather and riverflow models to a range of storms but to limit the inundation modelling to just one ‘design storm’.

The design storm can be chosen from past events, or built from an understanding of the riverflow statistics. For most applications, this design storm will be a 2% AEP flood.

In this approach, we take the increase in peak flow from the rainfall-to-riverflow modelling, and use it as a multiplication factor for increasing the peak flow of a design flood event under climate change. An inundation model takes this information combined with other aspects, such as tide and storm surge, to show not only where flooding would occur, but how deep and fast floodwaters could flow through the community. This section explains the factors involved in inundation modelling.

While the process for converting rainfall into river flows is reasonably well-established and computationally fast, converting river flows and sea conditions at the mouths of rivers into accurate flood inundation levels is comparatively new. It is also computationally slow because to derive an accurate estimate, calculations have to be done at a fine spatial scale. In many cases, the size of the calculation grid can be as small as 7 m by 7 m and the resultant models can use several million computational grid points. While this level of refinement may seem unduly high it is necessary if accurate results are required. Without this level of refinement and the field data on ground levels, it is not possible to ascertain if, where and when the stopbanks will be breached. Since only a small section of stopbank needs to be overtopped to cause inundation, and the location of this section is critical to the flooding, the elevations of the stopbank must be accurately measured and modelled in sufficient detail to be sure that the model correctly predicts where the failure would occur.

Note that in the inundation simulations, stopbank failure by overtopping is the only mechanism considered. The model needs to treat such overtopping failures correctly, i.e., it allows for the gradual erosion of the stopbank over time. Failure by other mechanisms such as slumping following piping of water under the stopbanks is currently beyond the ability of the present generation of inundation models.

When a stopbank fails, the water that breaks through flows in all directions. Modern inundation models are able to model the spread of this water to predict the areas that will be flooded, and the depths and speed of this flooding.

For an inundation model to produce reliable results, it must use high quality data. Several types of data are needed to run the model. These are:

- High-resolution topographic data for the areas at potential risk of flooding. These data come from LIDAR surveys, or digital airborne photogrammetry. Survey grade global position system (GPS) measurements may also be used. Information on the elevation of the near shore seabed and channel bed beneath the river water surface is also required. These data come from bathymetric survey of the seabed, and river channel measurements. The topographic data are critical to the success of inundation modelling.

- Information on the roughness of the ground. This affects how fast the water flows across the ground. Classification of the ground cover types and use of suitable look-up tables provide these data.

- Information on the expected flood flows issuing onto the flood plain. This information comes from the rainfall-to-river flow model, and is in the form of a flow hydrograph, i.e., a graph of flow against time.

- Information on the downstream conditions that block the exit of the flood to the sea. This information is a mixture of mean sea level, the state of the tide expected during the flood and storm surge, i.e., the extra height of the sea caused by the low barometric pressure over the sea effectively "sucking" water up on to the land. Both mean sea level and storm surge are expected to be affected by climate change.

- Information on special features of any particular flood plain situation, e.g., culvert and bridge dimensions and soffit levels.

Councils are increasingly making use of the tools available to map flood plains and inundation levels for the purpose of better understanding and managing flood risk for their communities for the current climate. The same tools and models can be used to model the effects of climate change.

3.9. Validation

All the model results for current conditions can be checked ('validated') against measurements. For example, the weather models can be validated against rain gauge data. However, as gauges measure rainfall only at a point and the weather models are aiming to represent rainfall over an area, it may in fact be better to validate the catchment average rainfall by comparing the rainfall-to-river flow model output with measured flow. Further, it would be useful to compare the inundation expected from the inundation modelling with what occurred during a known event. This would then give confidence in the ability of the models to reproduce reality.

3.10. What to do with the results?

The steps outlined above will allow councils to produce estimates of the inundation levels associated with future 2% and 1% AEP levels under a warmer climate. It is equally possible to estimate the change in AEP for a given inundation height, that is, how much more frequent the current 1-in-50 year flood will be in a warmer climate. This information is relevant under the Building Act, Resource Management Act, Local Government Act, and regional policies and plans.

Undertaking a climate change study will be most cost-effective when done in conjunction with a study of the current flood risk. The findings of such an assessment can be applied whenever new developments are planned, or river control and flood protection schemes are reviewed or upgraded, to ensure the same minimum level of protection can be maintained over the lifetime of the development in question. Alternatively, councils may be able to plan for later upgrades of flood defences as flood risk increases. In that case, however, it is important to ensure future development still makes such staged upgrades possible.

Producing detailed projections of likely flooding with as much accuracy as is possible will provide councils with a basis for community consultation and informed decision-making consistent with the regulatory framework, resource constraints, and community expectations.

Computer models and techniques are being refined all the time, as are climate change predictions, so councils may wish to review the findings from time to time.

4. Assumptions and uncertainties

Several necessary assumptions have been made in using this approach to assess quantitatively the impacts on flooding of climate change. One of those is that the frequency of the events being studied will not change. That is, that while the intensity of these events will increase, the chances of the storms “turning up” has not changed. In fact, the expectation from climate change studies is that these significant storms are likely to be more frequent, particularly in the west. This means that, over the long term future, the actual number of inundation events may be under-estimated.

In changing the temperature of the air and sea, we have made an assumption that the relative humidity will not change, which implies that the air will take up extra moisture. In the absence of any evidence or compelling reason to the contrary, this assumption seems reasonable. The weather modelling approach appears to be realistic, given the future storms simulated by the model operate in much the way as today’s storms.

Another significant assumption is that the storms chosen for modelling are representative of the storms likely to be encountered in the future. Global climate change models are not predicting a significant change in the typical types of storms. Thus the storms, if carefully chosen, are likely to be representative of those that will occur in the future.

The conversion of rainfall into flows assumes that the land use does not change. Given that the climate results in an increased temperature, two changes may occur:

1. The natural vegetation may change over time. Precisely what these changes might be is not easily predicted. The consequences for floods may well be less or more interception of rainfall by vegetation, decreased or increased absorption of moisture by the ground, and changes to riverside vegetation resulting in less or more resistance to river flow during times of flooding.

2. Changes in the way people use the land, such as more or less urbanisation, and/or changes in agricultural production. Increased land clearance for agriculture may well lead to increased sediment in the river and a gradual build up of the downstream river bed with its attendant increase in flood risk.

3. Higher average temperatures are likely to change evaporation rates and freezing levels, which in turn could affect soil permeability and the speed with which rainfall runs off. These factors can be modelled in principle, but usually would be very complex.

It is beyond the scope of this report to investigate the complex implications of changes in land use under climate change for flood risk. It requires combining the climate change with the implications for vegetation change, which in its turn depends on the soil types and terrain. Where people are involved, regional, national, and even international economics may influence social decisions on the type and extent of changes in land use by humans.

Once a flood reaches the flood plain, the flood inundation calculations assume that:

1. Flooding will occur from over-topping of the riverbank and/or stop banks, e.g., slumping failure of the stop banks by undermining is not considered.

2. The riverbed will scour in a predictable manner. This is a large source of error in inundation modelling because the degree and location of river scour is difficult to determine and can be greatly influenced by random factors such as a large tree falling into the river.

3. The topography of the flood plain is up to date, and, in particular, that the crest heights of stop banks are accurately known.

The importance of these factors will vary from case to case, but need to be considered in assessing and mitigating flood risk.

In addition to the assumptions outlined above, there are a number of uncertainties associated with the models and calculations recommended in this report. The main uncertainties with relevance for the resulting change in flood risk include:

1. Future climate change will depend on future greenhouse gas emissions. The scenarios used in this report assume that no global efforts are made to reduce greenhouse gas emissions. An effective implementation of global agreements

such as the Kyoto Protocol and subsequent next steps could reduce the amount of global climate change and its consequences on flood risk.

2. Climate models used to predict temperature changes for New Zealand have uncertainties, and there are differences in regional patterns between models. While there is relatively good agreement of the general temperature trend between models, it cannot be ruled out that future climate change could, for example, change ocean circulation patterns in such as way that the temperature change for New Zealand could be even higher, or lower, than the range indicated in the guidance material currently available.

3. The climate models are currently unable to predict whether there will be a systematic change in weather patterns, and natural climate patterns such as the El Niño/La Niña pattern. A change in those patterns could result in a change of the frequency with which typical storm systems reach New Zealand.

5. Further reading

Preparing for climate change. A guide for local government in New Zealand (2004), New Zealand Climate Change Office, Ministry for the Environment

Climate Change Effects and Impacts Assessment (2004), report prepared for the Climate Change Office of the Ministry for the Environment by David Wratt, Brett Mullan and Jim Salinger (National Institute of Water & Atmospheric Research Ltd), Sylvia Allan and Tania Morgan (MWH New Zealand Ltd), and Gavin Kenny (Earthwise Consulting Ltd), in consultation with a range of people from local government organisations.

Coastal Hazards and Climate Change: A guidance manual for local government in New Zealand (2004), report prepared for the Climate Change Office of the Ministry for the Environment by scientists, planners and engineers from NIWA, Beca Consultants Ltd, DTec Consultants Ltd, and Tonkin and Taylor Ltd, in consultation with a range of people from local government organisations.

All documents are available at

www.climatechange.govt.nz/resources/local-govt/guidance.html

Bandaragoda, C.; Tarboton, D.G.; Woods, R.A. (2004), Application of TOPNET in the distributed model intercomparison project. *Journal of Hydrology 298*: 178-201.

Appendix: Results for the Buller Catchment example

This appendix reports on the use of the above approach in assessing the impact of climate change on flooding in the Buller catchment. Here we will show the decisions we made in choosing the weather events and climate change scenarios, and the results achieved by the weather, rainfall-to-river flow, and inundation models to calculate the flood risk from current and future 1% and 2% AEP events.

Select base event(s)

The events we selected were chosen to be representative of a range of rainfall generating weather systems, and hence are not necessarily the worst ever experienced. They were also chosen, somewhat pragmatically, as events for which we had sufficient data for modelling. The three chosen started on 12 November 1999, 14 August 2000, and 8 December 2001, and generally between 3 and 7 days of weather was modelled. Rainfall totals for the events were around 91 mm, 95 mm and 537 mm respectively. These totals are not extreme events and would have return periods of less than 1 year.

Select climate change scenarios

We chose target years of 2030 and 2080, with mid-low and mid-high points to cover uncertainty, from Table 2 of *Preparing for climate change* (see Further Reading, main report). More details can be found on pages 11 and 12 of *Climate Change Effects and Impacts Assessment.* The relevant values are:

West Coast	Average change in the annual temperature (ºC)
1990-2030s	0.1 to 1.2
1990-2080s	0.2 to 3.5

We chose the roughly 25 and 75 percentiles of the total annual average temperature range, which gave temperature increases that we approximated to 0.5°C and 1°C for 2030, 1°C and 2.7°C for 2080. Choosing 1°C for both time scales saves significantly on the cost of the modelling. 2030 and 2080 were chosen as time scales that were representative of the design lifetime of much of the infrastructure a council would manage.

Screening results

The results of the screening method, drawn from Table 7 (shown below, and which indicates the percentage increase in rainfall per 1°C) of *Preparing for climate change*, suggest that for a 6-hour duration 1 in 50 year event (2% AEP) and for 2030, mid-low and mid-high rainfall multipliers should be 3.5 (0.5°C increase), and 7.1 % (1°C increase) and by 2080 should be 7.1 and 19.2% for increases of 1°C and 2.7°C respectively.

As there were insufficient representative gauges in the catchment, rainfall information produced by the weather model for current conditions was used as the base rainfall information. This rainfall was increased by the factors suggested in the MfE guideline tables. The current and future rainfall estimates were then used as input into the Topnet model of the catchment.

ARI (years) **Duration**	**2**	**5**	**10**	**20**	**30**	**50**	**60**	**70**	**80**	**90**	**100**
< 10 minutes	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
10 minutes	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
30 minutes	7.4	7.5	7.6	7.6	7.7	7.7	7.7	7.7	7.7	7.7	7.7
1 hour	7.1	7.2	7.4	7.4	7.5	7.5	7.5	7.5	7.5	7.5	7.5
2 hours	6.7	7.0	7.1	7.2	7.3	7.3	7.3	7.3	7.4	7.4	7.4
3 hours	6.5	6.8	7.0	7.1	7.1	**7.2**	7.2	7.2	7.2	7.2	7.2
6 hours	6.3	6.6	6.8	7.0	7.0	7.1	7.1	7.1	7.1	7.1	7.1
12 hours	5.8	6.2	6.5	6.6	6.7	6.8	6.8	6.8	6.9	6.9	6.9
24 hours	5.4	5.9	6.2	6.4	6.5	6.6	6.6	6.6	6.7	6.7	6.7
48 hours	4.6	4.9	5.1	5.2	5.3	5.4	5.4	5.4	5.4	5.5	5.5
72 hours	4.3	4.6	4.8	5.0	5.1	5.2	5.2	5.2	5.3	5.3	5.3

Increasing the rainfall for our 3 storms led to increases in river flow as shown in Table 1. Average changes are shown in Table 2.

Results of the screening test

An inspection of the flow model output shows that, for the current climate scenario, the models have reproduced well the measured peak flows. These good results come from modelling the weather at sufficient resolution, and from a refined hydrological model.

This screening test suggests that for the Buller catchment, climate change is likely to produce increases in peak flow of up to (mid-high scenario) 20% by the 2080s. As this is likely to cause a significantly larger flooding risk, a more detailed analysis would be justifiable.

Using the weather model to determine the rainfall increase for the projected temperature rise

These systems were modelled with the RAMS mesoscale model at 5 km resolution. The model was initialised with United Kingdom MetOffice unified global model analyses at 60 km resolution. Rainfall was output at hourly intervals.

The temperature of the air and the sea surface were adjusted in the weather model in accordance with the climate change scenarios. The weather model height fields were adjusted to achieve hydrostatic balance. This is necessary for the model to be able to adjust to the new climate.

The Buller catchment is interesting, in that it lies behind the Paparoa ranges, and is hence in the lee of these coastal hills. This complicated the response to the climate change scenarios, in that the Paparoas appeared to take the "brunt" of the change, with little and sometimes even less rainfall spilling over into the Buller catchment. This led to the response of the model for storms being complicated, with the rainfall showing little change for 0.5°C and 1°C scenarios. Bigger changes were seen for the 2.7°C scenario, particularly on the larger storm. This has meant that the interpretation of the results is difficult, and has led to wider standard errors than would be expected for catchments that don't sit in the eastward lee of a major mountain range.

Table 1: The changes in riverflow expected from the screening test changes in rainfall.

Nov-99		**Case 1**	
Measured peak m^3/s	**Scenario**	**Model peak m^3/s**	**% change**
2020	0	1850	0
	0.5°C/3.5%	1919	4
	1°C /7.1%	1993	8
	2.7°C /17.75%	2208	19
Aug-00		**Case 2**	
Measured peak m^3/s	**Scenario**	**Model peak m^3/s**	**% change**
1555	0	1382	0
	0.5°C /3.5%	1430	3
	1°C /7.1%	1481	7
	2.7°C /17.75%	1629	18
Dec-01		**Case 3**	
Measured peak m^3/s	**Scenario**	**Model peak m^3/s**	**% change**
5150	0	5306	0
	0.5°C /3.5%	5541	4
	1°C /7.1%	5785	9
	2.7°C /17.75%	6531	23

Table 2: Average percentage changes in riverflow.

Scenario	**Mean Changes**	**Std Error of the Mean**
0.5°C (3.50%)	**3.8**	0.4
1.0°C (7.10%)	**7.9**	0.7
2.7°C (17.75%)	**19.9**	1.9

From Table 5, it is apparent, compared to the screening method increases, that the weather modelling examples have a significantly higher increase in rainfall for the mid-high scenario (2.7º C increase) for 2080 events. While Table 3 shows the were only small changes for the 0.5 and 1.0°C cases, particularly for the lighter events, the 2.7°C event had rainfall changes ranging from 18 to 48%.

In this analysis we have combined 3 weather events by simply averaging the increases in peak flow. Given the range of results across the three storms, and given that the more intense storm showed significantly higher increases, it is apparent from Table 4 that we have sampled too few storms to be confident of our results. Investigating several more storms, particularly intense ones, may help improve the confidence in these results.

A more detailed analysis of the weather model output was undertaken to test the validity of this work, and some of the assumptions that have been made.

One implicit assumption is that the remodelling of the storm for a warmer climate would not lead to a significantly different storm developing, and hence invalidate the comparisons. Figure 1 to Figure 6 show the changes in rainfall for each of the global warming scenarios for each of the events. The rainfall shows consistent changes in intensity or pattern of the time series, with no significant extra developments.

These figures also show that the Buller catchment, lying as it does in the lee of the Paparoas, has no significant overall increase in rainfall for the first two climate change scenarios, but there are large changes in the rainfall at other locations. For example, the area to the south of the catchment, near Mt Cook, shows large increases in rainfall with the first two scenarios for the first two events. Indeed, there are increases in rainfall on the upwind side of the Paparoas, but this appears not to spill over into the Buller catchment.

Results of the weather modelling have shown that, while the screening approach is a first step, it is quite simplistic. It does not take into account any of the topographic and catchment characteristic effects, and only accounts for the greater moisture holding capacity of the air. The weather modelling enables us to approximately estimate the positive feedback that the increase in moisture will have on storms and explicitly models the effects of the topography. In this example, the effect of the Paparoas, while not influencing the screening approach, has been shown to be significant in the weather modelling.

Translating projected rainfall into river flow

The hourly rainfall from the weather models was used as input into the Topnet (see Bandaragoda *et al*, 2004, in further reading, main report) model of the Buller catchment. This is a sophisticated spatially-distributed model that is capable of replicating the hydrological characteristics of this catchment.

Figure 7 shows the change in the rainfall over the Buller catchment for a 2.7°C increase in temperature. Figure 8 shows the consequences of this change, assuming all other things remain unchanged, on the likely flood at the Te Kuha river flow measurement station just upstream of Westport.

Table 3: **The changes in catchment-averaged rainfall from the weather modelling of the climate change scenarios. Table 4 presents an analysis of the percentage changes given in the right hand column.**

Nov-99 Case 1		
Scenario	**Mean rain mm**	**% change**
0	95	0
0.5	94	-1
1	98	3
2.7	112	18
Aug-00 Case 2		
Scenario	**Mean rain mm**	**% change**
0	44	0
0.5	45	2
1	40	-9
2.7	60	36
Dec-01 Case 3		
Scenario	**Mean rain mm**	**% change**
0	207	0
0.5	224	8
1	252	22
2.7	306	48

Table 4: **The average percentage changes in catchment averaged rainfall from the weather modelling of the climate change scenarios.**

Scenario	**Mean changes**	**Std Dev**	**Std Error of the Mean**
0.5°C	**3.1**	4.7	3.3
1°C	**5.2**	15.5	11.0
2.7°C	**33.7**	15.1	10.7

Table 5: **A comparison of the screening and weather modelled changes in rainfall.**

Scenario	**Screening result changes**	**Weather model changes**
0.5°C	**3.5**	**3.1**
1.0°C	**7.1**	**5.2**
2.7°C	**17.75**	**33.7**

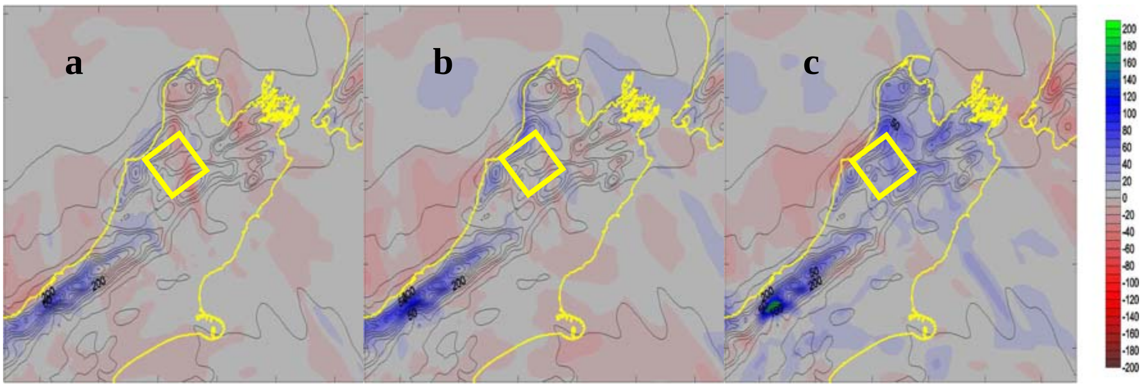


Figure 1: **Changes in rainfall (mm) for sample storm 1 (November 1999) for each of the global warming scenarios included in this study, a) +0.5 C warming (b) +1.0C warming and (c) +2.7 C warming. Note, blue corresponds to increases in rainfall, red corresponds to decreases. The black contour lines are the accummulated rainfall (mm) for the period 00 UTC 10 Nov. to 03 UTC 12 Nov, 1999 as simulated by RAMS for the current day.**

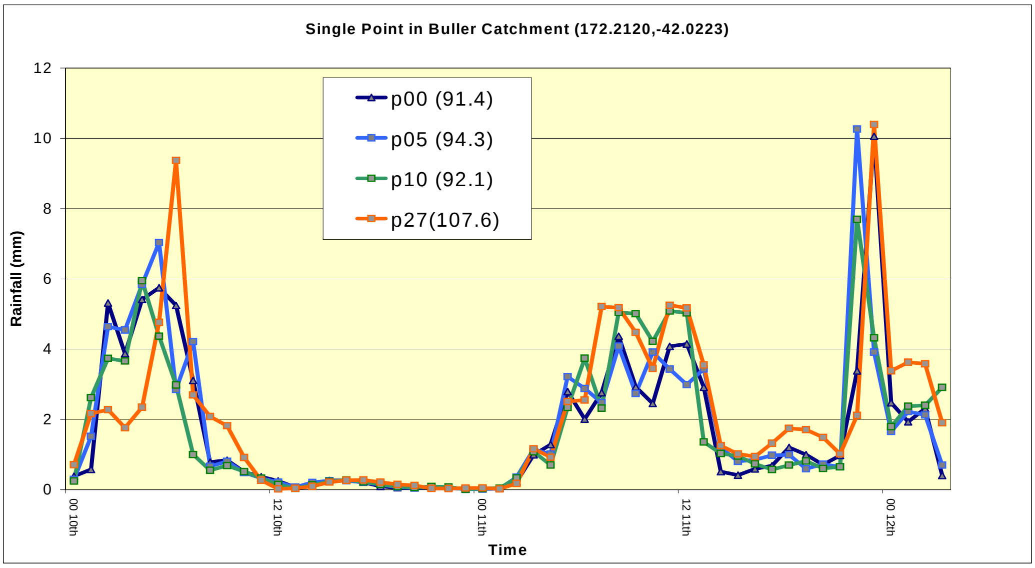


Figure 2: **Timeseries of rainfall (mm) for a point in the centre of the Buller Catchment (lee of Paparoas) for the period 00 UTC 10 Nov. to 03 UTC 12 Nov., 1999 for the current day (p00) and for the three global warming scenarios (+0.5C=p05, +1.0C=p10, +2.7C=p27) as simulated by the RAMS model.**

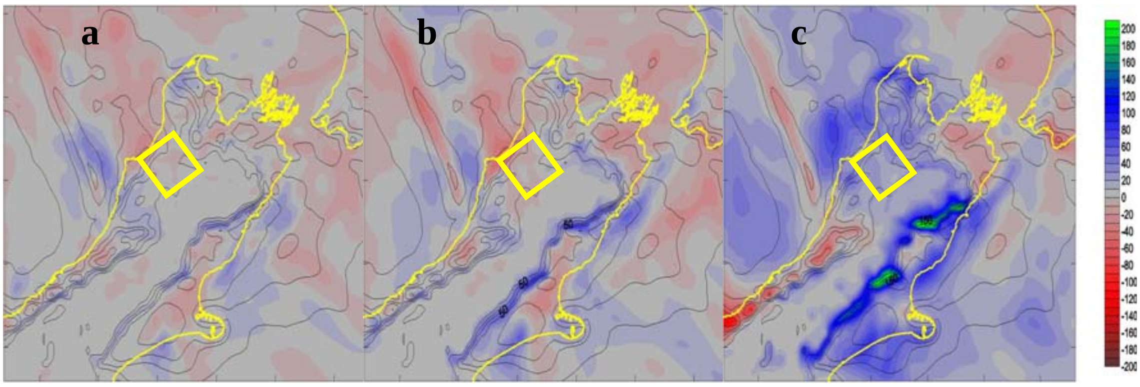


Figure 3: Changes in rainfall (mm) for sample storm 2 (August 2000) for each of the global warming scenarios included in this study, a) +0.5 C warming , (b) +1.0C warming , and (c) +2.7 C warming. Note, blue corresponds to increases in rainfall, red corresponds to decreases. The black contour lines are the accummulated rainfall for the period 12 UTC 14 Aug. to 00 UTC 21 Aug., 2000 as simulated by RAMS for the current day.

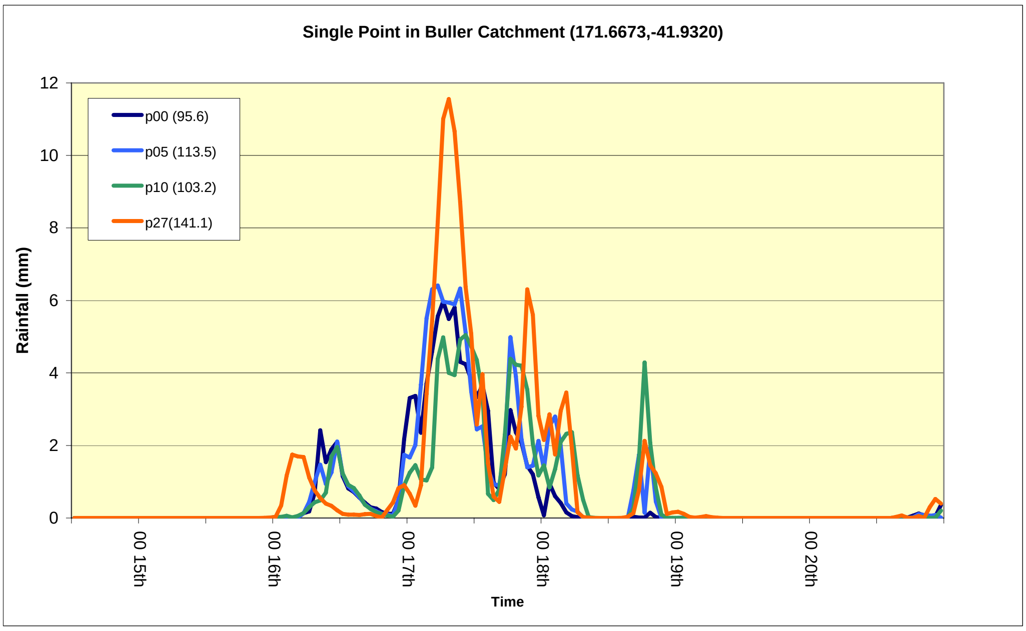


Figure 4: Timeseries of rainfall (mm) for a point in the centre of the Buller Catchment (Paparoas) for the period 12 UTC 14 Aug. to 00 UTC 21 Aug., 2000 for the current day (p00) and for the three global warming scenarios (+0.5C=p05, +1.0C=p10, +2.7C=p27) as simulated by the RAMS model.

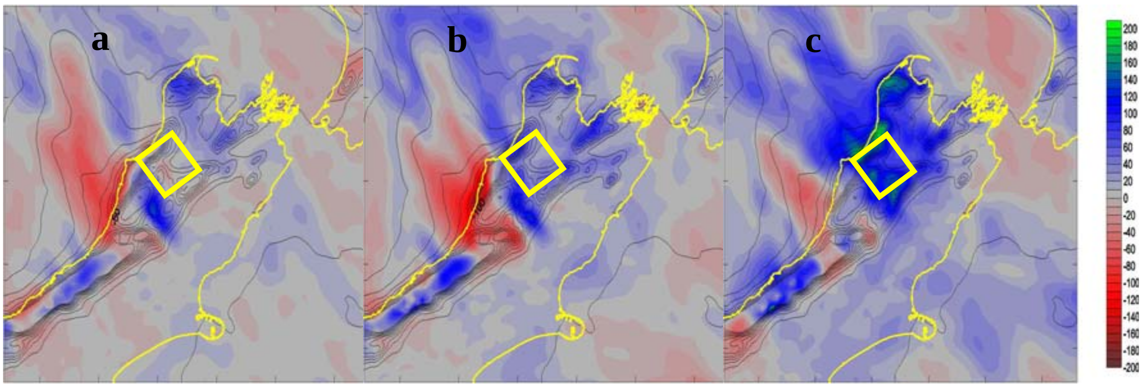


Figure 5: Changes in rainfall (mm) for sample storm 3 (December 2001) for each of the global warming scenarios included in this study, a) +0.5 C warming, (b) +1.0C warming, and (c) +2.7 C warming. Note, blue corresponds to increases in rainfall, red corresponds to decreases. The black contour lines are the accummulated rainfall (mm) for the period 12 UTC 1 Dec. to 12 UTC 8 Dec., 2001 as simulated by RAMS for the current day.

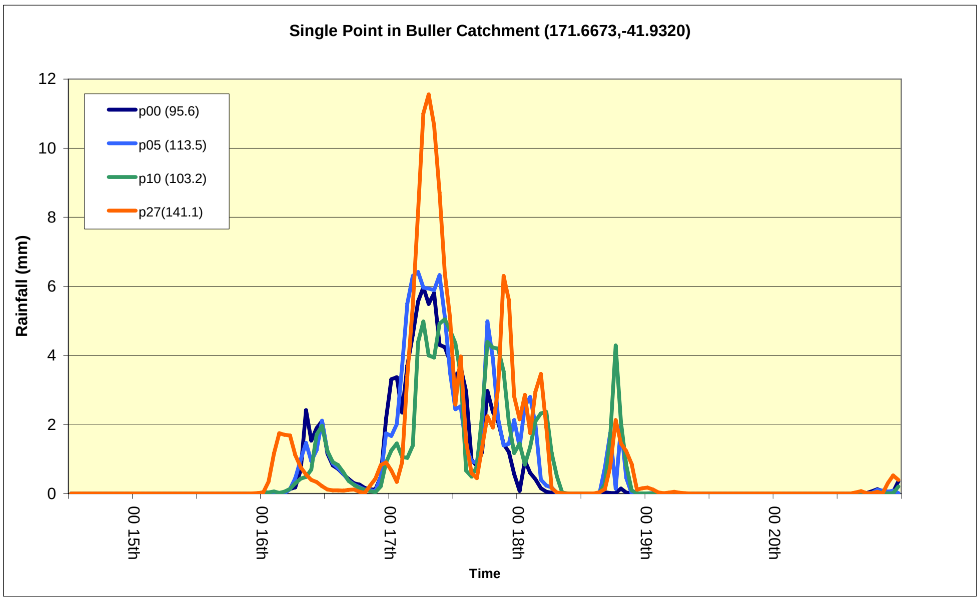
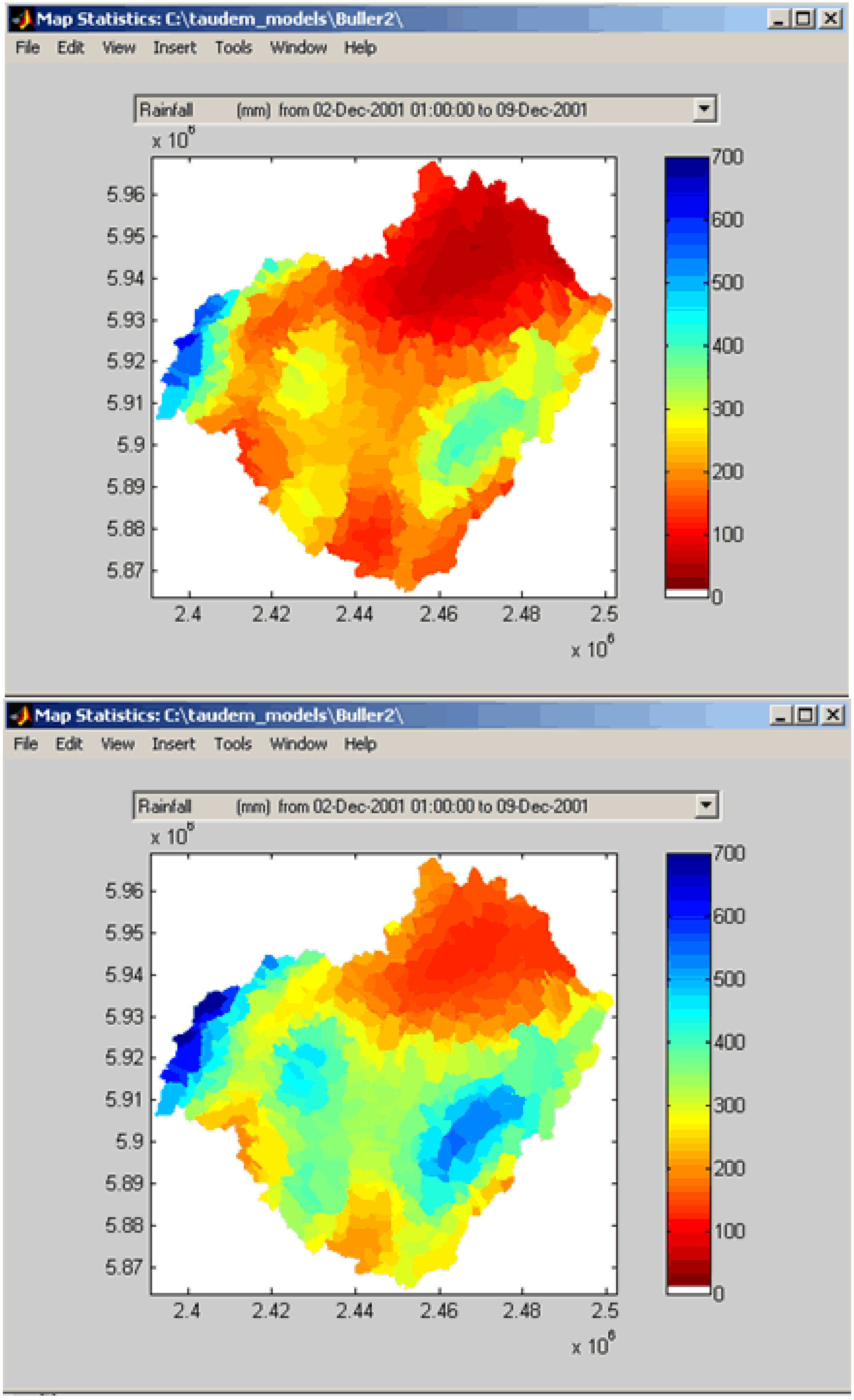


Figure 6: Time series of rainfall (mm) for a point in the centre of the Buller Catchment (Paparoas) for the period 12 UTC 1 Dec. to 12 UTC 8 Dec., 2001 for the current day (p00) and for the three global warming scenarios (+0.5C=p05, +1.0C=p10, +2.7C=p27) as simulated by the RAMS model



Map Statistics: C:\taudem_models\Buller2\

Rainfall (mm) from 02-Dec-2001 01:00:00 to 09-Dec-2001

Map Statistics: C:\taudem_models\Buller2\

Rainfall (mm) from 02-Dec-2001 01:00:00 to 09-Dec-2001

Figure 7: **The top panel shows the calculated rainfall for the December 2001 storm over the Buller for the base case, i.e., for the current climate conditions. The bottom panel shows what is anticipated for a 2.7°C increase in temperature. Note the change of scale, the scale bars show the rainfall accumulated over the event in mm, between the two panels, and the increase in the high rainfall areas of the Paparoa Range in the west of the catchment.**

The results shown in Figure 7 and Figure 8 are for a large storm. Similar calculations were carried out for two other, smaller, storms and these results indicate a less dramatic increase in the flood peak magnitude. A summary of the results is shown in Table 6. These results show that the model has replicated well the flow observed for the current climate, giving confidence that the results from the climate change scenarios are valid.

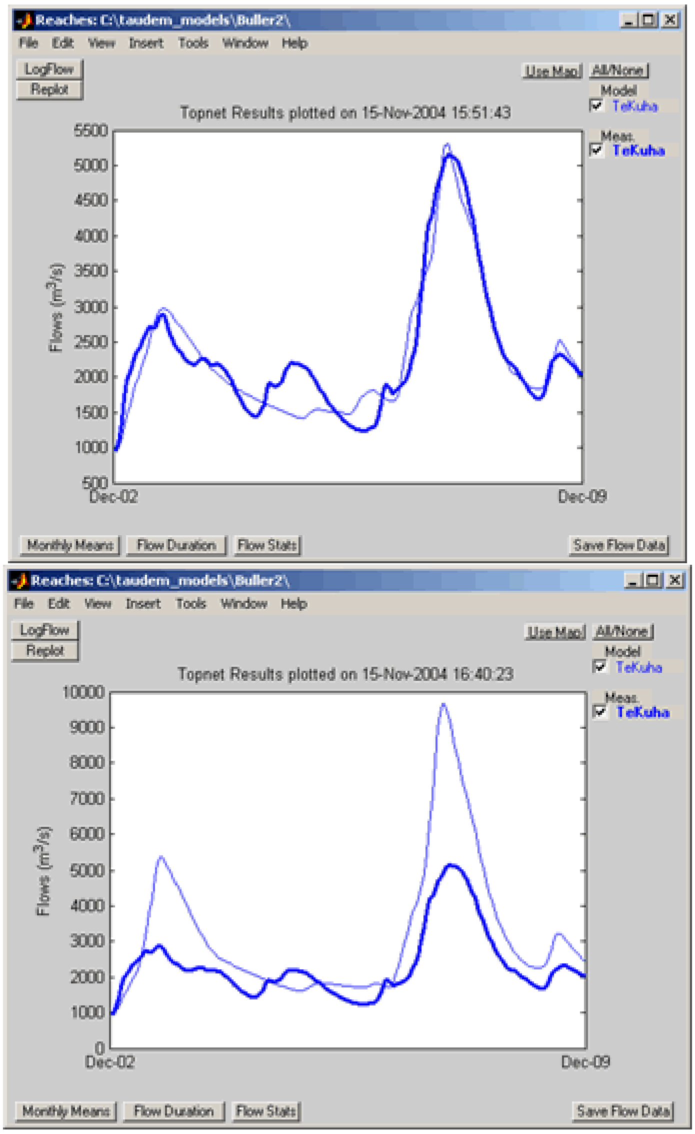


Figure 8: **The top panel shows the measured (bold line) and calculated (fine line) flows for the Buller River at Te Kuha for the current climate. The bottom panel shows the measured flows for the Buller River at Te Kuha for the current climate and calculated flows for an anticipated 2.7°C increase in temperature. Note the change of scale between the two panels. The calculated flood peak in the bottom panel is nearly twice that shown in the top panel**

Table 6: Flood peaks and their changes from the base case (scenario 0) for the three projected temperature increases (0.5°C, 1.0°C and 2.7°C). Note that for two smaller floods, November 1999 and August 2000, projected climate change leads to small reductions in the flood peak for the less extreme climate change scenarios. Table 7 present an analysis of the percentage changes given in the right hand column.

Peak flows are in m3/s, Scenarios in degrees C**

Nov-99

Measured peak m^3/s	**Scenario**	Model peak m^3/s	% change
2020	0	1850	0
	0.5	1800	-3
	1	2052	11
	2.7	2216	20

Aug-00

Measured peak m^3/s	Scenario	Model peak m^3/s	% change
1555	0	1382	0
	0.5	1362	-1
	1	1169	-15
	2.7	1543	12

Dec-01

Measured peak m^3/s	Scenario	Model peak m^3/s	% change
5150	0	5306	0
	0.5	6156	16
	1	7103	34
	2.7	9674	82

Since reliance on the results from analysis of a single event is unwise, the results from the three events given in Table 6 have been combined in Table 7. The figures in red shown the mean change for each temperature change scenario while the column to the right of these numbers, headed “Std Error of the Mean”, gives an indication of their reliability. The interpretation for the two less extreme scenarios, 0.5°C and 1.0°C temperature increases, is that the corresponding results in red are not very different from “no change”, while for the 2.7°C scenario it is more likely that the increase in flood flow is significant. The relatively low confidence in the significance of these results arises from the small number of cases that could be examined and it may be that there are differences between winter and summer events that have not been detected by this limited analysis. Although it is tempting to say that the higher increases seen for the bigger event may be more applicable to the 2% AEP event, rather than the average including the lesser events, there is no real justification for that. Again, further events may need to be modelled.

Table 7: **Average percentage changes in the flood peak from the base case.**

Scenario	Mean % changes	Std Error of the Mean
0.5	**3.9**	7.4
1	**9.7**	17.4
2.7	**37.5**	27.3

Table 8 shows the comparison of the peaks flows estimated by the screening and weather modelling approaches. As with the changes in rainfall, the weather modelling has shown significantly higher peak flows for the 2.7°C scenario. Unlike the rainfall, the peak flows for the 0.5 and 1.0°C scenarios are similar. The greater sophistication of the weather modelling approach is leading to results that may not be expected from a more simplistic approach.

Table 8: **A comparison of the screening and weather modelled changes in peak flow.**

Scenario	Screening result changes	Weather model changes
0.5°C (3.50%)	**3.8**	**3.9**
1.0°C (7.10%)	**7.9**	**9.7**
2.7°C (17.75%)	**19.9**	**37.5**

The estimation of the increase in flood size resulting from the different climate change scenarios has focused on the effect on rainfall as this is expected to be the dominant change. However, other more subtle changes may also occur over time and may need to be considered. In particular, a general warming of the climate may lead to changes in land use as crops that were formerly climate limited may become economically viable. Movement of population may result in larger amounts of impervious area. In some cases, increased agricultural activity may offset the effects of increased urbanisation. Development of areas upstream of a flood plain may result in increased sediment in the river and over time this may result in a rise in the channel bed and cause more frequent flooding.

While the modelling demonstrated here can address some of these issues, others are still being actively researched. In the case of the Buller these many and varied potential consequences of climate change on the catchment have been ignored in favour of the direct consequences of modified rainfall, which is believed to be the overwhelming contribution to flooding risk.

Assess any other relevant changes, e.g., tide, storm surge

The Buller River discharges into the sea near Westport. This is a relatively low-lying area, and the sea level is expected to be important in determining flooding levels. In order to model the effects of higher sea levels in a warmer climate, we have used Figure 9 to assess the likely changes for 2030 and 2080. The figure shows that for 2030 a sea level rise between 0.065m (mid low) and 0.12m (mid high) could be expected, and for 2080 between 0.17 and 0.49 m.

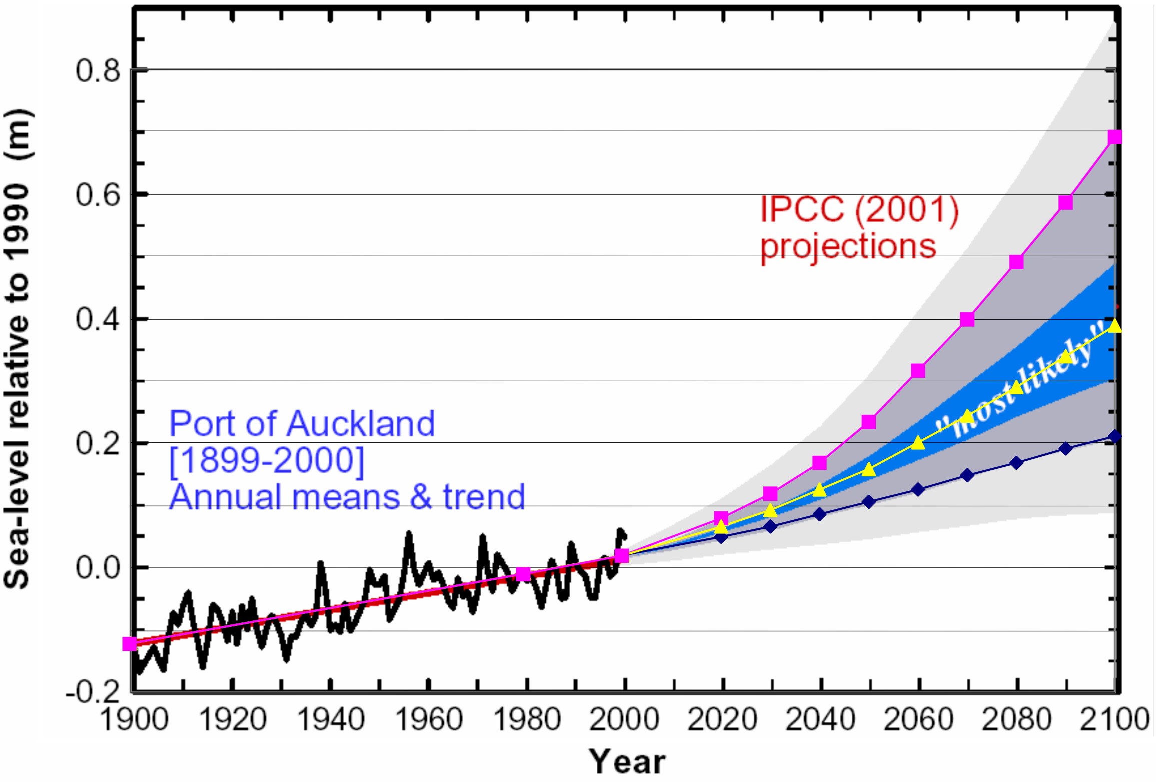


Figure 9: **The sea level rise measured and expected for the Port of Auckland.**

Storm surge

From the weather model output it is possible to diagnose the likely changes in the storm surge component. The results show that storm surge component due to the inverse barometer effect will change only a small amount for the cases simulated in this study (Figure 9 and Figure 10). Figure 10 shows the time-series of mean sea-level pressure as simulated by RAMS for the current day and the +2.7 C climate change scenario. It can be seen that the pressures are never more than 2 hPa lower, so the maximum increase in sea level from this pressure decrease would be at most 2 cm (0.02 m). (Every 1 hPa drop in pressure is approximately equivalent to a 1 cm rise in sea level). However, note that the current day storm, with its pressure drop of 1014 to 985 hPa (29 hPa) would have lifted the sea level 29 cm by comparison.

As the weather modelling results showed little change in the surface pressure, no change was made to the storm surge component.

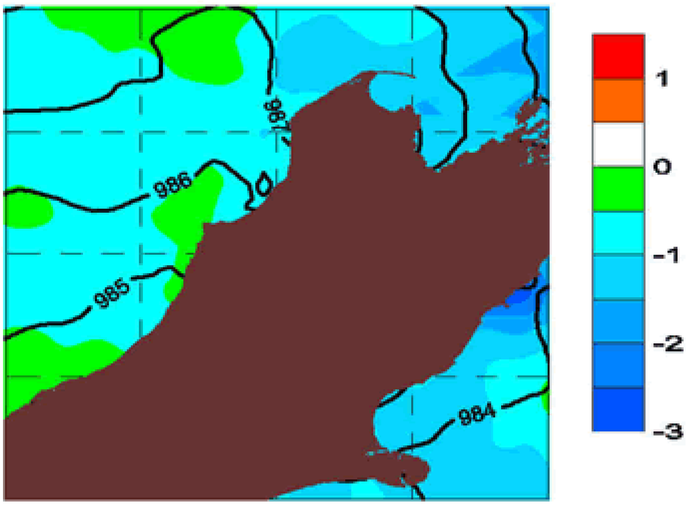


Figure 9: The difference in mean sea-level pressure fields (hPa) between the RAMS globally warmed (+2.7 C) environment and the RAMS current day environment at 0000 UTC 8th Dec, 2001. The colour scale is shown on the right, with colder colours representing areas where the pressures are lower for the +2.7 C simulation. The black contours are the mean sea-level pressures at 0000 UTC 8th Dec 2001 as simulated by the RAMS model for the current day, the contour interval is 1 hPa.

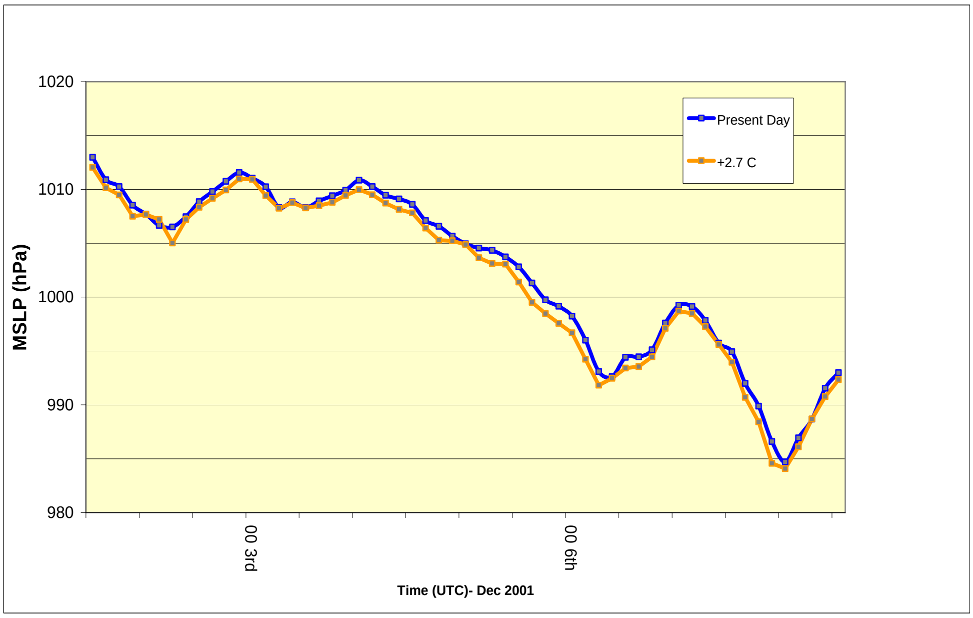


Figure 10: Time series of Mean Sea Level Pressure for a point (171.5 E, 41.7 S) which is just offshore from Westport as simulated by the RAMS model for the period 1200 UTC 1st Dec 2001 to 1200 8th Dec 2001 and for the "same" storm in a globally warmed (+2.7 C) environment

Translate projected river flow, & any other factors (tide, storm surge), into projected flooding

Figure 11 shows the area used for the Westport flood inundation study.

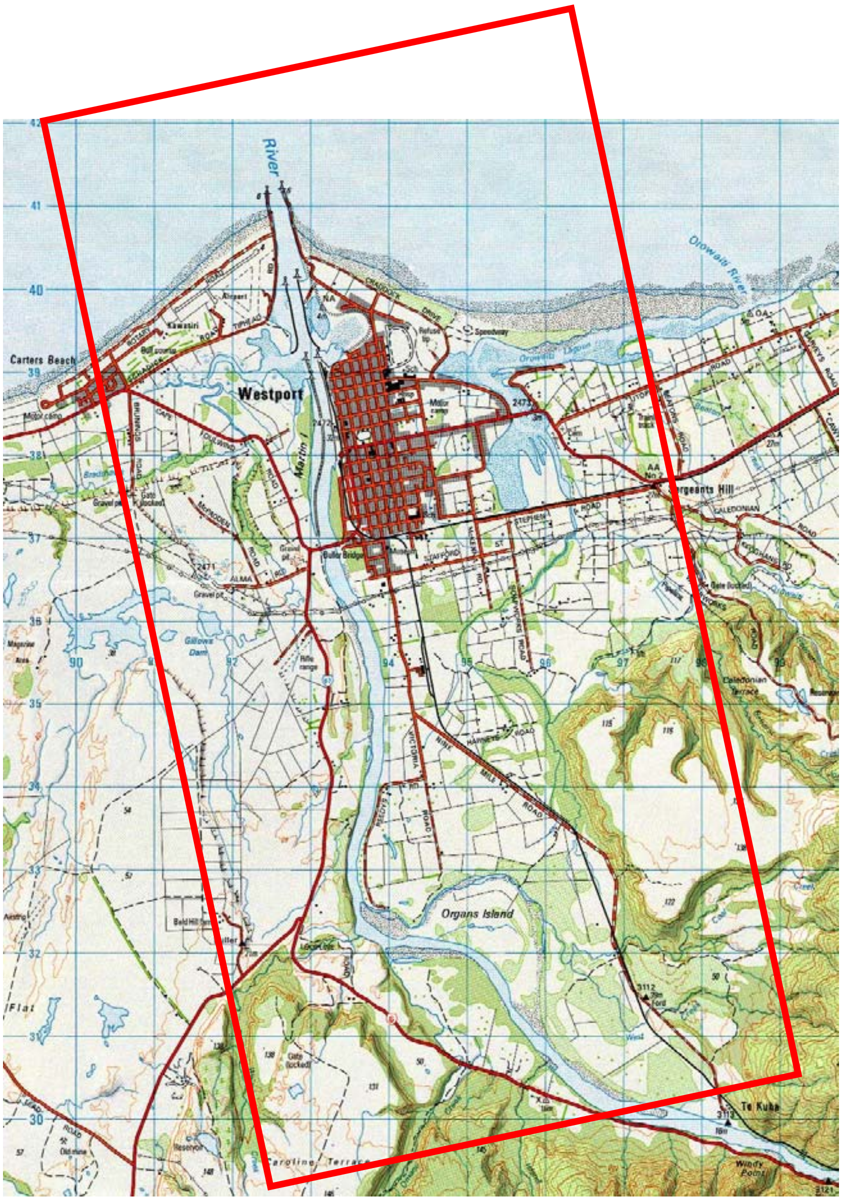


Figure 11: **The Buller River mouth and the town of Westport. The red box shows the area covered by the flood inundation modelling.**

In the case of the Westport model the general elevation data were taken from the 1:50,000 scale topographic maps and bathymetric maps (for sea-bed and river channel data), with refinement in the town area using digital photogrammetry and GPS surveys for the rest of the flood plain, exposed river bed and tops of the stop banks.

Once all the data had been assembled and the model built it was validated against measured data for existing conditions. The model was validated against flood levels from the 1970 flood that had an annual exceedance probability AEP of about 0.02

The inundation modelling of Westport is complicated by the fact that it can occur as a result of a river flood, a high sea level brought about by a high tide and an on-shore wind, or a combination of these factors. For the case of Westport an AEP of inundation was pre-set at the design value of 0.02. Some innovative statistical probability developments were needed to determine what this meant in terms of river flood AEPs and sea level AEPs. This is because the seriousness for inundation of a moderate flood in the river can be exacerbated by a high sea level and vice-versa. To help understand what combination of river flood and sea level events could lead to an inundation AEP of 0.02 a series of inundation model runs were made with different sets of flood and sea-level data. For each run the area of inundation was extracted. From these data a graph that shows the percentage of Westport that will be inundated for different AEP values can be constructed, such as that shown in Figure 12. This work was undertaken as part of the standard flood risk assessment for Westport under current climate conditions, and was not done specifically for the climate change work.

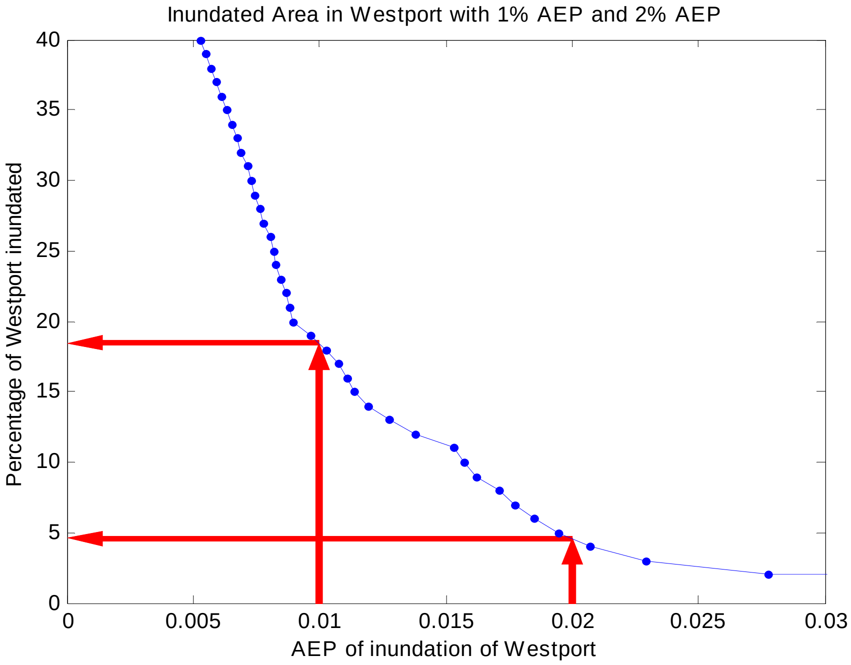


Figure 12: **AEP vs extent of Westport inundated for the base case, showing extents for 1% and 2% AEP inundation events**

Once the base case and the relevant graphs have been produced for the selected AEP, investigating the impact of a climate change consisted of supplying the inundation model with the revised flood and sea level data for each scenario and then calculating the area of the town that would be inundated. The new probability of this occurring under a climate change was then estimated and appropriate steps taken to upgrade the flood protection works to the design standard.

Figure 13 to Figure 16 show the expected extent of flooding for the different climate scenarios, while Table 9 summarises the results in terms of the increase in inundated area. The results in Table 9 show how the rise of flooding will change with Climate Change. All simulations use current the stopbank configuration which is planned to be upgraded. The figures indicate the areas most at risk, and more importantly, where the inundation is likely to come from and thus where the commitment of future flood mitigation investment is likely to return the best value for each dollar spent.

Table 9: **Summary of the 2% AEP flood inundation results for Westport**

Scenario	**Temperature Rise °C**	**Flow Enhancement %**	**Peak flow (m^3/s)**	**Water level rise (m)**	**Peak sea level (m)**	**Inundation Extent % Westport**
Base case	0	0	8,785	0	1.24	4.3
Mid-low 2030's	0.5	3.9	9,180	0.065	1.27	12.8
Mid-high 2030's Mid-low 2080's	1	9.7	9,692	0.15*	1.35	29.6
Mid-high 2080's	2.7	37.5	12,198	0.49	1.69	79.1

* This scenario is a combination scenario that reduced the amount of inundation computing required. As a consequence a compromise "Water level rise" was used that is the mean of the 2030 mid-high and 2080 mid-low values.

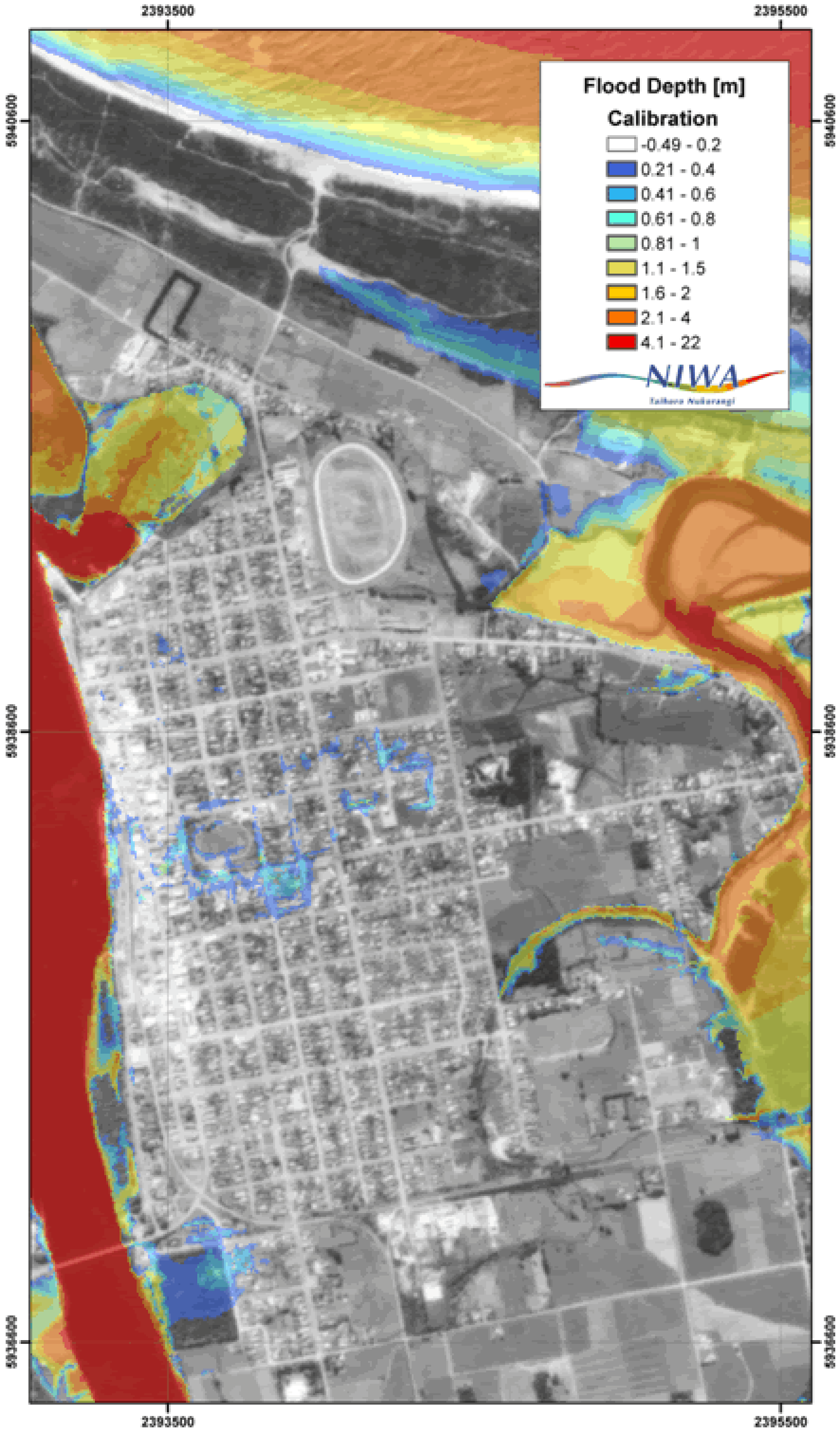


Figure 13. **Westport flooded with an example of a 2%AEP inundation event that is the base case. The river flood and sea level peaks used in this simulation were 8785 m3/s and 1.24 m. 4.3% of Westport is flooded with water to a depth of more than 0.2 m in this example. Areas flooded where the depth is less than 0.2 m are not shown.**

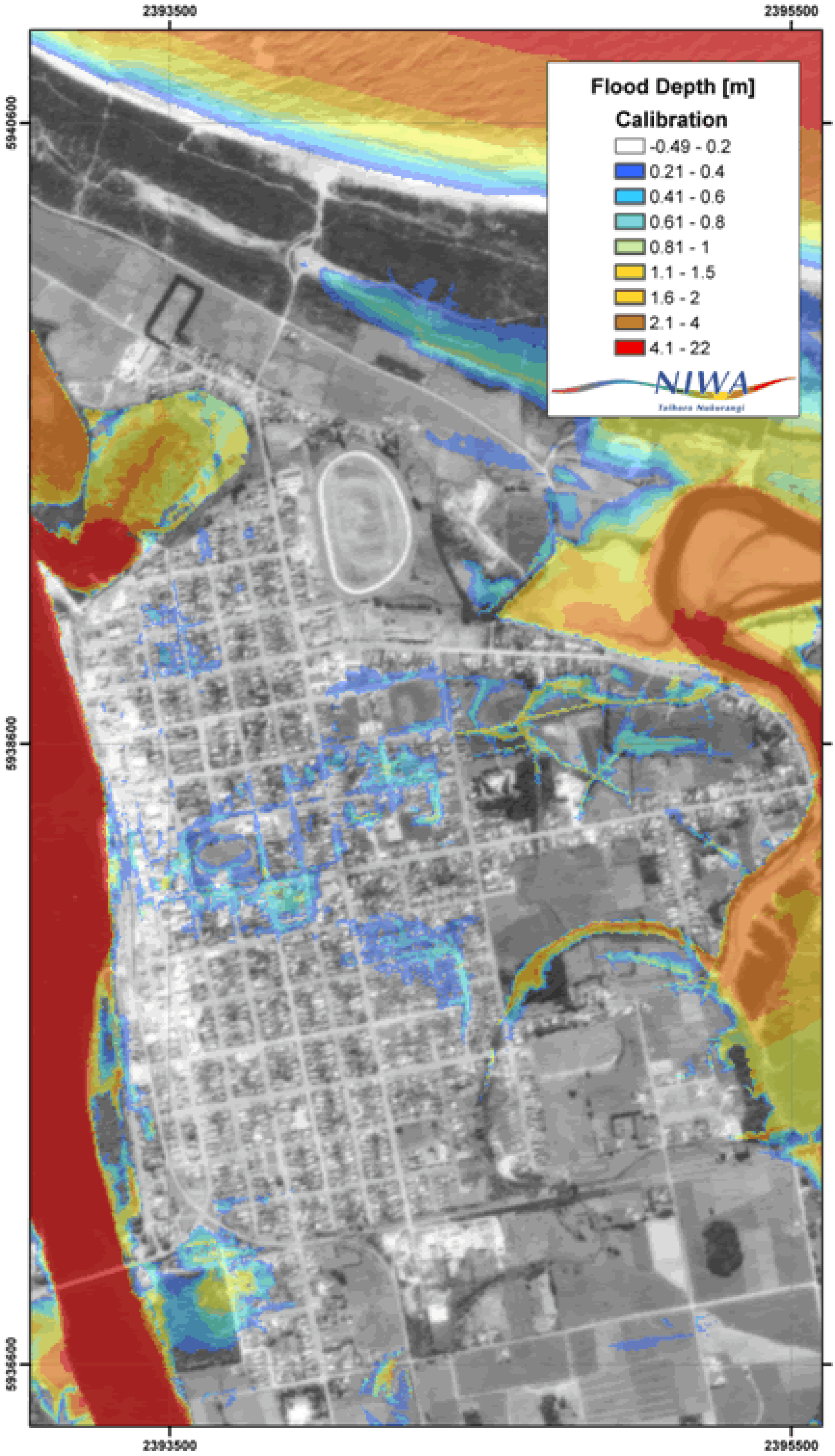


Figure 14: Inundation in Westport from the midlow scenario for 2030. The river flood and sea level peaks used in this simulation were 9180 m3/s and 1.265 m. 12.8% of Westport is flooded with water to a depth of more than 0.2 m in this scenario. Areas flooded where the depth is less than 0.2 m are not shown.

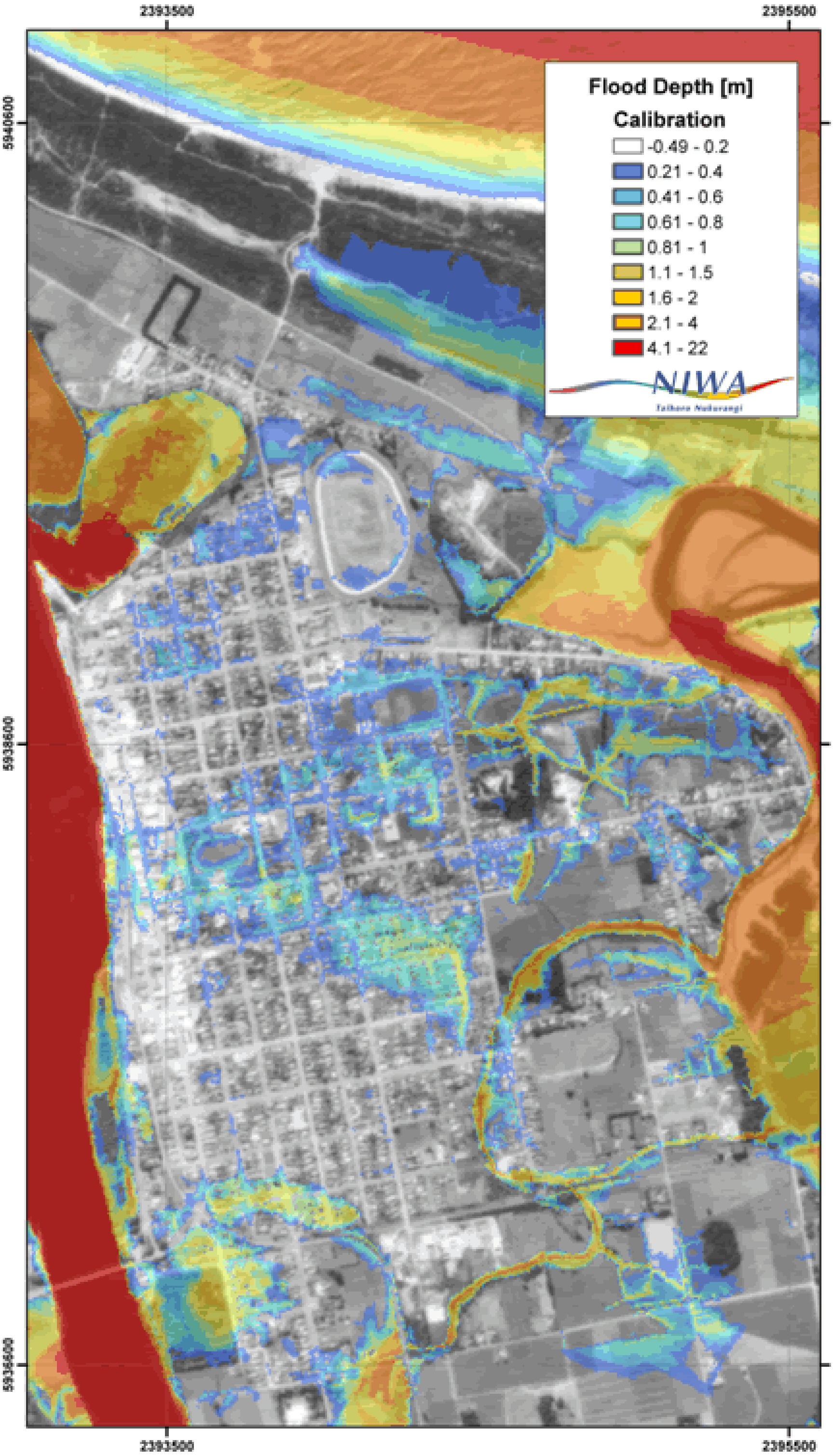


Figure 15: Inundation in Westport from the midhigh (2030)-midlow (2080) scenario. The river flood and sea level peaks used in this simulation were 9692 m3/s and 1.35 m. 29.6% of Westport is flooded with water to a depth of more than 0.2 m in this scenario. Areas flooded where the depth is less than 0.2 m are not shown.

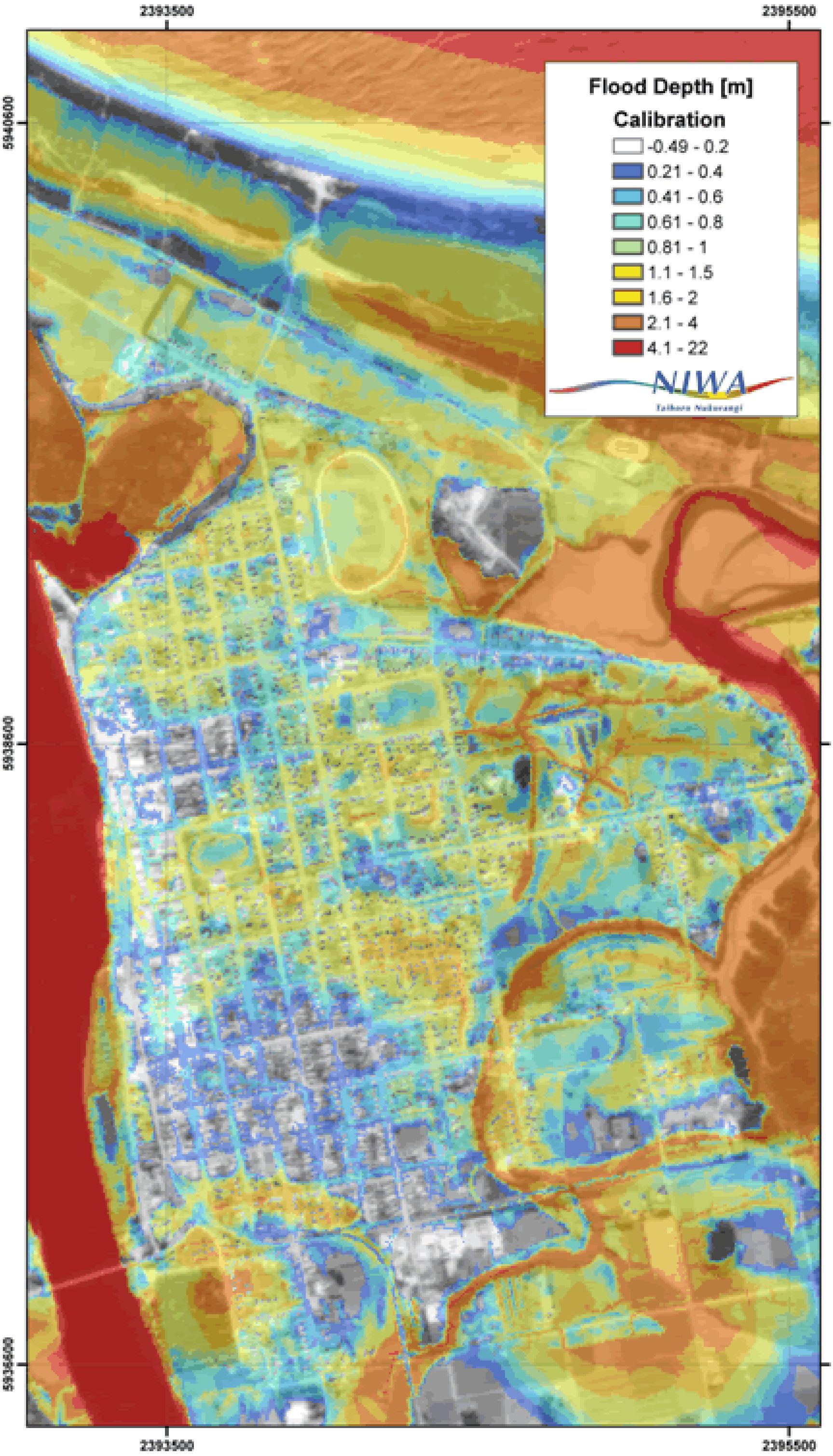


Figure 16: **Inundation in Westport from the mid-high scenario for 2080. The river flood and sea level peaks used in this simulation were 12198 m3/s and 1.69 m. 79.1% of Westport is flooded with water to a depth of more than 0.2 m in this scenario. Areas flooded where the depth is less than 0.2 m are not shown.**