Ministry for the Environment
Manatū Mō Te Taiao

Tools for Estimating the Effects of Climate Change on Flood Flow

A Guidance Manual for Local Government in New Zealand

   

May 2010

New Zealand Government

This guidance manual was commissioned by the Ministry of the Environment and is based on a report prepared by Ross Woods, Brett Mullan, Graeme Smart, Helen Rouse, Michele Hollis, Alistair McKerchar, Richard Ibbitt, Sam Dean, and Daniel Collins, National Institute of Water and Atmosphere.

Comments on the guidance manual were provided by Tim Davin (IPENZ), Brin Williman (MDC), Charles Wilmot (IPENZ), Tony Miller (GHD), Terry Day (CAE), Tracy Ayre (IPENZ), Gary Macdonald (BECA), Graham Levy (BECA), Sue-Ellen Fenelon (BECA), Greg Ryan (EW), Kim Wright (GNS), Wendy Saunders (GNS), Andrew Tait (NIWA), Rouse et al (NIWA), Jane Puddephatt (MWH), Trecia Smith (MAF), Helen Grant (ECAN) and Tony Oliver (ECAN).

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Ministry for the Environment
Manatū Mō Te Taiao

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Purpose

The main aim of this guidance manual is to help local authority staff – including river managers, engineering staff and asset managers – to manage and minimise the risks posed by increased flood risk due to climate change. More specifically, the manual provides good practice guidance for incorporating climate change impacts into flow estimation. It does this by providing:

- information on the key effects of climate change on flood risk
- methods for estimating changes in the frequency and/or magnitude of rainfall
- methods for converting changes in rainfall to changes in flow rate
- methods for converting changes in flow rate to changes in inundation
- some case studies to illustrate these methods.

The manual offers a list of options but is neither exhaustive nor prescriptive. In other words, it is not a handbook for flood estimation or flood risk management.

This guidance manual has been used as a primary source of information for a summary document, *Preparing for future flooding: A guide for local government in New Zealand*. *Preparing for future flooding* also shows how you can consider the consequences of future flood risk in a risk management framework and highlights options and principles for managing future flood risk.

Climate change and flooding

Climate change is expected to lead to increases in *extreme* rainfall, especially in places where *mean* rainfall is expected to increase. Extreme rainfall is the most common trigger for floods in New Zealand. Wetter weather in some areas may also change the antecedent conditions, which means that floods might occur more often. Changes in storminess are harder to predict, but it is likely that tropical cyclones will be more intense, and such weather systems can transform into intense sub-tropical lows that bring heavy rainfall to New Zealand. Places that currently receive snow are likely to see a shift towards increasing rainfall instead of snowfall, along with changes in the snowline and snow depth. Sea-level rise will increase base levels for coastal river reaches. All of these factors need to be considered when looking at estimations of flooding.

Climate change is also likely to have a number of indirect effects. For example, changes in precipitation will lead to changes in sediment transport, in turn affecting the riverbed levels. This could be complicated in the coastal reaches of rivers because sea-level rise slows the flow of water out to the sea. If this is likely to be a significant issue for your catchment, then detailed modelling of these effects may be required. Antecedent conditions are also likely to be affected; for example, catchments in the east and north are likely to be drier on average. Warmer temperatures and windier conditions are also likely to affect evapotranspiration. These factors may be important for estimating non-flooding flows, such as water resource availability.

The climate is naturally variable, and on a decadal timescale New Zealand rainfall and flooding are affected by the Interdecadal Pacific Oscillation, or IPO. The IPO is a cycle of 15 to 30 years between warm and cool waters in the north and south Pacific, and has a significant role in modulating the climate of New Zealand. Over the next 50 years or so the changes in climate resulting from increases in greenhouse gases are in the same order of magnitude as IPO variability, so both IPO and greenhouse gas effects may need to be considered.

Screening and advanced methods

The methods discussed in this manual are standard techniques for incorporating climate change impacts into flow estimation. They range from simple and straightforward engineering approaches to complex scientific models. However, the fundamental choice is between screening methods and advanced methods. This decision will depend on the value of assets and the size of the community under consideration. Screening methods are appropriate for detecting issues which require further investigation, but insufficient for very large assets such as floodable urban areas. Some physical settings (eg, coastal rivers) require particular advanced modelling approaches.

Estimating changes in rainfall due to climate change

This manual provides projected changes in annual mean temperature for the six greenhouse gas emission scenarios developed for the Intergovernmental Panel on Climate Change (IPCC), for each region of New Zealand. These temperature changes can then be used with a range of factors for estimating increases in extreme rainfall to provide a basic screening method for estimating changes in rainfall. A number of more advanced methods for estimating rainfall are also discussed. These include weather generators, empirical adjustments, analogue selection from observed data, downscaling of global models, regional climate models and mesoscale weather models. When selecting the most appropriate method you should weigh up data availability, the desired accuracy and the expertise available.

Estimating changes in flood flows

This manual discusses estimating flood flows from the new estimates of rainfall that incorporate climate change impacts. The manual describes several screening and advanced methods, highlighting how climate change can be incorporated into flow estimation by discussing in more detail three models that are presently used in New Zealand: TP108, RORB and TopNet. Again, when selecting the most appropriate method you should weigh up data availability, the desired accuracy and the expertise available.

Estimating changes in inundation

Coastal and low-lying riverine communities are particularly vulnerable to increased inundation due to climate change impacts on rainfall, river flow and sea level. Screening methods are available to identify areas potentially susceptible to increased inundation. Advanced hydrodynamic modelling methods are also described for use in situations that require greater precision, particularly when considering coastal inundation.

Using case studies

Case studies are presented to provide illustrations of how the various methods have been applied in the real world. We present four case studies, with each one showing the three steps of estimating rainfall, converting rainfall to flows, and converting flows to inundation. The case studies demonstrate how a mixture of methods – including screening or more advanced methods – can be used together to estimate the impact of climate change on flood flows.

Discussion of issues for engineering

Incorporating climate change estimates into flow estimation can reveal various issues pertinent to engineering design. The manual discusses some of these issues, such as the appropriate use of historical records, clear reporting flow estimates, dealing with uncertainties in estimates, using professional judgement and appropriate scenario choice.

1 Introduction

1.1 Overview

The Ministry for the Environment works closely with scientists and local government staff to understand the potential impacts of climate change on the natural resources managed by territorial local authorities. This manual focuses on the effects of flooding from freshwater systems such as rural and urban rivers (ie, not coastal flooding). Through both inundation and erosion, flooding can have an impact on local authority infrastructure such as roading, water supply and irrigation, wastewater systems and drainage, and river flood protection works. Flooding also affects other assets, both private and public, including houses, businesses and schools.

The manual provides best practice information and guidance for integrating climate change into flow estimations. It has been written primarily for river managers and flood engineering staff in local government, but is also likely to be useful to designers of public and private infrastructure and consulting engineers. More specifically, it provides:

- information on the key effects of climate change on flooding
- methods for estimating changes in rainfall
- methods for converting changes in rainfall to changes in flow rates
- methods for converting changes in flow rate to changes in inundation
- case studies to illustrate these methods.

This manual has been used as a primary source of information for a summary document, *Preparing for future flooding: A guide for local government in New Zealand*. *Preparing for future flooding* also shows how you can consider the consequences of future flood risk in a risk management framework and highlights options and principles for managing future flood risk. These principles include:

- adopting a precautionary approach
- ensuring adaptive management
- taking a low-regrets or even no-regrets approach to risk treatment
- avoiding locking in options that limit further adaptation in the future
- targeting progressive risk reduction
- planning an integrated, sustainable approach.

Preparing for future flooding is targeted at those who are involved in local government decision-making, in particular strategic and policy planners, asset managers, natural hazards analysts, river managers, emergency management and 'lifeline' utilities and infrastructure managers.

1.2 Structure of the manual

After this introduction, chapter 2 summarises what we know about the impacts on flooding of climate change in New Zealand, using the most recent projections from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report from 2007.

The next three chapters describe a series of methods that can be used in consecutive steps to:

- estimate the impacts of climate change on future rainfall (chapter 3)
- convert changes in rainfall to changes in run-off flows (chapter 4)
- convert changes in flows into changes in inundation (chapter 5).

Each of these chapters discusses a number of tools which are available for each of the three steps. The tools we describe fall into two main categories: screening tools and advanced methods. This categorisation is in line with the approach taken in the *Climate Change Effects and Impacts Assessment* Manual (Ministry for the Environment, 2008a, referred to here as the *Climate Change Effects* manual). Screening tools are usually simple yardsticks that aim to show whether there is a potential risk posed by climate change impacts. It is appropriate to use mid-range greenhouse gas emission scenarios for an initial screening using this type of tool, although a range of scenarios can then be used if the initial screening highlights a potential issue. (See the *Climate Change Effects* manual, p 64, for more on developing scenarios.)

Advanced methods are used when screening suggests a significant impact is possible (*Climate Change Effects* manual, p xi), and provide a more detailed assessment of the potential risks. Chapters 3, 4, and 5 each conclude with a table which summarises the advanced methods and guidance to help select the most appropriate method. A risk management approach suggests the need to use a range of climate change scenarios to provide options for decision-makers when carrying out an advanced study.

To help ground this screening and modelling in real-world situations, chapter 6 has a series of case studies illustrating different approaches to working through the processes described in this manual. The case studies provide examples of where particular options were selected and linked together to estimate the change in flood hazard as a consequence of climate change.

Finally, chapter 7 discusses some of the issues raised by consideration of climate change impacts that are of particular relevance to engineering design.

1.3 Using the manual

In most cases, users of this manual will need to progress through the consecutive steps of estimating changes in rainfall, then river flow, then inundation (chapters 3, 4 and 5). Projects to assess the impacts of climate change on flood hazards will need to select tools that provide a level of detail appropriate to the decisions which will be based on the project results. This risk management approach means that the method chosen will depend on a number of factors, such as the size of the community or the value of the asset at risk. More advanced methods have more certain predictions, but this increase in certainty requires increased resources (in terms of expertise, person time and data input requirements).

Where the consequences of the potential flood event are high, this increase in resources is justified. For example, a project to identify which river basins in a region are likely to experience a significant change in flood hazard could reasonably use a screening method. However, a project to re-evaluate the design flood[1] for a major flood protection system, using a full risk assessment approach as advocated in the *Climate Change Effects* manual, would use one of the advanced tools from each of the three chapters. Some of the advanced methods described in this manual will require technical expertise and experience to use, and also for interpreting the results.

1.4 Supporting guidance

In addition to this manual, a range of complementary guidance is available on climate change and hazard management from the Ministry for the Environment, including:

- *Climate Change Effects and Impacts Assessment: A Guidance Manual for Local Government in New Zealand* (2nd edition, May 2008)
- *Coastal Hazards and Climate Change: A Guidance Manual for Local Government in New Zealand* (2nd edition, July 2008).

This manual aims to be self-contained to the extent that it includes all key information on climate change impacts in New Zealand and the estimation of the effects of these on flood magnitude. However, there are areas of overlap, and the two guidance manuals listed above should be used alongside as key resources. It is also important to note this manual is not a handbook for design flood estimation: it provides a list of possible options, but is neither exhaustive nor prescriptive.

The Ministry for the Environment also provides guidance for local government planners on a range of topics on the Quality Planning website (http://www.qp.org.nz/). Current guidance that may be of use for managing flood hazards and climate change includes:

- *Climate Change Guidance Note*
- *Natural Hazards Guidance Note*
- a number of articles relating to flood hazards in the Quality Planning library
- a report on natural hazard management in the Quality Planning research category.[2]

Standards New Zealand released the standard NZS9401, *Managing Flood Risk: A Process Standard*, in November 2008. It outlines a risk management approach to managing flooding. In addition, a *River Manager's Guide* is being compiled for local government at the time of publishing this manual.[3] The guide will collate existing local body knowledge on statutes and principles, agencies and stakeholders, natural environment management, flood management, operations and maintenance, sediment management, water quality and human interaction (such as recreation and other human use of the river resource).

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1 Design flood is the flood expected to occur from a hypothetical storm of specific storm duration and recurrence interval. For example, a 25-year/24-hour design storm means that the storm duration is 24 hours and the recurrence interval is 25 years. See the Glossary.

2 http://www.qp.org.nz/qp-research/natural-hazards-aug06/index.php

3 See http://www.envirolink.govt.nz/Envirolink-tools/ for further information and updates on progress.

2 The Impact of Climate Change on Flooding

2.1 Introduction

This chapter provides background information on the processes that lead to river flooding and how changes in climate might affect those processes. It provides a context for the technical methods in the following chapters. The chapter goes on to outline how predicted climate changes will affect flood flows, and concludes with a brief discussion of the implications of climate variability and change for some engineering design analyses.

2.2 Physical processes leading to flooding in New Zealand

The most common meteorological process leading to river flooding in New Zealand is heavy rainfall, which can greatly increase the water level in rivers and lakes and cause water to overflow into surrounding areas. When rainfall reaches the ground some of it runs into rivers by either surface or sub-surface pathways. The rest of the rainfall is stored in the soil and in surface depressions and lakes, or drains away to groundwater. Run-off from rainfall entering storage is also reduced by evaporation.

Flood run-off depends on many factors, including the amount, intensity and duration of rainfall, the topography, vegetation and soil characteristics of the catchment, the wetness of the catchment before the storm (referred to as the antecedent or initial conditions) and evaporation in the catchment. Rainfall-driven floods vary in both their duration and extent, and may result from:

- brief localised events (eg, thunderstorms in urban areas or steep catchments)
- storms lasting a day or two and causing flooding in limited areas
- a repeated sequence of storms over a region, which saturate the soil and fill surface depressions and lakes, so that subsequent storms in the sequence produce more run-off because less water is able to be stored, which may lead to major widespread flooding.

Although the magnitude of a flood is often described using the peak water level or peak river flow rate during the flood, this is only a partial indicator of flood severity. The severity of inundation by floodwaters also depends on the volume of floodwater during the portion of the event when inundation takes place. For coastal river reaches, inundation is affected by sea level, including tides and storm surge.

In some parts of New Zealand, flooding can also be exacerbated by snow melt (eg, in Otago and Southland). Warm temperatures and rainfall on a deep snowpack can lead to rapid snow melt, which can occasionally be sufficient to cause a flood. Other types of flooding not considered in this manual include inundation by groundwater or high sea levels, or dam-break floods. Refer to the *Coastal Hazards and Climate Change* manual (Ministry for the Environment, 2008b) for details on coastal flood hazards and a discussion of sea-level rise.

The impact of floodwaters on communities also depends on non-meteorological factors, including how many people and what assets are at risk, and the effectiveness of flood protection and flood warning systems. The level of risk posed by the flood will help determine which of the methods described in later chapters should be used. For lower levels of risk, screening methods are more appropriate, while for higher levels of risk both screening and advanced methods should be used.

2.3 Decadal variability in rainfall and flooding

Flood hazards vary over time for reasons other than climate change. Natural shifts in climate on decadal time-scales will also impact on flooding. It is important to recognise these other sources of variability so that climate change impacts are kept in context. Flood hazards also change for reasons not directly associated with climate, such as land-use change (eg, urbanisation, deforestation). These impacts are outside the scope of this manual.

2.3.1 IPO influences on rainfall

Changes in New Zealand rainfall viewed over several decades show some association with changes in the phases of the Interdecadal Pacific Oscillation (IPO), a cycle of 15 to 30 years between warm and cool waters in the north and south Pacific. The IPO multi-decadal sea surface temperature pattern is similar to that of ENSO (the El Niño–Southern Oscillation), but with more variation in the extra-tropics,[4] especially in the north Pacific (Folland et al, 2002).

The IPO has been shown to be associated with long-term fluctuations in New Zealand's climate (Salinger et al, 2001) and sea level (Goring and Bell, 1999). The increase in New Zealand temperatures around 1950 occurred shortly after the change from positive to negative phase IPO (see figure 1). The switch from negative to positive IPO in the late 1970s coincided with significant rainfall changes. Figure 2 maps annual rainfall changes between negative and positive IPO periods centred on 1978.

In the later (positive IPO) period, rainfall increased in the west and south of the South Island but decreased in the north and east of the North Island, relative to the earlier (negative IPO) period. This rainfall pattern is partly associated with the changing prevalence of El Niño versus La Niña events. In the positive IPO phase after 1977, more frequent El Niño events produced rainfall increases in the western South Island, whereas fewer La Niña events resulted in decreased rainfall in the Bay of Plenty and Northland. In other regions the observed effect of the IPO on rainfall is relatively unimportant (see green shading in figure 2). Decadal variability associated with the IPO can also have consequences for rainfall extremes (and therefore, in all likelihood, flooding).

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4 The mid-latitudes (approximately 30°S–50°S).

Figure 1: Time-series of the Interdecadal Pacific Oscillation

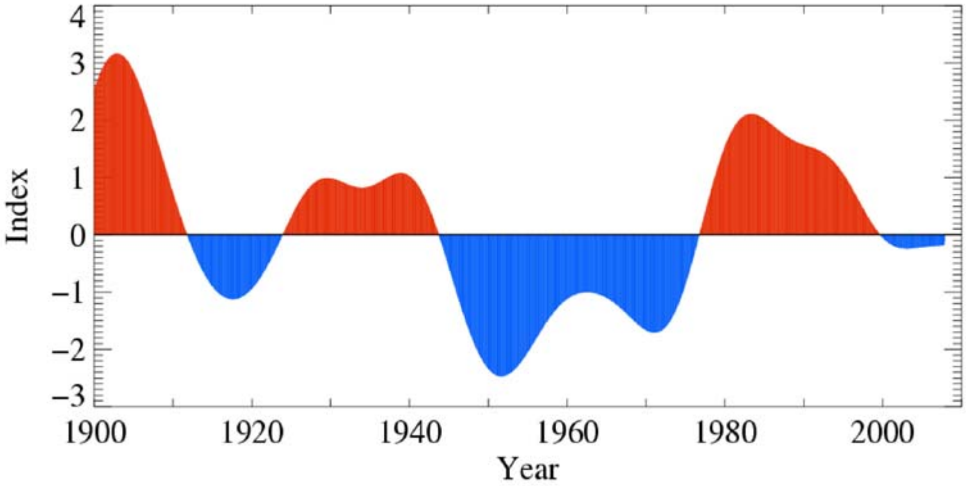
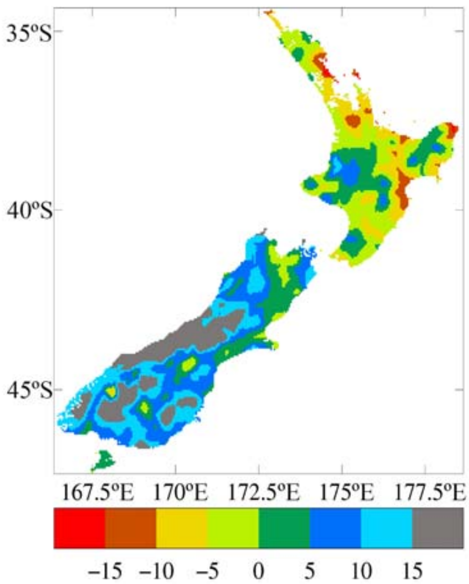


Figure 2: Percentage change in average annual rainfall, 1978–1998 period compared to 1960–1977 period

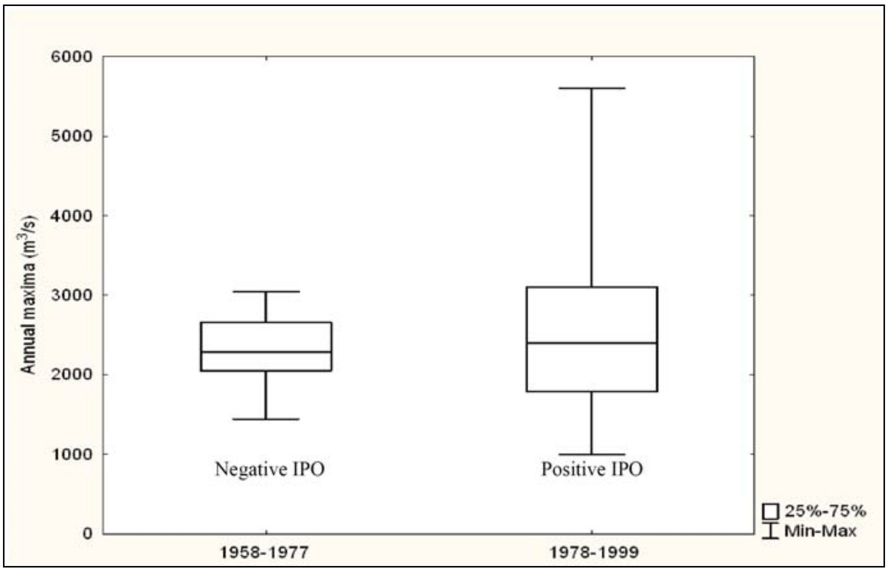


2.3.2 IPO influences on flooding

The decadal fluctuation in wind and rainfall over New Zealand also leads to variations in river flow and flooding. McKerchar and Henderson (2003) compared flood records for 1947–1977 (negative IPO) and 1978–1999 (positive IPO). They showed that a decrease in flood size occurred after 1978 in the Bay of Plenty region of the North Island. They also showed that increases in flood size and low-flow magnitude occurred in the South Island for most rivers with headwaters draining from the main divide of the Southern Alps and Southland. An example of this for the Rakaia River is shown in figure 3.

An important practical implication of these results is that in the north and east of the North Island, and in the south and west of the South Island, any analysis of extreme values relating to flood data should include an assessment of IPO influences. For these regions, short flood records lying mainly within the 1947–1977 period or mainly within the 1978–1999 period are likely to be biased and not representative of the long-term flood risk. Such flood records should be adjusted to compensate for the bias, using the observed decadal variability in flood magnitude at hydrologically similar sites with longer records.

Figure 3: IPO control of annual maximum floods for the Rakaia River: box plots comparing the distribution of annual maximum floods for the Rakaia River recorded at the Gorge/Fighting Hill sites for two periods, 1958–1977 and 1978–1999



Source: Adapted from McKerchar and Henderson, 2003.

Notes: The box plots compare the minima, the 25, 50 and 75 percentile values, and the maxima for the two periods. Twenty-five per cent of the floods from 1978 to 1999, during the positive phase of the IPO, were larger than anything observed from 1958 to 1977.

The periods 1947–1977 and 1978–1999 correspond to distinct phases of the IPO. The positive IPO phase that began in the late 1970s has ended, although there is as yet no indication of a return to strong negative values of the IPO index (figure 1). However, it is likely there will be more La Niña activity, and fewer El Niño events, over the next two decades compared to the 1978–1999 period. This would favour rainfall reductions in the southwest of New Zealand and increases in the northeast (ie, the reverse of the change shown in figure 2).

2.4 Climate change impacts on flooding

2.4.1 Climate change scenarios

Climate change is expected to affect flooding through a range of mechanisms, including rainfall, temperature, sea-level and river channel changes. Although it is impossible to know with certainty how climate change will affect flooding in New Zealand, we can have confidence in certain trends, such as the trend for increasing rainfall in the west. This confidence stems from a wide array of historical analyses combined with simulation modelling of the past and future. Climate change modelling studies mathematically depict the physics of the Earth's climate system and are driven by emissions scenarios. Because the robustness of our climate change projections are rooted in the scenarios used to drive the climate change modelling analyses, it is useful to understand how these scenarios differ from one another.

There are many ways to develop climate change scenarios, depending on the data sets available and the requirements for impacts modelling. The climate change impacts shown in the *Climate Change Effects* manual are based on statistical downscaling of global climate model projections. These models are driven by a range of IPCC emissions scenarios (Nakicenovic and Swart, 2000). The IPCC has selected six of these emissions scenarios, which are known as illustrative marker scenarios and identified as B1, B2, A1T, A1B, A2 and A1FI, in order of increasing influence on global temperature increase over the 21st century (IPCC 2007).

The emissions scenarios span a reasonable range of plausible futures and depend on changes in population, economic growth, technology, energy availability and national and international policies. We cannot indicate whether any one emission scenario is more likely than another, so the guidance in this manual takes account of all six SRES illustrative marker scenarios (IPCC 2000) while focusing on a 'middle-of-the-road' scenario termed the A1B scenario. (See section 2.1 in the *Climate Change Effects* manual for more discussion on emissions scenarios.) The scenario projections in the *Climate Change Effects* manual were developed from a multi-model ensemble of 12 global climate models, using the A1B emissions scenario to represent the changes in greenhouse gases. The consequences of other emissions were accounted for by a simple rescaling of the A1B downscaled projections.

2.4.2 How changes in climate may affect rainfall

Extreme rainfall

Any consideration of the effect of climate change on flooding must start with the effects on rainfall. Projected changes in both mean rainfall and rainfall extremes are relevant. The intensity of extreme rainfalls is associated with temperature increases (Ministry for the Environment, 2008a), and so a consideration of future temperature change is also necessary. This is addressed in detail in chapter 3, but the expected impacts are summarised briefly here.

As a result of climate change, heavier and/or more frequent extreme rainfalls are expected over New Zealand, especially where the mean rainfall is predicted to increase. The percentage increase in extreme rainfall depths is expected to be approximately 8 per cent per degree Celsius of temperature increase.

Changes in seasonal rainfall

Climate change is expected to lead to increases in extreme rainfall, especially in places where mean rainfall is also expected to increase. Therefore, changes in seasonal and annual rainfall patterns, as well as changes in extreme rainfall, will be important factors for understanding future flooding.

Changes in annual rainfall are discussed in the *Climate Change Effects* manual, and the 100-year trends are shown in the low part of figure 2.3 of that manual.

The 100-year trends in projected seasonal rainfall for a mid-range (A1B) scenario, averaged over the 12 climate models downscaled for New Zealand, are shown in figure 4. The four maps in figure 4, one for each season, show percentage changes in rainfall over 2080–2099 relative to the baseline (model) climatology of 1980–1999. This calculation is made for each model separately, and the results are then averaged. In the winter and spring seasons all models show similar trends.

Substantial increases in mean seasonal precipitation are projected for the west of the South Island, with decreases in mean seasonal precipitation for the east and north of the North Island. These precipitation changes are associated with an increased westerly wind flow across New Zealand during these seasons. In summer and autumn, trends vary across models, but, on average, reductions in seasonal precipitation are indicated in the west of the North Island particularly.

Figure 4 shows only the 12-model average, and there are large differences between models (see the range in tables 2.4 and 2.5 in the *Climate Change Effects* manual). Seasonal changes at selected grid points, co-located with cities and towns, are illustrated in figure 5. For many locations and seasons, either increases or decreases in precipitation are possible, sometimes in excess of ± 20 per cent. However, figure 5 also shows there is model agreement in some places. For example, in winter, models tend to agree on precipitation increases at sites exposed to the west (eg, Ruakura, Paraparaumu, Nelson and Queenstown) and decreases at sites exposed to the east (eg, Gisborne and Christchurch). The precipitation changes are very dependent on the atmospheric circulations developed within the models; the H symbol on various panels of figure 5 shows that where one particular model lies within the 12-model distribution can vary with season and location. This large uncertainty is something that has to be accepted in climate change projections at this time. Future work will attempt to quantify the uncertainty range (eg, as a frequency or probability distribution).

Figure 4: Projected percentage changes in seasonal mean precipitation for 2080–2099 relative to 1980–1999, averaged over 12 climate models for a mid-range (A1B) emissions scenario

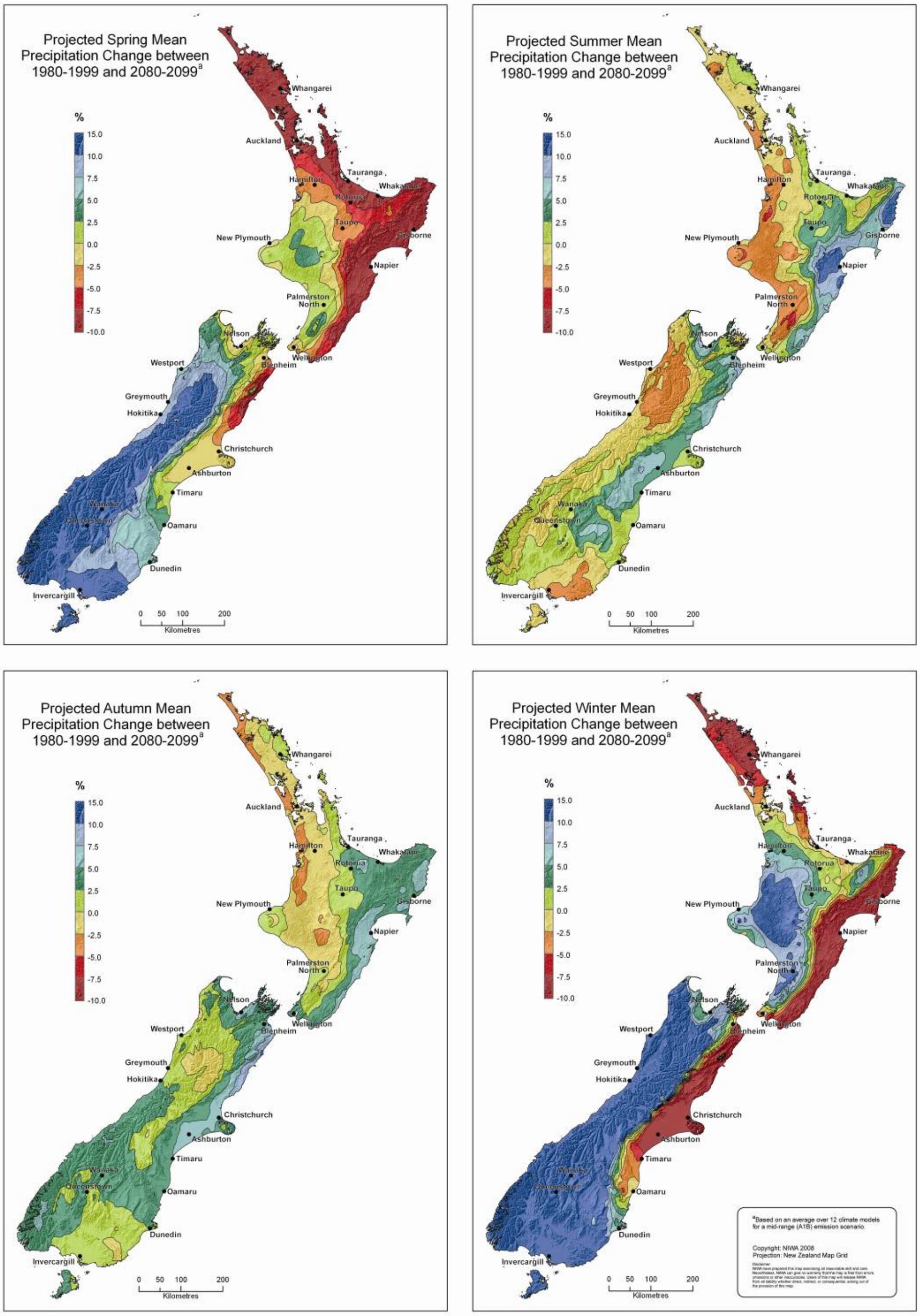
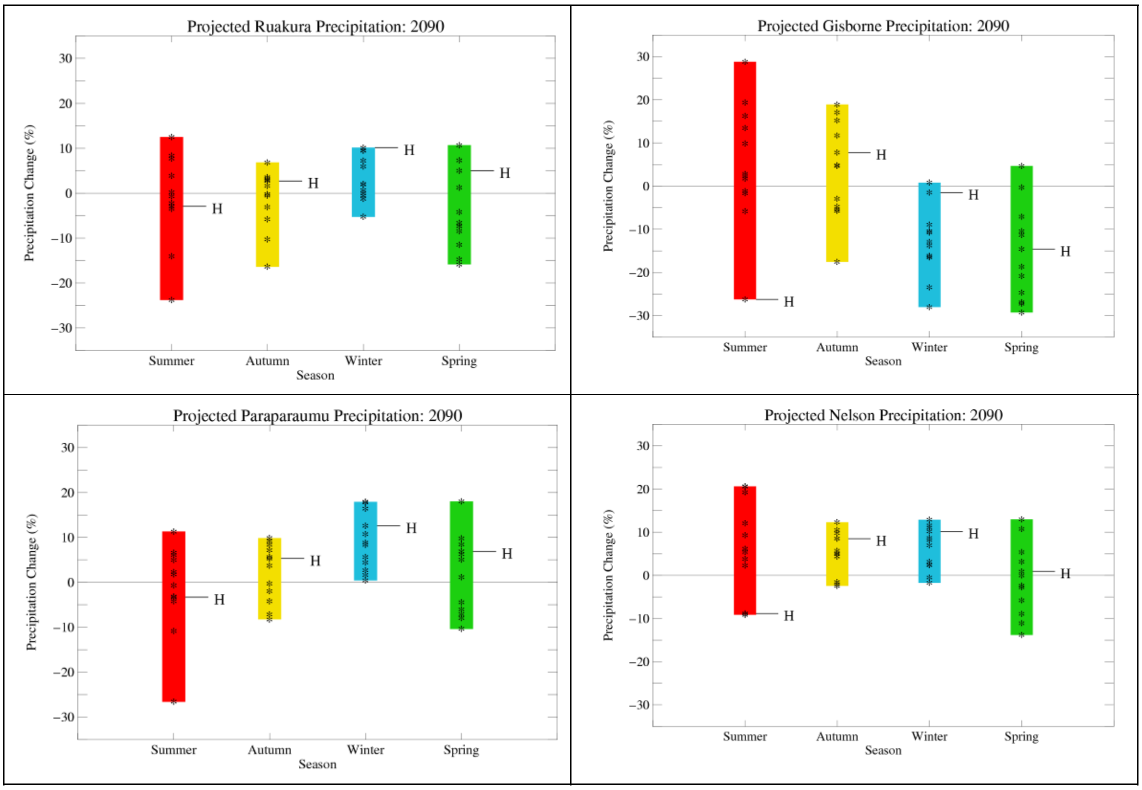


Figure 5: Projected percentage changes in seasonal mean rainfall at selected New Zealand locations, for a mid-range (A1B) emissions scenario



Notes: The vertical coloured bars highlight the range over the 12 climate models considered, with stars indicating individual models. The symbol 'H' marks the location of one particular model (known as ukmo_hadcm3) within the distribution.

2.4.3 Storminess and climate change

Although there is a perception that 'increased storminess' is likely under climate change, the evidence of observed changes over New Zealand is far from conclusive. The concept of 'storminess' can refer to the number of storms or to the intensity, which in turn could be judged on the basis of either strong winds or heavy rainfall. Changes in storminess will also affect the level of the sea through changes in storm surge and waves. This may be important for rivers and stormwater drainage near the coast. Also, storms can approach New Zealand from the sub-tropics and from mid-latitudes (extra-tropics), and different trends are possible in the two regions.

Storms from the sub-tropics

Since the 2001 Third Assessment report of the IPCC, a number of articles have been published about observed increases in intense tropical cyclones. These results are still being reviewed, and the IPCC's Fourth Assessment was cautious in its conclusions:

> There is observational evidence for an increase in intense tropical cyclone activity in the North Atlantic since 1970 … There are also suggestions of increased intense tropical cyclone activity in some other regions where concerns over data quality are greater (Section 1.1, page 30, IPCC, 2007).

Tropical cyclones that develop in the south-west Pacific can affect New Zealand. From 1971 to 2004, tropical cyclones in this region averaged nine per year, with no observed trend in either frequency (Burgess, 2005) or intensity (Diamond, 2006). In any case, only about one cyclone per year moves south of 30 °S and comes close enough to New Zealand to have a direct impact, and no resulting change in New Zealand's storminess from ex-tropical cyclones has yet been detected.

For the future, the IPCC (2007) states that "it is *likely*[5] that future tropical cyclones will become more intense" which implies larger peak wind speeds and increased heavy precipitation. Some model studies suggest a decrease in the total number of tropical cyclones, but the IPCC assigns little confidence to such a projection at this stage.

Such changes in tropical cyclones are potentially important for New Zealand because these weather systems can transform into intense sub-tropical lows as they move south and bring widespread heavy rainfall and damaging winds, waves and storm surge to New Zealand (eg, Cyclone Giselle, better known as the Wahine storm, in April 1968, and Cyclone Bola in March 1988).

Storms from mid-latitudes

Several recent studies have been made of trends in southern hemisphere extra-tropical cyclones. Over the period 1979 to 1999, there has been about a 50 per cent increase in the number of explosively deepening cyclones (the so-called 'weather bombs') per year (Lim and Simmonds, 2002). These rapidly deepening systems occur mainly to the south of 50°S but can form in the western Tasman Sea in the winter season. Although they form a small percentage (around 1 per cent or less, depending on location) of the total number of cyclones, they can be important for New Zealand. A recent example of an explosive deepening cyclone in the Tasman was the storm that affected Northland on 26/27 July 2008: this storm registered the lowest pressure on record (962 hectopascals) of any storm approaching New Zealand, but did not cause large-scale flooding because of its rapid movement.

Changes in the number of southern hemisphere cyclones have also been documented (Simmonds and Keay, 2000). Over the 40-year period, 1958–1997, there has been a general reduction in the mean cyclone density over most regions south of 40°S, with the greatest reductions near 60°S, but little change in the Tasman Sea. At the same time, systems have become more intense on average in the Australian Bight and the Tasman Sea, and weaker over the eastern Pacific. Just why the reduction in overall numbers should be occurring is not well understood, although one modelling study (Zhang and Wang, 1997) has suggested that under moister conditions (as would occur in a warmer atmosphere) cyclonic eddies transfer energy poleward more efficiently, and thus fewer cyclones would be 'required' to effect the same energy transport.

For the future, the IPCC (2007) states that "extra-tropical storm tracks are projected to move poleward, with consequent changes in wind, precipitation and temperature patterns". There is no comment in the IPCC report on what this could mean for New Zealand.

[5] In IPCC terminology, "likely" means a 66 per cent chance or greater of occurring.

2.4.4 How changes in climate may affect flooding

Extreme rainfall

The major impact of climate change on New Zealand river floods is expected to come through increases in extreme rainfall (in coastal river reaches sea-level rise will also affect inundation). As noted above, the relationship between rainfall intensity and flood magnitude depends on several factors and is not linear; so, for example, an 8 per cent increase in rainfall intensity does not necessarily lead to an 8 per cent increase in flood peak discharge, which does not necessarily lead to an 8 per cent increase in flood inundation. In many cases, the increases in flow and inundation will need to be estimated using our understanding of how the rainfall–run-off inundation processes are related to an increase in rainfall. This could be based on computer modelling of flow and inundation.

In the Westport flood study (see chapter 6), rainfall increases of 3 per cent, 5 per cent and 33 per cent for different temperature scenarios caused modelled peak river flow to increase by 4 per cent, 10 per cent and 37 per cent, respectively. As a consequence, flood inundation was estimated to increase from 4 per cent of Westport township being inundated under the current climate, to 13 per cent, 30 per cent and 80 per cent, respectively, for each of the three temperature scenarios used in that study: (i) mid-low for 2030, (ii) mid-high for 2030 (also used as mid-low for 2080), and (iii) mid-high for 2080.

Those results are specific to the Westport situation and depend on the assumptions made in that study. To work through the impacts of a change in extreme rainfall in your situation, methods such as those outlined in chapters 4 and 5 need to be applied to the specific flood risk.

Initial conditions

The changes in seasonal rainfall outlined above imply wetter initial conditions (eg, wetter soils, higher lake levels) in places and during seasons where seasonal rainfall is increasing faster than seasonal evaporation. This would be expected to increase flood magnitude. Conversely, if seasonal rainfall is projected to decrease, then initial conditions would be expected to be drier and floods smaller. Increases in temperature and wind are also likely to increase evapotranspiration.[6] This may be important for estimating flows for water resource considerations, but is less likely to be important for extreme flooding events. These changes can be taken into account either by adjusting the initial conditions of event-based simulation models (eg, via the curve number in TP108, or the run-off coefficient in the Rational Method), or by using continuous simulation models (eg, TopNet), which keep track of the initial conditions internally.

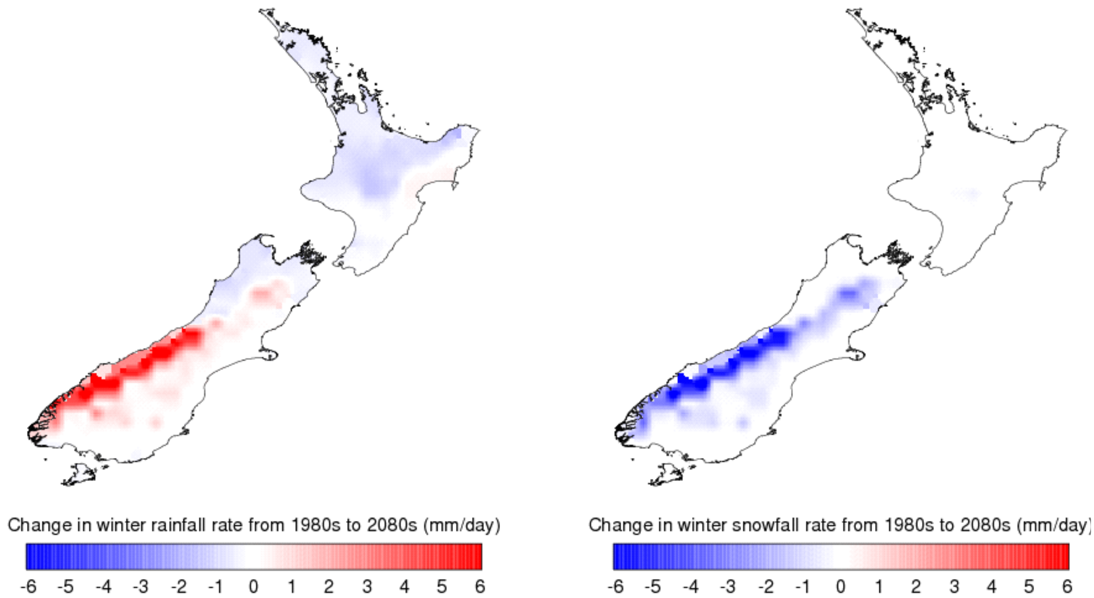
[6] The combined process of evaporation from the Earth's surface and transpiration from vegetation.

Snow versus rain

For locations that currently receive significant snowfall, the projected increases in temperature suggest a shift towards increasing rainfall instead of snowfall. This means that for rivers where the winter precipitation currently falls mainly as snow and is stored until the snow-melt season there is the possibility of larger winter floods. It is also likely the spring melting will occur earlier and faster. These impacts have not yet been quantified, but are in addition to the temperature-driven increases in extreme rainfall that result from a warmer atmosphere. They can be accounted for by simulation models such as a regional climate model linked to a catchment model. An example of this is given in figure 6.

The two maps in figure 6 show the change in winter rainfall (left) and snowfall (right) between 1980 and 2080, as simulated by NIWA's regional climate model (RCM) under the medium-high A2 emissions scenario. They suggest that changes in total winter precipitation in the Southern Alps may be dominated by a significant shift from snowfall to rainfall. They also suggest that spill-over onto the eastern side of the main divide may be affected by this change, since rain is less easily transported by the dominant westerly winds. The net change in total precipitation (see figure 4) is consistent with an increase in precipitation on the west coast of the South Island and a decrease in the North Island due to changes in large-scale atmospheric circulation. The snow simulation in the RCM is not yet validated, and so the values shown are currently considered to be illustrative only.

Figure 6: Projected changes in winter rain (left) versus winter snow (right), simulated for a medium-high emissions scenario (A2) using NIWA's regional climate model



Note: The snow simulation in the regional climate model is not yet validated, and as such the values shown are currently considered to be illustrative only.

Erosion and sediment transport

Changes in climate can also affect flood magnitude indirectly. For example, increases in rainfall intensity can lead to increases in erosion, and when the eroded material is delivered to the river system it may lead to changes in river channel shape and position, and consequent changes in the likelihood of inundation. For example, extra sediment may be deposited in the bed of a river, raising the level of the bed (known as aggradation), and thus reducing the flood-carrying capacity of the channel. As a result, for a given river flow rate less water can be conveyed by the channel and more water will overflow and cause inundation. The opposite situation may also occur, where an increase in floodwaters in a channel results in greater water velocities and hence increases the forces required to transport sediment. This can lead to increased erosion and down-cutting (degradation) in the channel. Within a river system patterns of aggradation and degradation vary in both time and space, making changes in channel position and level – and thus changes to flood-plain inundation – very hard to predict. Numerical morphodynamic modelling is likely to be required to quantify changes to sediment transport and channel morphology.

Sea-level rise

Another important impact of climate change on flood severity is through changes in sea level. Projected sea-level rise as a result of climate change is discussed thoroughly in the *Coastal Hazards and Climate Change* manual (Ministry for the Environment, 2008b), which suggests using a risk-based approach to assess sensitivity to different amounts of future sea-level rise. As part of the risk assessment process, the manual recommends considering the potential consequences of higher sea levels. The Ministry recommends planning for the following projection of future sea-level rise:

- for planning and decision timeframes out to 2090–2099, a base value sea-level rise of 0.5 metres relative to the 1980–1999 average be used along with an assessment of potential consequences from a range of possible higher sea-level rise values. At the very least, all assessments should consider the consequences of a mean sea-level rise of at least 0.8 metres relative to the 1980–1999 average
- for planning and decision timeframes beyond the end of this century, an additional allowance of 10 millimetres per year be used.

Refer to tables 2.2 and 2.3 on page 21 of the *Coastal Hazards and Climate Change* manual for more detail on this issue.

These potential sea-level changes mean the base water level in coastal river reaches may be significantly higher than the current level. Calculations of flood inundation should take this higher base level into account in coastal river reaches. (This matter is discussed further in chapter 5.)

2.5 Climate change or IPO: which is more important?

Climate variability due to the IPO (see section 2.3) will continue to be an important factor in determining flood risk. The impacts of climate change over the next 40 to 50 years will be similar in magnitude to the impacts of the IPO, and so both need to be considered when assessing changes in flood magnitude. Climate change trends will become more important, and will change the background state as time goes on, so the mean climatic conditions around which the variation is happening will continue to move further away from the historical mean conditions that have effectively been the basis for flood designs in the past.

2.6 Summary

- The most common cause of river flooding is extreme rainfall.
- Climate change is likely to lead to increases in extreme rainfall, especially in places where mean rainfall is expected to increase.
- Changes in storminess as a result of climate change are harder to predict, but it is likely that tropical cyclones will be more intense, and such weather systems can transform into intense sub-tropical lows that bring heavy rainfall to New Zealand.
- As the snowline rises, places that currently receive snow are likely to see a shift towards increasing rainfall instead of snowfall.
- Sea-level rise will increase base levels for coastal river reaches.
- The climate is naturally variable. On a decadal timescale New Zealand rainfall and flooding are affected by the Interdecadal Pacific Oscillation (or IPO) in some places. IPO effects may need to be considered when calculating flood risk.

3 Methods to Estimate Changes in Extreme Rainfall

3.1 Introduction

The first step in estimating the effects of climate change on river flood flows is to estimate the change in rainfall. Simple methods for carrying out this step have been disseminated to councils since the first edition of the *Climate Change Effects* manual in 2004. This chapter looks at screening and advanced tools that can be used to help river managers estimate changes in extreme rainfall due to climate change.

3.2 Screening methods

Factors used for deriving extreme rainfall information

The most straightforward method for estimating extreme rainfall for preliminary screening is given in the Ministry for the Environment's *Climate Change Effects* manual (Ministry for the Environment, 2008a). That manual lists (in its table 5.1, p 65) ways to estimate a variety of climatic factors at both the screening and advanced levels. For calculating both heavy rainfall and flood, the *Climate Change Effects* manual suggests using a factor by which rainfall is adjusted for each 1 degree Celsius of temperature change. This factor can be used in combination with HIRDS[7] (the High Intensity Rainfall Design System, see Glossary) and local rainfall data to estimate the effect of climate change on extreme rainfall statistics (see the Stoney Creek small catchment case study in chapter 6 for a worked example). Table 1 below lists these factors for a range of average recurrence intervals and a range of durations of precipitation (sourced from the *Climate Change Effects* manual).

These factors can also be used with extreme rainfalls from sources other than HIRDS; for example, the map of 24-hour design rainfalls mentioned in Stormwater Rainfall-Runoff Model TP108 in chapter 4, or any other suitable source of design rainfall information.

The *Climate Change Effects* manual also notes that if a screening assessment using the mid-range scenario, based on table 1, does not reveal any significant impacts, best practice would indicate the need to re-run the screening using a scenario from the upper bound of possible future climate change.

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7 HIRDS is currently being updated (March 2010), with the addition of a new feature to enable the rainfall adjustment factor to be included automatically.

Table 1: Factor of percentage adjustment per 1°C to apply to extreme rainfall, for use in deriving extreme rainfall information for screening assessments

	ARI (years)						
Duration	**2**	**5**	**10**	**20**	**30**	**50**	**100**
< 10 minutes	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
30 minutes	7.2	7.4	7.6	7.8	8.0	8.0	8.0
1 hour	6.7	7.1	7.4	7.7	8.0	8.0	8.0
2 hours	6.2	6.7	7.2	7.6	8.0	8.0	8.0
3 hours	5.9	6.5	7.0	7.5	8.0	8.0	8.0
6 hours	5.3	6.1	6.8	7.4	8.0	8.0	8.0
12 hours	4.8	5.8	6.5	7.3	8.0	8.0	8.0
24 hours	4.3	5.4	6.3	7.2	8.0	8.0	8.0
48 hours	3.8	5.0	6.1	7.1	7.8	8.0	8.0
72 hours	3.5	4.8	5.9	7.0	7.7	8.0	8.0

Note: This table recommends *percentage* adjustments to apply to extreme rainfall per 1 degree Celsius of warming, for a range of average recurrence intervals (ARIs.). The percentage changes are mid-range estimates per 1 degree and should be used only in a screening assessment. The entries in this table for a duration of 24 hours are based on results from a regional climate model using the medium-high (A2) emissions scenario. The entries for 10-minute duration are based on the theoretical increase in the amount of water held in the atmosphere for a 1 degree increase in temperature (8 per cent). Entries for other durations are based on logarithmic (in time) interpolation between the 10-minute and 24-hour rates.

Note that the largest percentage increase in table 1 is 8 per cent per 1 degree Celsius of local warming, and this factor applies to the longest ARIs and the shortest durations. This upper limit of 8 per cent has theoretical support in that it is the rate of increase in the moisture-holding capacity of air as temperature increases. Studies have found that, at least in the extra-tropics and for a regional average, the 8 per cent increase agrees well with global and regional model estimates (Pall et al, 2007). However, the possibility of precipitation extremes increasing faster than this 8 per cent cannot be ruled out (Lenderink and van Meijgaard, 2008), particularly for short duration falls of one hour or less. Preliminary NIWA regional modelling results also show 'hot spots' where rainfall extremes are larger than 8 per cent per 1 degree of warming,[8] although further work is required to establish whether this is due to changes in the intensity or the frequency of storms. Nevertheless, our recommendation at this time is to apply the factors of table 1 for all locations. Further research is needed before we can have any confidence in the location of such hot spots.

8 There is a lot of noise in a 30-year simulation, and this affects estimates of extremes. Another model run starting with slightly different initial conditions but forced by the same emission scenario and with similar warming, will show different 'hot spots'.

3.2.2 Influence of temperature on extreme rainfall

Table 1 provides percentage adjustments to apply to extreme rainfall per degree Celsius of warming. The recommended temperature increase to use is the annual average increase for each region, shown below in tables 2 and 3 (taken from tables 2.2 and 2.3 of the *Climate Change Effects* manual). Tables 2 and 3 give the projected annual temperature increases at 2040 and 2090, separately for each regional council area of New Zealand, for the six IPCC illustrative marker scenarios. The table columns show the 12-model averages, along with the lowest and highest temperature changes across the 12 models, as a function of the emission scenario (note that A1T and B2 give the same result and so are shown as a single column). As an example, for the Auckland region in 2090, the annual temperature is projected to increase by an average of 1.4 degrees for the lowest B1 emission scenario (with a range between 0.6 and 2.6 degrees), and by an average of 3.0 degrees for the highest A1FI emission scenario (with a range between 1.3 and 5.8 degrees).

Table 2: Projected changes in annual mean temperature (in °C), 1990 to 2040, by regional council area

	IPCC scenario				
Regional council area	**B1**	**B2/A1T**	**A1B**	**A2**	**A1FI**
Northland	0.6 [0.2, 1.2]	0.8 [0.3, 1.5]	0.9 [0.3, 1.8]	1.1 [0.4, 2.2]	1.3 [0.4, 2.6]
Auckland	0.6 [0.2, 1.1]	0.8 [0.3, 1.5]	0.9 [0.3, 1.7]	1.1 [0.4, 2.1]	1.3 [0.5, 2.5]
Waikato	0.6 [0.2, 1.1]	0.8 [0.3, 1.4]	0.9 [0.3, 1.6]	1.1 [0.4, 2.0]	1.3 [0.5, 2.4]
Bay of Plenty	0.6 [0.2, 1.1]	0.8 [0.3, 1.4]	0.9 [0.4, 1.6]	1.1 [0.4, 2.0]	1.3 [0.5, 2.4]
Taranaki	0.6 [0.2, 1.0]	0.8 [0.3, 1.4]	0.9 [0.4, 1.6]	1.1 [0.4, 2.0]	1.3 [0.5, 2.3]
Manawatu–Wanganui	0.6 [0.2, 1.1]	0.8 [0.3, 1.4]	0.9 [0.3, 1.7]	1.1 [0.4, 2.0]	1.3 [0.4, 2.4]
Hawke’s Bay	0.6 [0.2, 1.1]	0.8 [0.3, 1.4]	0.9 [0.3, 1.6]	1.1 [0.4, 2.0]	1.3 [0.5, 2.3]
Gisborne	0.6 [0.2, 1.0]	0.8 [0.3, 1.3]	0.9 [0.4, 1.5]	1.1 [0.4, 1.9]	1.3 [0.5, 2.2]
Wellington	0.6 [0.3, 1.0]	0.8 [0.3, 1.3]	0.9 [0.4, 1.5]	1.1 [0.5, 1.9]	1.3 [0.6, 2.2]
Tasman–Nelson	0.6 [0.2, 0.9]	0.8 [0.3, 1.2]	0.9 [0.4, 1.4]	1.1 [0.5, 1.8]	1.3 [0.5, 2.1]
Marlborough	0.6 [0.2, 0.9]	0.8 [0.3, 1.2]	0.9 [0.4, 1.4]	1.1 [0.4, 1.7]	1.3 [0.5, 2.0]
West Coast	0.6 [0.2, 0.8]	0.8 [0.2, 1.1]	0.9 [0.3, 1.3]	1.1 [0.3, 1.5]	1.3 [0.4, 1.8]
Canterbury	0.6 [0.2, 0.8]	0.8 [0.3, 1.1]	0.9 [0.3, 1.3]	1.1 [0.4, 1.6]	1.3 [0.5, 1.9]
Otago	0.6 [0.1, 0.9]	0.7 [0.1, 1.1]	0.9 [0.2, 1.3]	1.1 [0.2, 1.6]	1.3 [0.2, 1.9]
Southland	0.6 [0.1, 0.9]	0.7 [0.1, 1.1]	0.8 [0.1, 1.3]	1.1 [0.1, 1.6]	1.2 [0.1, 1.9]
Chatham Islands	0.6 [0.2, 1.2]	0.8 [0.3, 1.5]	0.9 [0.3, 1.8]	1.1 [0.4, 2.2]	1.3 [0.4, 2.6]

Notes: The average change, and the lower and upper limits (in brackets), are provided separately for the IPCC’s six illustrative marker scenarios. The B2 and A1T scenarios produce the same warming, and so are shown in a single column.

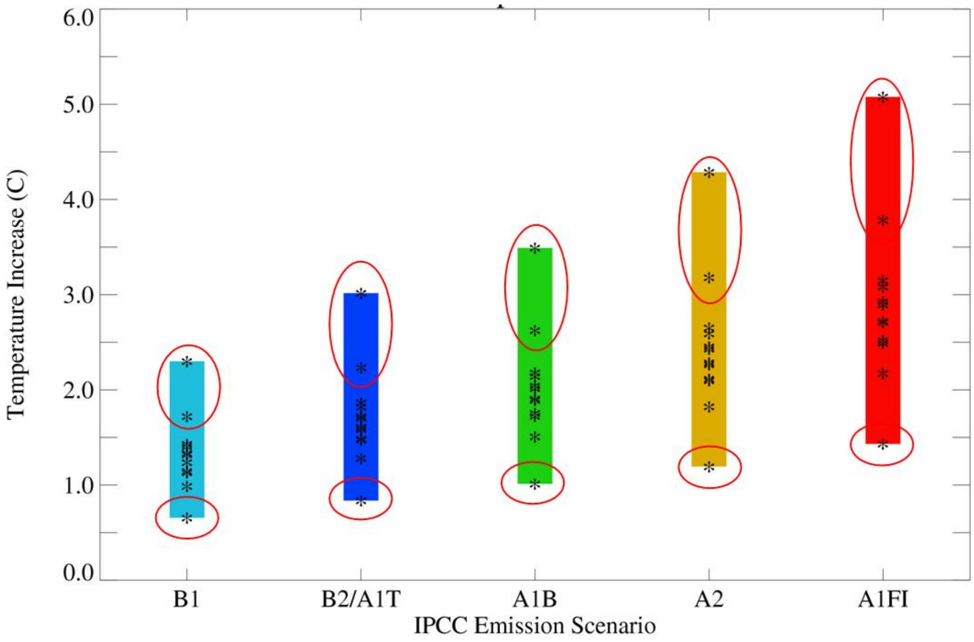
Table 3: Projected changes in annual mean temperature (in °C), 1990 to 2090, by regional council area

	IPCC scenario				
Regional council area	**B1**	**B2/A1T**	**A1B**	**A2**	**A1FI**
Northland	1.3 [0.6, 2.7]	1.7 [0.7, 3.5]	2.1 [0.9, 4.1]	2.5 [1.1, 5.0]	3.0 [1.3, 5.9]
Auckland	1.4 [0.6, 2.6]	1.8 [0.7, 3.4]	2.1 [0.9, 4.0]	2.5 [1.1, 4.9]	3.0 [1.3, 5.8]
Waikato	1.4 [0.6, 2.5]	1.8 [0.7, 3.3]	2.1 [0.9, 3.8]	2.5 [1.0, 4.7]	3.0 [1.3, 5.5]
Bay of Plenty	1.4 [0.6, 2.5]	1.8 [0.8, 3.3]	2.1 [0.9, 3.8]	2.5 [1.1, 4.7]	3.0 [1.3, 5.6]
Taranaki	1.4 [0.6, 2.4]	1.8 [0.7, 3.2]	2.1 [0.9, 3.7]	2.5 [1.1, 4.5]	3.0 [1.3, 5.3]
Manawatu–Wanganui	1.3 [0.6, 2.5]	1.7 [0.7, 3.3]	2.1 [0.9, 3.8]	2.5 [1.0, 4.7]	3.0 [1.2, 5.5]
Hawke’s Bay	1.3 [0.6, 2.4]	1.7 [0.7, 3.2]	2.1 [0.9, 3.7]	2.5 [1.0, 4.5]	3.0 [1.2, 5.4]
Gisborne	1.4 [0.6, 2.4]	1.8 [0.8, 3.2]	2.1 [0.9, 3.6]	2.5 [1.1, 4.5]	3.0 [1.3, 5.3]
Wellington	1.3 [0.6, 2.3]	1.7 [0.8, 3.1]	2.1 [0.9, 3.6]	2.5 [1.1, 4.4]	3.0 [1.3, 5.2]
Tasman–Nelson	1.3 [0.6, 2.3]	1.7 [0.8, 3.0]	2.0 [0.9, 3.5]	2.5 [1.1, 4.3]	2.9 [1.3, 5.1]
Marlborough	1.3 [0.6, 2.3]	1.7 [0.8, 3.0]	2.0 [0.9, 3.5]	2.5 [1.1, 4.3]	2.9 [1.3, 5.0]
West Coast	1.3 [0.7, 2.2]	1.7 [0.8, 2.9]	2.0 [1.0, 3.4]	2.4 [1.2, 4.1]	2.9 [1.4, 4.9]
Canterbury	1.3 [0.7, 2.2]	1.7 [0.9, 2.9]	2.0 [1.1, 3.4]	2.5 [1.3, 4.2]	2.9 [1.6, 5.0]
Otago	1.3 [0.8, 2.1]	1.7 [1.0, 2.8]	2.0 [1.2, 3.2]	2.4 [1.4, 3.9]	2.8 [1.7, 4.6]
Southland	1.3 [0.8, 2.0]	1.6 [1.0, 2.7]	1.9 [1.2, 3.1]	2.3 [1.4, 3.8]	2.8 [1.7, 4.5]
Chatham Islands	1.3 [0.6, 2.7]	1.7 [0.7, 3.5]	2.1 [0.9, 4.1]	2.5 [1.1, 5.0]	3.0 [1.3, 5.9]

Notes: The average change, and the lower and upper limits (in brackets), are provided separately for the IPCC’s six illustrative marker scenarios. The B2 and A1T scenarios produce the same warming and so are shown in a single column.

There is not much variation across New Zealand in the rate of warming, unlike the strong gradients seen in the precipitation changes. Figure 7 shows the information from table 3 averaged over all of New Zealand. It is apparent from this that three of the climate models are outliers: one is colder and two are warmer than the cluster of the remaining nine models. For purposes of consistency, if the rainfall pattern from a particular model is being used in a scenario risk assessment, then it is desirable to use the appropriate temperature change from that same model.

Figure 7: Change in New Zealand average annual temperature to 2090 (°C), by IPCC emissions scenario



Note: The vertical coloured bars highlight the range over the 12 climate models considered, with stars indicating individual models and circles to indicate outliers.

3.3 Advanced methods

In order to estimate changes in flood flows, you need to start with rainfall time-series that have been adjusted to take account of climate change influences. A wide range of approaches are possible, from statistical and empirical adjustments to observed rainfall data, through to numerical model simulations of future climate.

3.3.1 Weather generators

A weather generator is a stochastic model[9] for simulating a daily time-series of linked climatic elements – commonly rainfall, maximum and minimum temperature, solar radiation and wind run (Wilks, 1992; Thompson and Mullan, 2001). The weather generator is first tuned to current site data, and then adjustments for future climate change can be made to the climatological means and standard deviations, and to other parameters such as the frequency of a wet day. This approach has been used widely in agricultural modelling, where simultaneous variations in a number of climate elements in addition to rainfall are required.

9 A stochastic model is a tool for estimating probability distributions of potential outcomes by allowing for random variation in one or more inputs over time.

3.3.2 Empirical adjustment of daily rainfall data

Most of the methods that estimate changes in flood magnitude due to climate change require rainfall information at a daily or finer time resolution. The rainfall changes previously developed in the *Climate Change Effects* manual (section 2.2.2) provide information at a monthly timescale and are not suitable on their own for assessing changes in flood risk. A method for empirically adjusting a daily rainfall time-series is described here, which uses the scenarios of mean rainfall change and also adjusts the distribution to increase the most extreme daily amounts.

Step 1 (below) adjusts the daily data using monthly rainfall offsets. The distributional adjustment in steps 2 to 4 have the effect of decreasing the number of days per year when rain falls and allocating more precipitation into the upper tail of the rainfall distribution. The formula in step 2 is based on analysis of extreme rainfalls at a few grid points in the Wellington region for one of the regional climate model runs (see figure 8). The formula changes the frequency of rain days – reducing the number of rain days by decreasing the probability of a rain day by 1.75 per cent per degree Celsius increase in annual-average temperature. Further work is required to clarify how appropriate this formula is across all of New Zealand.

Step 1 Adjust the daily data using the monthly rainfall offsets (*Climate Change Effects* manual, table 2.4 for 2040, table 2.5 for 2090). The change in monthly climatological rainfall is then calculated (eg, a 10 per cent increase in a monthly climatology of 100 millimetres means an extra 10 millimetres). The monthly climatological rainfall is estimated by averaging over many years so that the resulting monthly totals represent the current state of the climate. The monthly change in rainfall so obtained (eg, 10 millimetres) is then expressed as a percentage change for the current month. For example, if the current monthly total is 120 millimetres, then the percentage change is 10 millimetres divided by 120 millimetres, which equals 8.3 per cent. This percentage change is then applied to each rain day in the month. This step does not change the number of rain days in the record or alter the inter-annual variance in monthly rainfalls.

Step 2 Allow for the changes in frequency of rain days. This reduction in low-rainfall days helps to balance the increased rainfall extremes in step 3. Thus, if:

- NW = number of rain days
- NT = total number of days in a year (ie, 365.25)
- ΔT = warming

then the number of rain days will change from NW to (rounded down to the nearest integer) NW – 0.0175 * ΔT * NT.

This corresponds to about seven fewer rain days per year per degree of warming. The reduction is applied to days with the lowest rainfall by ranking all rain days in an ascending order and setting the calculated number (0.0175 * ΔT * NT) of lowest rainfall days to zero rainfall.

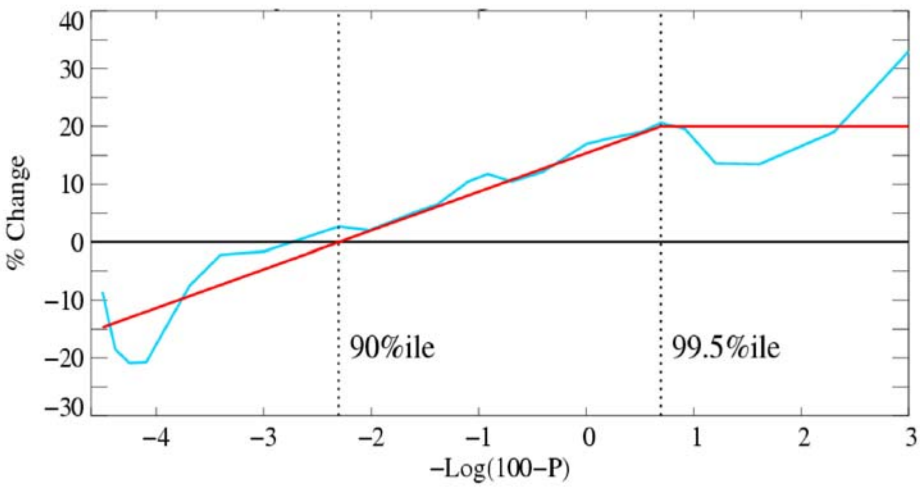
Step 3 After applying steps 1 and 2, calculate the rainfall percentiles P from the adjusted daily data (all months and years combined). Note that the percentiles are calculated over rain days only (ie, ignoring dry days). The percentile values are then changed according to the formula:

Change in daily rainfall (in % per °C) = 6.15 * [1. – ln (100–P)/2.3].

This formula gives zero change at percentile P = 90, + 8 per cent per degree Celsius change at P = 99.5, and about –6 per cent per degree Celsius change at P = 0. For P > 99.5, the change is capped at +8 per cent per degree of local warming (taken as the change in annual-average temperature). This 8 per cent per degree value is widely recognised as the rate at which the water vapour saturation level increases in the atmosphere (the Clausius–Clapeyron relationship), and is the upper limit recommended in the *Climate Change Effects* manual for adjusting return periods of extreme rainfall. Apply these percentage changes in rainfall to the results of step 2.

Step 4 Recalculate the total rainfall over the whole period (all months and years included) after step 3, and check to see the total rainfall is still consistent with the total in step 1, after the prescribed scenario changes are applied. If it is not consistent, then adjust all daily rainfalls by the factor required for consistency (eg, if the total rainfall is 130 millimetres after step 1, but the total rainfall is 137.2 millimetres after step 3, then multiply all rain days by the factor 130 millimetres divided by 137.2 millimetres). If this adjustment leads to some daily rainfalls dropping below 0.1 millimetres (the threshold for a measurable rainfall), then reset rainfall on these days to the minimum, 0.1 millimetres, and adjust all daily rain days, with rainfall greater or equal to 1.0 millimetres, by multiplying them with a consistency factor (less than 1).

Figure 8: Percentage change in rainfall amount as a function of the percentile in the distribution of daily rainfall: NIWA regional climate model data (averaged over several grid squares in the Wellington region) with local warming of 2.5°C (blue line) and idealised rainfall distributional-adjustment model (red line)



Notes: The horizontal co-ordinate is minus the natural logarithm of (100-P), where P is the percentile in the distribution of daily rainfall amounts. This coordinate scale accentuates the high-end rainfalls. Note that the model rainfall changes are approximately linear over a wide range in this co-ordinate space.

We can now illustrate this method in table 4. Note that our example has just 30 days of data, of which many have zero rainfall, whereas in practice we would have several decades of data. In step 1 below, we apply a hypothetical 10 per cent increase in monthly climatological rainfall of about 100 millimetres to the current monthly total of 120 millimetres, so the total rain for the month is now 130.0 millimetres (ie, 0.10 * 100 millimetres + 120 millimetres). In step 2, we apply the 1.75 per cent formula to find that our 30 days should have 9.48 (rounded down to 9) rain days instead of 10; that is, we need one fewer rain day. So we rank the rain days in ascending order and find the smallest daily rainfall (the shaded 0.5 millimetres on day 12) and set it to zero. The total rain for the month is now 129.5 millimetres.

In step 3, we compute a percentile for each non-zero daily rainfall (after the rain day reduction in step 2), then compute the percentage change per degree for rainfall extremes, assume 1.0 degree Celsius annual average warming, and apply each percentage change to the corresponding day's rainfall. The total rain for the month is now 132.7 millimetres. In step 4, we scale the rain for the total period (in this case only one month) by 130.0 millimetres divided by 132.7 millimetres, to obtain a total rain of 130.0 mm, consistent with the total rain after applying the monthly climate change scenario in step 1. None of the non-zero rainfalls have been reduced below 0.1 millimetres (the threshold for measurable rainfall) by this scaling, so the process stops.

Table 4: Applying the empirical adjustments of rain

Day of month	1	2	3	4	5	6	7	8	9	10	11	12	13	…	30	Total	NW*
Climatological monthly total (average over many years)																100.0	
Rain (mm)	60.0	0	14.0	13.0	12.0	0	7.0	6.0	4.0	2.0	1.5	0.5	0	…	0	120.0	10
Step 1	**Adjust by 10% for climate change impacts**																
Rain (mm)	66.0	0	15.2	14.1	13.0	0	7.6	6.5	4.3	2.2	1.6	0.5	0	…	0	130.0	10
Step 2	**Reduce to account for changes in frequency**																
Ranking in ascending order	10		9	8	7		6	4	3	2	1			…			9.48**
Rain (mm)	66.0	0	15.2	14.1	13.0	0	7.6	6.5	4.3	2.2	1.6	0***	0	…	0	129.5	9
Step 3	**Calculate percentiles and adjust to give changes in intensity**																
Ranking in ascending order	9		8	7	6		5	4	3	2	1			…			
Percentiles for non-zero rain	100		87.5	75.0	62.5		50.0	37.5	25.0	12.5	0.0			…			
Per cent change per degree	8.0		-0.6	-2.5	-3.5		-4.3	-4.9	-5.4	-5.8	-6.2			…			
Rain (mm)	70.2	0	15.1	13.7	12.5	0	7.3	6.2	4.1	2.0	1.5	0	0	…	0	132.7	9
Step 4	**Apply distributional changes**																
Rain (mm)	68.8	0	14.8	13.5	12.3	0	7.1	6.1	4.0	2.0	1.5	0	0	…	0	130.0	9

* NW indicates the number of rain days.

** This is the target number of rain days when using the 1.75 per cent reduction.

*** The shaded 0 mm value was set to zero to reduce the number of rain days.

3.3.3 Analogue selection from observed data

Whereas the previous two methods are limited to adjusting *daily* rainfalls, analogue selection can be applied to the rainfall data of any temporal resolution. The approach here is to select a subset of past rainfall data that has specific characteristics anticipated in a future climate; for example, choosing rainfall data from the hottest years, or periods with a certain mix of circulation types, such as a negative IPO. Analogue selection has been applied to future New Zealand rainfall (Sansom and Renwick, 2007) and to hydrological studies (Yates et al, 2003).

3.3.4 Downscaling global model results

Estimates of changes in rainfall can be made by downscaling the results from global climate models (GCMs). GCMs do not have the resolution to simulate very intense convection, but one approach that could be used in New Zealand is to apply adjustments to observed rainfall probability distributions, guided by distributional changes predicted by the GCMs (Semenov and Bengtsson, 2002). The statistical distribution of daily rainfall can be fitted to a 'gamma distribution', and GCMs analysed to evaluate how the shape and scale factors of this distribution change under a warming scenario. Similar parameter changes can then be applied to the rainfall distribution at a site. This approach is conceptually similar to that discussed in section 3.3.2 and is not discussed further here. (Refer to Appendix A3.3 in the *Climate Change Effects* manual for possible applications of this method.)

3.3.5 Mesoscale weather model

A mesoscale weather model[10] (eg, the Regional Atmospheric Modelling System, Cotton et al, 2001) can be used to simulate the effects of climate change on rainfall. Such models can be used for case studies or weather forecasting and have detailed representations of the physical processes that influence precipitation. In a case study the model is used twice: once to simulate an event that could or has occurred under the current climate, and a second time with an increased air temperature consistent with the warming from a climate change scenario. The warmer air is able to hold more moisture and so more precipitation is possible. A model of this kind provides detailed information on the location, structure and timing of precipitation across the catchment or region of interest, rather than assuming a uniform percentage increase in rainfall. An example of this type of weather modelling is included as part of the Westport case study in chapter 6.

3.3.6 Regional climate model

NIWA has developed a capability for modelling global and regional climate based on the UK Met Office's unified model framework (Drost et al, 2007). A global climate model (GCM) developed at the UK Met Office, known as HadCM3, has been used to generate boundary conditions in the New Zealand region and hence to run a regional climate model (RCM). The RCM simulates all the atmospheric processes that are important in the creation of heavy rainfall events and can allow these processes to change under global warming.

The RCM does not itself simulate river flows, but the impact of climate change on flood flows can be quantified for major catchments throughout New Zealand by coupling bias-corrected climate information from the RCM into a catchment hydrological model (eg, TopNet, described further in section 4.3). The RCM can provide all the climate inputs required by these models, such as surface temperature and rainfall, at hourly resolution, for both the current and future climate. The RCM-TopNet simulations can potentially provide scenarios of flood risk (changes in flood frequency and magnitude, and seasonality) for all major river catchments of New Zealand.

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10 A numerical weather prediction model designed to simulate phenomena with horizontal scales between a few kilometres and several hundred kilometres.

Simulations of the RCM suitable for this purpose already exist. These include a current climate experiment for 1970 to 2000, which makes use of observed sea surface temperatures, and two future climate experiments for 2070–2100. These future experiments use two very different greenhouse gas emission scenarios, known as B2 and A2 (low and moderately high) to span the uncertainty in possible future emissions. The RCM can also be forced with historical observed data, for which two reconstructions are available. This data comes from weather models that incorporate as many observations as possible, and the RCM then interpolates from the regional circulation to the local climate. This allows for the direct comparison of RCM output with observations of individual flood-causing weather systems, without the need to rely on long-term averages.

The quantification of uncertainty in the model outputs is a key step in making the research results relevant to users who are involved in assessing insurance risks, making investments in flood protection works and planning land use. Simulations of the RCM-TopNet model driven by observed circulation reconstructions can be compared with rainfall and river flow observations to allow detailed bias corrections to be established for use in future climate runs. The changes observed in these future runs could then be used to estimate changes in flood risk and the uncertainty in those projections. Although the RCM is at a high resolution of 30 kilometres with regard to climate studies, it has a relatively low resolution when compared to individual river catchments. However, TopNet is capable of adjusting for this problem.

The main weakness of the RCM-TopNet methodology lies in the reliance on only one – or possibly two – GCMs when making future projections and so it is unable to capture any uncertainty due to the use of different models (unlike the use of statistical downscaling, see section 3.3.4). A significant advantage is the capturing of realistic changes in regional rainfall extremes with a resolution of one hour, although in some areas of the country the changes may be significantly greater than those given by the screening method given in section 3.2.

3.4 Summary

- A number of more advanced methods for estimating extreme rainfall have been discussed, including weather generators, empirical adjustments, analogue selection from observed data, downscaling of global models, mesoscale weather models and regional climate models.
- These methods provide estimates of how climate change may affect extreme rainfall. Each method, in its own way, converts forecasts of climate change into time-series of rainfall. They differ in their complexity, data requirements, and reliability of results.
- More complex methods require greater expertise to carry them out, so it is recommended that you consider three factors when deciding how to develop extreme rainfall forecasts:
  - what climate data is available?
  - what accuracy and precision do we need?
  - do we have access to the expertise and computing facilities to undertake the analysis and modelling?
- Table 5 contains a summary of the advanced methods for estimating rainfall, and will help you to choose the most appropriate method.

Table 5: Summary of advanced methods for estimating rainfall as a guide to selecting the most appropriate method

Method	Description	Advantages	Disadvantages	Data and climate change requirements
Weather generators (WGs)	Statistical and empirical models of local weather features	Easy to make multiple simulations or generate very long time-series of daily weather sequences. Match daily variability well. Can handle multiple weather parameters (typically rainfall, max/min temperature, solar radiation and wind run) with realistic cross-correlations.	Accuracy of simulations depends on realism of assumed underlying distributions. Have insufficient low-frequency (year-to-year) variability, a problem known as *overdispersion.* Not always straightforward to adjust parameters for future climate.	Observed station data to fit WG parameters to current climate. Future simulation time-series, or some other method to generate WG parameter changes, for future climate.
Empirical adjustments	Adjusts historical rainfall records with monthly climate change projections	Very easy to apply, and provide daily output. Can adjust rainfall distribution (eg, greater extremes) as well as mean rainfall changes.	Not physically based (although adjustments may be guided by physics models such as a regional climate model).	Observed station time-series. Future scenarios of monthly rainfall changes (and annual temperature change if making adjustments to the distribution).
Analogue selection from observed data	Mimics climate change by comparing with selected historical events	Straightforward in principle. Selecting a number of analogues (eg, best N) will give a distribution of resulting climates.	The various ways to select analogues can lead to different answers. Analogues selected independently for different sites may not be consistent with each other.	Observed data for analogue selection. General climate change trends.
Downscaling of global models	Converts GCM results to local results based on local statistics	Relatively straightforward to apply to many GCMs once downscaling approach has been decided.	Output is monthly. Statistically based approach will misrepresent some physical realities. Climate trends may move outside the range of observations.	Current observed data to generate downscaling relationships. Global model data (usually monthly) for future scenarios.
Mesoscale weather models (RAMS)	Used to simulate the effects of climate change on rainfall for a small region	Physically based. Output data obtained at high spatial and temporal resolution.	Computer intensive. Usually run for short-period case studies only.	Three-dimensional weather data fields for initialisation of model.
Regional climate models (RCMs)	Used to simulate more detailed climate change at the regional scale	Based on physical equations of the climate system. Output data obtained at high time and space resolution for virtually any weather and climate variable of interest.	Very computationally intensive; produces large amounts of data. Requires running a global climate model to generate boundary conditions around the RCM domain (atmosphere + sea surface).	Three-dimensional weather and climate data fields for the entire simulation period of the model.

Note: Data requirements specifically related to climate change are underlined.

4 Methods to Estimate Changes in Flood Flows

4.1 Introduction

After estimating the change in rainfall, as described in chapter 3, the next step is to convert that rainfall change into a flood flow (an amount of water flowing in a river). This chapter looks at both screening and advanced tools that can be used to help river managers estimate changes in flood flows.

Historical data and ongoing data campaigns are vital components of any forecasts of flood flows. Although climate change means that future flow statistics will be different from those in the past, they are necessary to calibrate any model of river flow. Past extreme events can be used as indicators of future trends and are invaluable for assessing how climate change has affected river flows.

4.2 Screening methods

There are many different screening methods available to assess changes in flows in a changing climate. Common to each is relative ease of use and the ability to tune the method to replicate historical events, because they are all simple empirical methods. This ease, however, comes at a cost. By restricting themselves to historical data and by only vaguely representing real-world processes, screening methods generally offer less confidence in making forecasts for events that fall outside the range of historical observations.

Empirical screening methods generally draw on a few basic approaches: the Rational Method, the US Soil Conservation Service (SCS) method, and the unit hydrograph. Here we discuss the Rational Method and one approach presently used in New Zealand that employs both the SCS and unit hydrograph methods.

4.2.1 Unit hydrograph and SCS methods

The unit hydrograph method reflects how a catchment converts a hyetograph (a graph of the distribution of rainfall over time) into a hydrograph (a graph showing changes in river flow over time), while the SCS method empirically relates peak flood flow to rainfall using land-cover-related parameters. To illustrate how the unit hydrograph and SCS methods can be adapted to incorporate climate change, TP108 is used as an example, although these approaches can be generalised across other implementations of the basic methods.

TP108 is a standard model for computing design flood hydrographs in small catchments in the Auckland region (Auckland Regional Council, 1999). It has been used outside the region, but it must be stressed that the model was not developed to do so. Also note that it is currently being updated by the Auckland Regional Council to GD2009/001.

A key input to TP108 is the 24-hour rainfall total, P, which is mapped for the Auckland region (Auckland Regional Council, 1999). The formula for event run-off is:

$$Q = (P - Ia)^2 / (P - Ia + S)$$

where:

- Q is run-off depth (millimetres)
- P is rainfall depth (millimetres)
- S is the potential maximum retention after run-off begins (millimetres)
- Ia is initial abstraction (millimetres), which is 5 millimetres for permeable areas and zero otherwise.

The retention parameter S (measured in millimetres) is related to catchment characteristics through:

$$S = (1000/CN - 10)\ 25.4.$$

The value of the curve number (CN) ranges from 0 for zero run-off to 100 for complete run-off; its value depends on a catchment's characteristics. The TP108 method for estimating CN values is given in the TP108 manual (Auckland Regional Council, 1999, section 2.2 and Appendix B). Note that TP108 does not give detailed guidance on how to adjust CN values for the effect of antecedent conditions, but does mention they influence CN values.

The remaining steps of TP108 convert the run-off depth (Q) into a flow hydrograph by assuming a particular temporal pattern for the storm rainfall and estimating a characteristic lag time for the catchment to respond to rainfall. In a screening approach, these calculations will be assumed to be the same for both the current and future climates and are not discussed further here. In a more sophisticated approach, you might consider whether the temporal rainfall pattern or initial abstraction might change, but this level of detail is generally not appropriate when the method is used as a screening tool.

To use this method as a screening tool in the Auckland region, apply it once with the current 24-hour rainfall from the map in the Auckland Regional Council guidelines (Auckland Regional Council 1999), and apply it a second time with: (i) the rainfall changed to reflect the expected changes in rainfall described in section 3.2; and (ii) the CN value changed to reflect any available information on how antecedent conditions may change with climate. Thus, the extreme daily rainfalls might be approximately 8 per cent higher by 2040, since extreme rainfall is expected to increase 8 per cent per degree of warming, and approximately 1 degree of warming is expected by 2040 in many parts of New Zealand. Tables 1 and either 2 (for 2040 estimates) or 3 (for 2090 estimates) from this manual can be used with this method.

It is important to note that TP108 is designed specifically for use in Auckland: it includes supporting information to guide its application, and this is what allows it to be used as a screening method. TP108 is an example of the wider class of unit hydrograph methods for estimating river flow from rainfall. For example, the HEC-HMS computer modelling system (eg, Scharffenberg and Fleming, 2006) is a freely available and more generic implementation of the unit hydrograph approach. However, without detailed guidance on assigning values to model parameters, HEC-HMS would be considered an advanced technique in the context of this manual rather than a screening method.

Although the simplicity of the SCS and unit hydrograph approaches offers an advantage over advanced techniques, both have their disadvantages. CN values have not been widely assessed for New Zealand and often reflect local hydrology poorly, and both the SCS and unit hydrograph discount the importance of changing pre-storm initial conditions (ie, antecedent soil moisture).

4.2.2 The Rational Method

The Rational Method is a widely used technique in engineering hydrology, although it is known to produce results that have large uncertainty (see McKerchar and Macky, 2001). It can be used as a screening tool in much the same way as described previously for TP108. Other similar models, such as the Modified Rational Method, can also be used as screening models. (For a comparison of the New Zealand performance of the Rational Method with two other methods, see McKerchar and Macky, 2001.)

The formula for the Rational Method can be written as:

$$Q = C\ i\ A / 3.6$$

where:

- Q is the estimate of the peak design discharge in cubic metres per second
- C is the run-off coefficient
- i is rainfall intensity in millimetres per hour, for a duration equal to the time of concentration of the catchment
- A is the catchment area in square kilometres.

Selection of the run-off coefficient, C, relies partly on knowledge of physiographic conditions and engineering judgement. It also depends on the rainfall intensity (eg, see Maidment, 1993, and Ministry of Works, 1978). When applying the formula ($Q = C\ i\ A / 3.6$) for future climates, the important point to note is that both i and C must be changed when considering climate change.

4.2.3 Rules of thumb for changes in regional flood frequency

As more detailed studies of the impacts of climate change on floods are undertaken, it may be possible to synthesise the results into 'rules of thumb'. This would be particularly true if the results from a variety of methods and locations produced robust and similar results. For example, an advanced method may have been applied to several river basins in a region and in all cases it is found that a consistent change in flood magnitude is predicted. At the time of writing we are not aware of any such rules of thumb, but it is conceivable that a rule of the form "the 100-year flood in the current climate will be an X-year flood by 2050" could be applicable (where X might be 60, or 40, or even less). For preliminary screening these rules of thumb may be suitable, provided evidence is available to support them. They are mentioned here not to recommend them but to alert the reader to their possible future existence.

Consider two hypothetical cases where all flood peaks on a given river increase by either 10 per cent or 30 per cent as a result of climate change. How would the recurrence interval of a 100-year ARI flood change in these two hypothetical cases? It is possible to use results from McKerchar and Pearson (1989) to suggest that over much of New Zealand (places where the 100-year ARI flood is between two and three times the mean annual flood), the average recurrence interval would approximately halve if flood peaks all increased by this hypothetical 10 per cent. For example, the flood size that is presently exceeded once every 100 years on average would in future be exceeded once every 50 years on average (based on the slopes of flood frequency curves presented by McKerchar and Pearson). If, instead, flood peaks were to increase by 30 per cent as a result of a more severe climate scenario, then the flood that is presently exceeded once every 100 years on average would be exceeded on average approximately once every 20 years.

A future edition of *Regional Flood Estimation in New Zealand*, updating McKerchar and Pearson, 1989, will provide national guidance on the impacts of climate change on flood magnitude. The 1989 edition of this estimation technique provides national coverage for estimating flood magnitudes, but it is becoming outdated because it does not use any flood data collected in the last 20 years. The regional flood estimation method is being updated and revised at present, and a national revision is expected to be available in 2015.

4.3 Advanced methods

As with screening methods, there are many different rainfall run-off methods available internationally, distinguished by the complexity with which they treat the processes of run-off generation and run-off routing through the catchment. These can be divided into storage-routing models and catchment hydrology. The incorporation of climate change into each of these classes of models is illustrated with two particular cases that have been used in New Zealand, although the general principles can be applied to all similar models.

4.3.1 Storage-routing models

The simpler of the advanced methods for predicting the effects of climate change on river flow are the storage-routing models. These models represent the downstream flow of water by way of linked reservoirs, devoting less attention to the physics of the rainfall run-off processes themselves. Two widely used models are HEC-1 and RORB. Incorporating climate change considerations into these models requires simulations driven by synthetic rainfall time-series under climate change, as obtained in chapter 3. For illustrative purposes only RORB is discussed here.

RORB[11] is a general run-off and stream-flow-routing programme used to calculate flood hydrographs from rainfall and other channel inputs (Laurenson et al, 2007). It converts time-series of storm rainfall for the sub-catchments of a river into a flood hydrograph at the outlet of the catchment. It subtracts losses from rainfall to produce rainfall excess and routes this through catchment storage to produce the hydrograph. It can also be used to design retarding basins and to route floods through channel networks.

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[11] Griffiths et al (1989) provide a brief description of the model, and more details are available from http://civil.eng.monash.edu.au/expertise/water/rorb

The model is areally distributed, non-linear, and applicable to both urban and rural catchments. It makes provision for temporal and areal variation of rainfall and losses, and can model flows at any number of gauging stations. In addition to normal channel storage, specific modelling can be provided for retarding basins, storage reservoirs, lakes or large flood-plain storages. Base flow and other channel inflow and outflow processes, both concentrated and distributed, can be modelled.

A suitably verified rainfall run-off model of the catchment can be used to assess the impacts of climate change on flood magnitude. For example, the model of the Waimakariri River described by Griffiths et al (1989) could be used to assess the impacts of climate change on Waimakariri River floods. The key steps are the development of changed rainfall time-series to use with the model (see chapter 3 of this manual) and verification that the catchment model is applicable (as in Griffiths et al, 1989).

4.3.2 Catchment hydrology models

The most advanced approach for incorporating climate change into river flow estimates is to use a fully distributed, physically-based catchment hydrology model. These models represent a catchment in great detail, including topography, soil and land uses, and discard empirical representations of hydrological processes in favour of general physical and biophysical principles. Their greater complexity brings both benefits and costs. Although there are many such models in operation worldwide (eg, TopNet, MIKE SHE), the method for addressing climate change is similar across all of them. For the purposes of this discussion, TopNet, a model developed specifically for New Zealand conditions, will be used.

TopNet (Bandaragoda et al, 2004; Clark et al, 2008) is a spatially distributed, time-stepping model of water balance. This physically-based catchment hydrology model differs from RORB and other storage-routing models in its highly detailed representation of hydrological processes and in its use of kinematic wave theory to route run-off. It is driven by time-series of rainfall and temperature data (hourly resolution or better), and of additional weather elements where available. TopNet simulates water storage in the snowpack, plant canopy, rooting zone, shallow subsurface, lakes and rivers. It produces time-series of modelled river flow throughout the modelled river network. It is used for both flood modelling and water balance modelling. A detailed description of the model equations is published in Clark et al, 2008.

As with RORB, the key steps in using TopNet for assessing climate change impacts on floods are the development of changed rainfall time-series (see chapter 3) and verification that the catchment model is applicable (see Gray et al, 2005). The key advantage of TopNet and other complex catchment and routing models is they are designed to reflect the underlying processes of floods. This gives modellers greater confidence in their ability to make inferences about events that fall outside the range of historical observations – as will be the case with climate change. A notable disadvantage, however, is they require greater attention in their development, in terms of both the underlying biophysics and calibration. A further consideration regarding the choice of catchment models is the degree of user expertise: a great deal of experience is required to operate these models soundly. Lastly, it should be noted that TopNet is currently more applicable for use in research, while models such as MIKE SHE are used more in the engineering domain.

4.4 Summary

- A range of methods have been presented that provide estimates of how altered rainfall predictions may affect river flow. The aim of each method is to convert extreme rainfall data into an estimate of peak flow.
- As with the methods presented in chapter 3, each method differs in its complexity, data requirements and reliability of results, as well as its user experience needs. Unlike the methods presented in chapter 3, all but the research models (ie, TopNet) are currently usable by practitioners.
- If more confidence in flow prediction is desired, research models are still valuable options.
- As was recommended in chapter 3, you should consider three factors when deciding how to develop predictions of flood flows:
  - what weather and landscape data is available?
  - what accuracy and precision do we need?
  - do we have access to the expertise and computing facilities to undertake the analysis and modelling?
- The summaries in table 6 will help you to choose the most appropriate method.

Table 6: Summary of advanced methods for estimating flood flows as a guide to selecting the appropriate method

Method (example)	Description	Advantages	Disadvantages	Data and climate change requirements
Rules of thumb	General approach based on past, more complex studies.	Easy to use; based on comprehensive analysis.	Uncertain applicability outside the rivers where studies were conducted.	Case-by-case considerations
Rational method	Empirical method to estimate peak flow.	Rapid implementation; low data requirements; widely used in the engineering community; guidelines for estimating run-off coefficient.	Not suitable where rainfall varies significantly across the catchment; limited accuracy in validation tests.	Design rainfall intensity; run-off coefficient, which depends on catchment characteristics (ie, slope, land cover, soil); time of concentration and catchment area.
SCS method (TP108)	Empirical and graphical method to estimate peak flow.	(As for the Rational Method.)	Limited database for New Zealand conditions; limited to small to medium-size catchments; limited accuracy in validation tests.	Rainfall; land-use description; hydrological soil group.
Unit hydrograph (HEC-HMS, TP108)	Empirical approach that converts a hyetograph into a hydrograph.	Relatively simple approach.	Limited to gauged catchments.	Storm hyetograph.
Storage-routing models (RORB, HEC-HMS)	Route rainfall or run-off through a simple catchment.	Moderate data requirements.	Lacks catchment complexities and detailed routing procedure.	Rainfall or run-off time-series; defined storage-routing network.
Kinematic wave models (TopNet)	Flow is routed through a catchment's river network based on kinematic wave theory.	Can be used for operational flood forecasting; more accurate than screening methods when in large complex catchments; ongoing scientific development.	Longer computation time; larger data requirements; larger cost of model calibration.	Time-series of distributed catchment run-off; digital river network calibrated parameters.
Catchment water balance models (TopNet, MIKE SHE)	Models river flow and other hydrological variables across a catchment based on biophysical principles.	Suitable for assessing both climate and land-use change impacts on water resources; ongoing scientific development.	Longer computation time; larger data requirements; larger cost of model calibration.	Rainfall and temperature time-series; digital river network; GIS data for soil, land cover and topography.

Note: Data requirements specifically related to climate change are underlined.

5 Methods to Estimate Changes in Flood Inundation

5.1 Introduction

As we have seen, the extent of the effect of climate-induced changes on inundation mainly depends on changes in flood flows and changes in sea level. We will now look at tools for estimating potential changes in inundation. Although 'off the shelf' flood-modelling software is widely available, the complex techniques described here should only be applied by experienced personnel with a full understanding of fluvial hydraulics.

The flood-related effects of climate-induced changes in sediment transport capacity and adjustments in channel morphology are not covered in detail in this manual. Climate-related sediment movement depends on flood size and frequency, and can be affected by sea-level rise and flood protection works. The implications of sea-level rise are particularly significant because a higher sea level causes a flatter river gradient near the coast. This reduces the velocity of floodwaters in the river channel, encourages silting and aggradation and further restricts river conveyance. As noted in section 2.4.4, changes to channel morphology include both aggradation and degradation, the extent of which can vary in time and space. Such changes are very site specific and will warrant specialised investigations.

5.1.1 Riverine inundation

In situations where flood-plain maps for a range of flood sizes are already available, estimating increased inundation due to increased river flows may be a straightforward process of reinterpreting the return period assigned to each existing inundation map (eg, a 100-year ARI map may become a 50-year ARI map in a particular case, if rules of thumb can be developed, as described in section 4.2.3). In all cases, the event to which the recurrence interval applies must be clearly specified. Usually, probabilities of exceedance relate to the water source of the flood, such as rainfall or river flow. The probability of different levels of inundation and joint probabilities of two or more events can be very complex and will require specialised studies (see the Westport example in chapter 6).

Where flood maps are not available, or are inappropriate for future scenarios, eg, where the shape of inflow flood hydrographs is expected to change significantly, new hydraulic modelling will be necessary.

As discussed in chapter 2, over the short term, inter-decadal climate variations may have a more pronounced effect on inundation than climate trends, and studies of regional flood frequencies in relation to climate patterns (such as the IPO) may be required.

5.1.2 Sea-level rise and storm surge

Coastal riverine communities must prepare for flooding that results from the effects of sea-level rise and storm surge. Predicted sea-level rise due to climate change will cause lower freeboard on coastal flood protection structures, increased inland influence of tides, and a flattening of river slopes in coastal reaches (see the *Coastal Hazards and Climate Change* manual, Ministry for the Environment, 2008b). The reduction of a river's slope reduces the energy of the flood flow, increases the depth of flow and reduces the sediment-transporting capacity of the flow. Any increase in the frequency of floods also increases the chance of floods occurring during adverse tidal conditions. These effects are complex, but the consequences can be calculated using hydrodynamic models. There is also the potential for increased frequency and magnitude of wind set-up and storm surge, which result when high winds and decreased barometric pressure raise the local ocean level.

In calculating potential future sea levels, note that the present sea level may be higher than the level at the time the local datum was established (eg, the Lyttelton mean sea-level datum was set in 1937).

The *Coastal Hazards and Climate Change* manual makes recommendations about the sea-level heights that should be considered in risk assessments. Tables 2.2 and 2.3 on page 21 of that guidance manual should be referred to for more detail on this issue, and for discussion on other coastal hazard drivers such as waves and storm surge.

5.1.3 Top water levels and freeboard

Common to both inland and coastal flooding design is the determination of top water levels (TWLs) and freeboard. TWLs are modelled heights that floodwaters are expected to reach during a flood. Freeboard is an allowance for limited knowledge that could not be included in the modelling, such as limited ground survey data and differences in model assumptions. In a sense, TWLs account for certainties while freeboard accounts for uncertainties. For the purposes of flooding design, climate change must therefore be disaggregated into what is known, which then informs TWL modelling, and what is not known, which is folded into the freeboard allowance. The 'knowns' are simply the products of advanced modelling methods to predict flood flows; the 'unknowns' are the uncertainties stemming from the scenarios and results from preceding modelling efforts.

Freeboard allows for the uncertainties in hydrological predictions, wave action, modelling accuracy, topographical accuracy, final flood defence levels and the quality of the digital elevation models. The increase in flood levels associated with climate change is in addition to freeboard, because the uncertainty freeboard incorporates is not reduced in future climate scenarios. Therefore, freeboard should not contain the 'core' component of climate change impacts, but may be increased to account for climate change uncertainties.

5.2 Screening methods

The simplest screening method is to assess whether land has been inundated in the past. If it has, and no flood remediation works have been carried out, it is clear that increased river flows and sea levels would cause increased inundation of these areas. More precise methods can be used to estimate whether thorough investigations are warranted. However, coastal flooding is particularly difficult to forecast because of the overlapping of two climate change effects: altered river flow and increased sea level. This combination means you need to be particularly cautious when interpreting screening studies in these cases.

The screening methods in this chapter can be used to assess whether a flood hazard is expected to change significantly, and to decide whether further investigations of the extent, depths and velocities of floodwaters are required.

5.2.1 Non-coastal river reaches

The following techniques can be used to roughly assess the effects of river floods on inundation. The techniques assume that climate change-adjusted river flows have been estimated using information derived from the methods described in chapter 4.

Where flood-plain maps for a range of flood sizes are already available, a useful indication of increased inundation due to increased river flows can be made by re-interpreting the return period assigned to each existing inundation map. For example, if the screening methods described in chapter 4 have enabled a return period to be interpreted for flood flows (perhaps the 100-year ARI flood flow has become the 50-year ARI flood flow, as above), the corresponding inundation map would be an appropriate first indication of inundation (ie, the old 100-year ARI map becomes the 50-year ARI map).

Where there are river flow recording stations in an area of interest, existing rating curves can be used to convert future river flows into corresponding river levels. Alternatively, in uniform reaches of the river, information on channel size and roughness can be used to convert river flows into river levels using a flow resistance equation (eg, Mannings equation; see section 6.2). These levels can be propagated across a digital representation of the local terrain using GIS techniques to obtain a rough estimate of the extent of flood inundation using GIS software such as ARCMAP or MapInfo. In ARCMAP (with the Spatial Analyst extension) the cut/fill procedure can be used.

Such methods can provide a quick assessment of whether flood inundation is likely, but they do have several drawbacks, including:

- there is usually no rating data for extreme flood flows
- the volume of floodwater from the river may not be sufficient to fill the flood plain before the river level falls
- the slope of the flood plain may prevent water from ponding on the flood plain
- no indication of out-of channel flood velocity is available.

5.2.2 Coastal river reaches

A raised sea level can be propagated across a digital representation of coastal terrain using GIS techniques to obtain a rough estimate of the extent of inundation, as described above. However, the interaction of river flood flows with varying sea levels is very complex and cannot be estimated using general GIS techniques, and more advanced hydraulic methods must be used.

5.3 Advanced methods

Advanced methods for assessing the depth and extent of inundation vary in their complexity but are all based on fluid hydraulics. Specifically, they vary in the dimensionality with which they represent reality; one-dimensional models approximate river flow along a single line, while three-dimensional models consider flow complexities, both across a channel and to depth.

Climate change is accounted for in each of the following approaches by (i) altering the flow that enters the modelled domain, and, in the case of coastal inundation, (ii) altering the hydraulic conditions under which water flows out of the modelled domain.

5.3.1 One-dimensional (1-D) numerical models

With 1-D models the river and its flood plains are represented by many cross-section slices. Each cross-section has a flat water surface and constant average velocity. Cross-sections are spaced closely enough to capture the main features of the topography. Flow circulation patterns cannot be resolved. Flow paths are determined by the model designer. Buildings cannot be represented in 1-D models and their effects are incorporated by increasing the cross-section roughness. Models of complicated situations take time to set up, but they run quickly on a desktop PC, so that Monte Carlo simulations are possible to help quantify uncertainty. Predicted cross-section flood levels can be interpolated to give a map showing the extent of inundation. Examples of 1-D models include AULOS, MIKE-11 and HEC-RAS.

5.3.2 Two-dimensional (2-D) models

A river and its flood plains are described by three-dimensional digital representations of the ground surface roughness and elevation. Water levels and velocities can vary in all horizontal directions. Plan-form flow circulation patterns are reproduced. At any given point, water velocities are the same at the water surface as at the bed (depth-averaged flow). Flow paths are determined by the ground topography and roughness. Models of complicated situations may take several days to run on a desktop PC. The model results indicate local flood depths and velocities at each node of the digital elevation model. Some models use 1-D equations for the river channel and 2-D equations for the flood plains. Examples of 2-D models are RiCOM, Hydro-2de, River2d and MIKE21.

5.3.3 Three-dimensional (3-D) models

In these models a river and its flood plains are described digitally as for a 2-D model, but calculated water velocities may vary in all three dimensions and secondary currents can be reproduced. These models are more commonly used for specific, detailed investigations, such as the flow around structures. Large or complex models require a supercomputer to reduce the run time. Examples of 3-D models include FLUENT, CFX and FLOW-3D.

5.4 Summary

- Where flood maps exist, screening-level estimates of increased inundation due to increased river flows can be a straightforward process of reinterpreting the return period assigned to each flood inundation map.
- For predicting effects where there is coastal interaction (sea-level rise or storm surge), new hydraulic modelling is necessary.
- Coastal riverine communities are most at risk and require specific hydraulic investigations.
- For non-coastal flood-prone communities, over the short term inter-decadal climate variations may have a more pronounced effect on inundation than climate trend. Studies of regional flood frequencies in relation to applicable climate patterns (eg, IPO) are required.
- A range of methods have been presented which provide estimates of how altered river flow predictions may affect inundation levels. The aim of each method is to convert extreme flow data into an estimate of flood height and spatial extent.
- As with the methods presented in chapters 3 and 4, each method differs in its complexity, data requirements and the reliability of results, as well as user experience needs. All are available to practitioners, subject to their experience.
- As was recommended in chapters 3 and 4, you should consider three factors when deciding how to develop predictions of inundation:
  - what flow, channel and coastal data is available?
  - what accuracy and precision do we need?
  - do we have access to the expertise and computing facilities to undertake the analysis and modelling?
- The summaries in table 7 will help you choose the most appropriate method.

Table 7: Summary of advanced methods for estimating inundations as a guide to selecting the appropriate method

Method (example)	Description	Advantages	Disadvantages	Data and climate change requirements
Screening methods	A general approach based on past, more complex studies.	Easy to use; based on comprehensive analysis.	Limited to inferences from past studies.	Case-by-case considerations.
1-D flow models (HEC-RAS, AULOS, MOUSE, MIKE-Urban, MIKE-11, Infoworks CS)	Produce flow depths and velocities down a 1-D channel.	Low data requirements and relatively rapid computation.	Linear flow paths determined by the modeller; lacks 2- and 3-D flow patterns.	Inflow hydrograph; downstream hydraulic conditions; river and flood-plain cross-sections; roughness coefficients; calibration observations.
2-D flow models (MIKE-21, Infoworks RS, RiCOM, Hydro-2de, River2d)	Produce flow depths and velocities across a complex 2-D terrain.	Simulate variable flow depth and flow velocity laterally.	More computationally intensive than 1-D; lack 3-D flow patterns.	As with 1-D models; digital elevation model of the river and flood plain.
3-D flow models (FLUENT, CFX, FLOW-3D, MIKE 3)	Produce flow depths and velocities around 3-D structures.	Simulate vertical flow patterns.	More computationally intensive than both 1-D and 2-D.	As with 2-D models; 3-D representation of structures.

Note: Data requirements specifically related to climate change are underlined.

6 Case Studies

6.1 Introduction

The tools outlined in chapters 3, 4 and 5 can be linked in different ways to provide estimates of changes in rainfall, flood flows and inundation. This chapter provides a number of case studies that show how these tools have been used in real-world situations. As far as possible, each case study starts by defining the problem being studied, and then gives a technical summary of how the tools were used to answer that question using the three steps of: (1) estimating the change in rainfall, (2) converting rainfall to a flow rate, and (3) estimating the consequent inundation. The aim in each case study is to show the calculated expected change in flood hazard due to climate change.

6.2 Stoney Creek

Stoney Creek, a small stream in Central Otago, passes through an area being sub-divided for residential development. An assessment is needed of the frequency with which the stream would overtop its banks, both under the current climate and under a 2040 climate (which is appropriate to the 50-year design life of the project). There are no stream-flow measurements available and no rain gauges in or close to the catchment.

The three steps in the study are:

1. use HIRDS and the *Climate Change Effects* manual factors to estimate current and future storm rainfalls (section 3.2.1)
2. convert storm rainfalls to flood peaks using the Rational Method (see section 4.2.2)
3. estimate the frequency of inundation using a flow resistance equation (Manning's equation in this case), field inspection and local knowledge.

6.2.1 Step 1: Estimate rainfall

The time of concentration for this two-square-kilometre catchment is estimated as being 20 minutes. Accordingly, 20-minute rainfall intensities are obtained from HIRDS under the current climate.

Rainfall intensities for the 2040 climate are estimated by first using table 1, which gives the percentage increase in rainfall intensity per degree Celsius of warming for a range of storm durations and recurrence intervals. For a 20-minute duration we need to interpolate between the rows of table 1 for 10 minutes and 30 minutes. For consistency with the way this table was created (see the *Climate Change Effects* manual), the interpolation should be logarithmic (although in this case it makes little difference if you use linear interpolation).

If P20 is the percentage increase in rainfall per degree of warming, then the logarithmic interpolation is calculated as:

$$P20 = P10\,[P30/P10]^{(20-10)/(30-10)}$$

For example, with a two-year ARI, P10 = 8 per cent, P30 = 7.2 per cent and so P20 = 7.59 per cent.

The next step in estimating rainfall change is to estimate the amount of warming. From the *Climate Change Effects* manual (table 2.2, Otago, last column) the average warming (across all emission scenarios) is 0.9 degrees Celsius for 2040. This happens to be the same as the average temperature increase for the middle-of-the-road (A1B) scenario in table 2 above. A check of the *Climate Change Effects* manual (figure 2.3, top-left map) shows there are no strong within-regional variations in the projected temperature rise for Otago.

The results of this calculation are given in table 8.

Table 8: Calculated rainfall intensities for the Stoney Creek case study

Average recurrence interval (years)	Intensity for 20-minute duration – current climate (mm/h)	Increase in rainfall for 0.9° C warming (%)	Intensity for 20-minute duration – 2040 climate (mm/h)
2	19.9	6.8	21.3
5	24.0	6.9	25.7
10	30.7	7.0	32.9
20	37.7	7.1	40.4
50	51.9	7.2	55.6
100	68.1	7.2	73.0

In table 8 we have assumed an increase of 0.9 degrees, which is the average of the projected increases given in table 2 for the A1B scenario for 2040. The projected increases for Otago range from 0.2 to 1.3 degrees, depending on which global climate model is used (these numbers are given in brackets in table 2, just after the 0.9°C value for Otago).

To assess the range of possible changes in rainfall, the calculations in table 8 should be repeated using other temperature rises from table 2. We suggest taking the mid-point between the mean and the lower bound for A1B (ie, for Otago, [0.9 + 0.2]/2 = 0.55 degrees), as well as the mid-point between the mean and the upper bound (ie, [0.9 + 1.3]/2 = 1.1 degrees). The extreme ends of the ranges are not used because they are slightly less likely than the central values (see the *Climate Change Effects* manual, section 2.1 and Appendix 3).

6.2.2 Step 2: Convert rainfall to flow

The formula for the Rational Method can be written (see section 4.2.2) as:

$$Q = C\, i\, A / 3.6$$

where:

- Q is an estimate of the peak design discharge in cubic metres per second
- C is the run-off coefficient
- i is the rainfall intensity in millimetres per hour, for a duration equal to the time of concentration of the catchment
- A is the catchment area in square kilometres.

Because the peak design discharge formula depends linearly on the rainfall rate, this method will predict that any percentage increase in rainfall intensity leads to the same percentage increase in peak design discharge, *provided* no other variables change. However, in this case the run-off coefficient, C, was assessed as being dependent on the return period of the event (Ministry of Works and Development, 1978), as well as the physiographic features of the catchment. The results of this calculation using 0.9 degrees Celsius as the temperature change for 2040 are given in the first four columns of table 9.

Table 9: Calculated flood flows for the Stoney Creek case study

Average recurrence interval (years)	Run-off coefficient (dimensionless)	Flood peak for current climate (m^3/s)	Flood peak for 2040 climate (m^3/s)	Water depth for current climate (m)	Water depth for 2040 climate (m)
2	0.45	5.0	5.3	0.46	0.48
5	0.45	6.0	6.4	0.51	0.53
10	0.55	9.4	10.0	0.67	0.70
20	0.55	11.5	12.3	0.76	0.79
50	0.65	18.7	20.1	1.01	1.06
100	0.65	24.6	26.4	1.20	1.25

6.2.3 Step 3: Convert flow to inundation

To assess the impacts of the change in flood peak on inundation in a simple screening study where detailed flood-plain mapping information is not available, the techniques described in section 5.1 are appropriate. In a uniform reach of river, information on channel width and roughness can be used to convert river flows into river levels using Manning's equation or a similar approach. In this example, the channel is approximately 10 metres wide and has a slope of approximately 0.003, so the estimated Manning roughness coefficient is 0.03 (see, for example, Hicks and Mason, 1998, for methods for estimating roughness). The Manning equation for depth of flow in a wide rectangular channel is:

$$D = [Q\ n / (W\ S_f^{1/2})\ ]^{3/5}$$

where:

- Q is flow in cubic metres per second
- W and D are width and depth, respectively, in metres
- S_f is the friction slope
- n is the Manning roughness coefficient.

Applying this equation to our case study, we obtain the results shown in the last two columns of table 9. The estimated water depths at the flood peaks have increased by between 0.02 metres and 0.05 metres, depending on flood magnitude. When using a screening technique, such a small change would not be considered significant in most practical settings. The uncertainty of these estimates should be assessed by varying the assumed and estimated input values for slope, width, roughness coefficient and peak flow within likely bounds; for example, the roughness coefficient can vary significantly with flow. If a larger change in depth had been predicted, then its significance for inundation could be investigated through a site visit to gather evidence on historical flood occurrence at the site, and by visually assessing or surveying the area that could be flooded if the predicted water levels were to occur.

6.2.4 Notes

This case study considered only one method for assessing potential climate change impacts, but it is good practice to use several different methods and compare the results where information is limited. Other sources of information would include national or regional (eg, local regional council) studies of flood frequency to supplement the Rational Method, and field inspection/surveying of the stream to supplement local knowledge of flood frequency. To compare the performance of the Rational Method in New Zealand it was checked against two other methods: TM61 and Regional Flood Frequency (see McKerchar and Macky, 2001). Note that estimating flood depths using Manning's equation with a single roughness coefficient at widely varying flows is a major simplification and would only be appropriate for screening.

6.3 The Hutt River case study

In the early 1990s, concern was expressed that climate change could increase the risk of Lower Hutt being inundated as a result of overtopping of the stopbanks downstream of the Taita Gorge (Leong, et al, 1992). This study used the knowledge available at the time to form a preliminary assessment of the likelihood of this happening. The study is an example of a 'screening assessment', since the rainfall scenarios used were simple scaled versions of measured events (similar to the approach outlined in section 3.3.2). No attempt was made to do sophisticated climate modelling, partly because of the state of climate modelling at the time, but also because there was no point doing a lot of work on rainfall estimates if the risk of inundation could be shown to be low.

6.3.1 Step 1: Estimate rainfall

The first step was to assess what rainfall data was available for the catchment. This data had to be at hourly time steps to provide sufficient detail to enable an adequate simulation of river flows. It was impractical to use all the rainfall data, so the values associated with the largest flood each year were extracted. The data also needed to provide a realistic picture of the spatial variation of rainfall over the catchment to enable the known rapid increase in rainfall across the catchment to be taken into account. (The rainfall varies from less than 1400 millimetres per year in the lower reaches to more than 6000 millimetres per year in the headwaters.) A table of the available automatic rainfall recorder records was compiled for the period 1971 to 1989.

In 1981, there was a substantial expansion in the network of automatic recorders, with up to 13 recorders in operation; before 1981, there were only four or fewer gauges operating. The increase in the number of gauges meant that in subsequent years separate spatial patterns could be made for each storm event. However, before 1981, all events had to use the same spatial rainfall pattern based on the network of daily and storage gauges operating in the catchment. This difference affected the reliability of the results obtained.

6.3.2 Step 2: Convert rainfall to flow

To determine the likelihood of inundation of Lower Hutt, a rainfall-to-flow model was built for the catchment to convert rainfall to river flow. The model was spatially distributed and enabled different amounts of rainfall to be used as input to allow spatial variation of rainfall to be taken into account. Thus, the parts of the model representing the headwaters had a lot more rainfall as input than areas near the catchment outlet.

Data for the 1986 storm was used to calibrate the model (by adjusting the coefficients from the run-off model). The calibrated model was then used to generate the floods for the years 1971–1985 and 1987–1989. The model results for each year were compared to the measured river flows, and conclusions were drawn about the quality of the model simulations. For simulations of floods before the expansion of the rainfall network in 1981, the flood peaks were generally underestimated. However, with the expansion of the rainfall network and the use of different spatial rainfall patterns for each event, good check results were obtained. The flood peak flows were overestimated by 1 per cent and their standard error of estimate, a measure of the random variation about the simulated value, was ± 9 per cent.

Every rainfall amount for each annual flood event was then successively increased by 5 per cent, 10 per cent and 15 per cent. The percentage increases in the rainfalls were chosen in order to bracket the increases likely to occur as a result of climate change and to provide a range of potential risk scenarios. The modified rainfalls were then run through the model to form corresponding climate change-affected flows. The peak flows were extracted from the data and used in an ‘extreme value’ analysis[12] to derive the changes in the design flows used for sizing the stopbanks along the Hutt River. The results showed that:

- a 5 per cent increase in rainfall would lead to an increase of 6.7 per cent in all flood flows
- a 10 per cent rainfall increase would lead to an increase of 13.4 per cent in flows
- a 15 per cent rainfall increase would lead to an increase of 20.3 per cent in flows.

The slightly greater proportional increases in flow arise from the fact that the catchment has a limited amount of natural storage, and so as the rainfall increases, proportionally more of it enters the river channel and contributes to the river flow.

6.3.3 Step 3: Convert flow to inundation

The final step in the investigation was to turn the increased flows into water levels and compare the new levels with the heights of the stopbanks. For sites on rivers with established sets of water-level and flow measurements, such as at Taita on the Hutt River, this can be easily done by using the ‘rating curve’. Note that a more complex inundation analysis would probably be necessary if the water was predicted to overtop the stopbanks.

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12 A statistical procedure that is used to take a series of annual peak flood flows and derive the magnitude of events expected to occur on average, say, once every 50 years.

6.3.4 Notes

The Hutt River study, which assumed only that rainfall would increase with climate change, concluded that:

- the model could accurately and reliably estimate flows in the Hutt River
- spatial rainfall patterns for each storm give better results than a standard pattern based on storage gauges
- rainfall increases of 5, 10 and 15 per cent led to flow increases of 6.7, 13.4 and 20.3 per cent, respectively. The 15 per cent increase scenario would represent a mid-range estimate for the rainfall changes expected by 2100
- the increases in flow will decrease the level of flood protection provided for Lower Hutt. For example, for the 15 per cent increase in rainfall scenario the current 100-year flood will become a 33-year flood in the future
- it would be unlikely that present stopbanks at Taita would be undermined by the 11 per cent increase in channel width that would result from the increase in flood flows
- since this work was undertaken, significant effort has been put into understanding the flood risk for the Hutt Valley. This has culminated in the development of the Hutt River flood management plan.[13]

The study was limited by the technology and tools available in the 1990s. If the study were repeated today a number of new methods, such as the Virtual Climate Network described by Tait et al (2006), could be used to provide better prediction of rainfall, flood flows and flood levels. The percentage increases in daily rainfall from table 1 could be applied to the historical data of Tait et al to produce rainfall for a future climate scenario. However, this would still need to be reconciled with any projected impacts of climate change on mean and seasonal rainfall.

6.4 The Westport case study

The aim of this 2005 study was to assess the extent, depth and likely locations of areas that could be inundated in the coastal town of Westport as a result of the Buller River flooding. The Buller River has inundated Westport in the past, so this case study is not a case of 'Will it occur?' but rather 'How bad might it be?' The Westport case is complex because flooding can be exacerbated by sea conditions (ie, the state of the tide and onshore storm surge). Consequently, a simple screening approach, while a necessary preliminary step, was not expected to provide the complete answer.

[13] See http://www.gw.govt.nz/hutt-river-flood-plain-management-plan/

6.4.1 Preliminary screening

The first step in the study was to carry out a preliminary screening, as follows.

1. A weather model was used to produce rainfall for current conditions because there were not enough representative rainfall gauges in the catchment. The model used was RAMS (see Pielke et al, 1992) run at a five-kilometre resolution.
2. The rainfall was used in a rainfall-to-flow model to produce flows in the Buller River, and the flow model was adjusted to obtain a satisfactory comparison with measurements.
3. Rainfalls were then increased using a percentage increase per degree Celsius, in line with the Ministry for the Environment guidelines at the time, *Preparing for Climate Change: A Guide for Local Government in New Zealand* (Ministry for the Environment, 2004b, table 7). New flood flows were generated from the new rainfalls.
4. The flood flows were then fed into a hydraulic model of Westport (with raised sea levels from the then current Ministry for the Environment guidelines) to generate the areas that would be inundated and the likely depths of inundation.

Based on the results from this screening, it was clear that significant areas of Westport could be at risk of inundation if rainfall amounts increased. Accordingly, a more sophisticated analysis was warranted.

6.4.2 Advanced analysis

A new analysis was undertaken, working through the three steps for estimating changes in rainfall, converting rainfall to flood flows, and then converting those flood flows to flood inundation. Details are given in Gray et al, 2005.

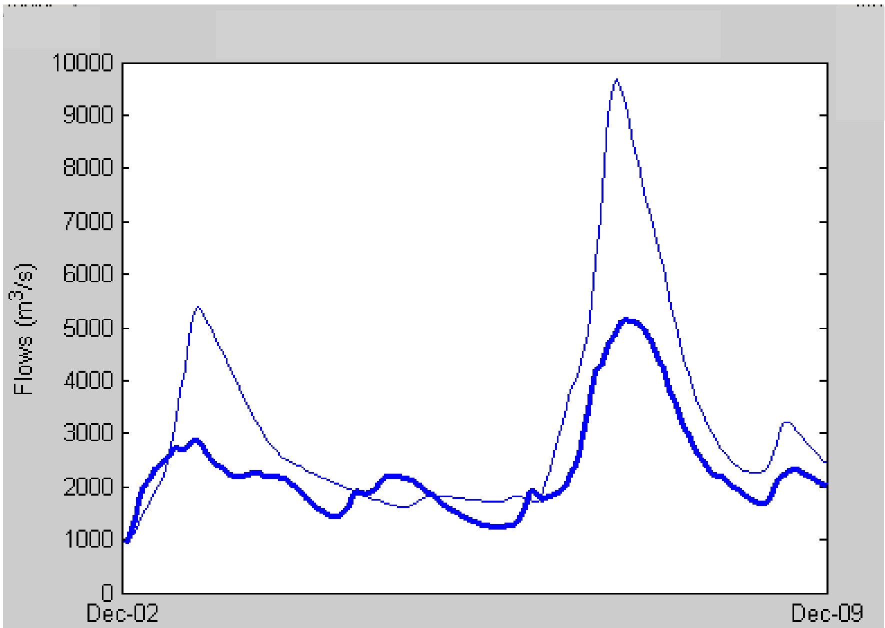
Step 1: Estimate rainfall

What changes would occur to the spatial rainfall distribution as a result of climate change? A range of climate change scenarios were considered to allow an assessment of the probable risks associated with the choice of a particular climate change scenario. Three historical events (12 November 1999, 17/18 August 2000 and 8 December 2001) were selected for study. In the detailed analysis, the simple scaling used in the screening process was replaced by modelled rainfalls for three possible future climates, with air temperature increased by 0.5, 1.0 and 2.7 degrees Celsius. The rainfall increased by 3, 5 and 33 per cent on average for the three temperature scenarios, through both an increase in the water holding capacity of the air as well as through changes in the intensity of the storms. The advantage of this approach over the simple scaling was that changes in the locations of areas of intense rainfall could be taken into account in generating the corresponding flood flows.

Step 2: Convert rainfall to flow

Each rainfall scenario was run through the rainfall-to-flow model of the catchment to derive the whole input hydrograph at an hourly time step. The TopNet model was used in this study. Figure 9 shows for the mid-high 2080 scenario there is a significant projected increase in peak flow on the Buller River at Te Kuha. The example shown in figure 9 compares recorded data for a flood in December 2001 (a river flood peak of this size occurs about once every four years at this site) against modelled river flow for the mid-high scenario in 2080. The modelled flow was produced using a TopNet model, which had been verified against recorded data (Gray et al, 2005, figure 8). There is a large change in projected flood peak magnitude for this example.

Figure 9: Comparison of flood hydrographs for the Buller River at Te Kuha for the base case (thick line) and mid-high 2080 scenario (thin line)



Step 3: Convert flood flow to inundation

The various flood hydrographs were then fed into the hydraulic model, built using the Hydro-2de system (see Beffa and Connell, 2001), of the Buller River and the low-lying areas on the true right bank, where Westport is situated. Hydro-2de is a two-dimensional flood inundation model (see section 5.3.2). Using the morphology of the river channel and the topography of the land, the model calculated the water levels and velocities on the river flood plain, which includes Westport. The flow of water in the town was analysed with respect to its location and depth, and maps were produced that showed the inundation hazard.

Inundation modelling of Westport is complicated by the fact that inundation can occur as a result of a river flood, a high sea level brought about by a high tide or an onshore wind, or a combination of these factors. For the Westport case an annual exceedance probability (AEP) of inundation was pre-set at the design value of 0.02, corresponding to the 50-year average recurrence interval standard for floor levels from the Building Act 2004. A joint probability distribution was used 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. 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 this data a graph that shows the percentage of Westport that would be inundated for different AEP values could be constructed.

Once the base case and the relevant graphs had been produced for the selected AEP, investigating the effect of climate change impacts on rainfall amounted to 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 was then estimated.

The results of these calculations are summarised in table 10. In this case the climate change scenarios included different target years (2030s and 2080s), as well as an assessment of the effects of uncertainty in climate change projections by looking at both a mid-low and a mid-high scenario. Note that the climate scenarios used here were based on the 2004 *Climate Change Effects* manual, which has since been updated.

Table 10: Summary of 2 per cent AEP flood inundation results for Westport

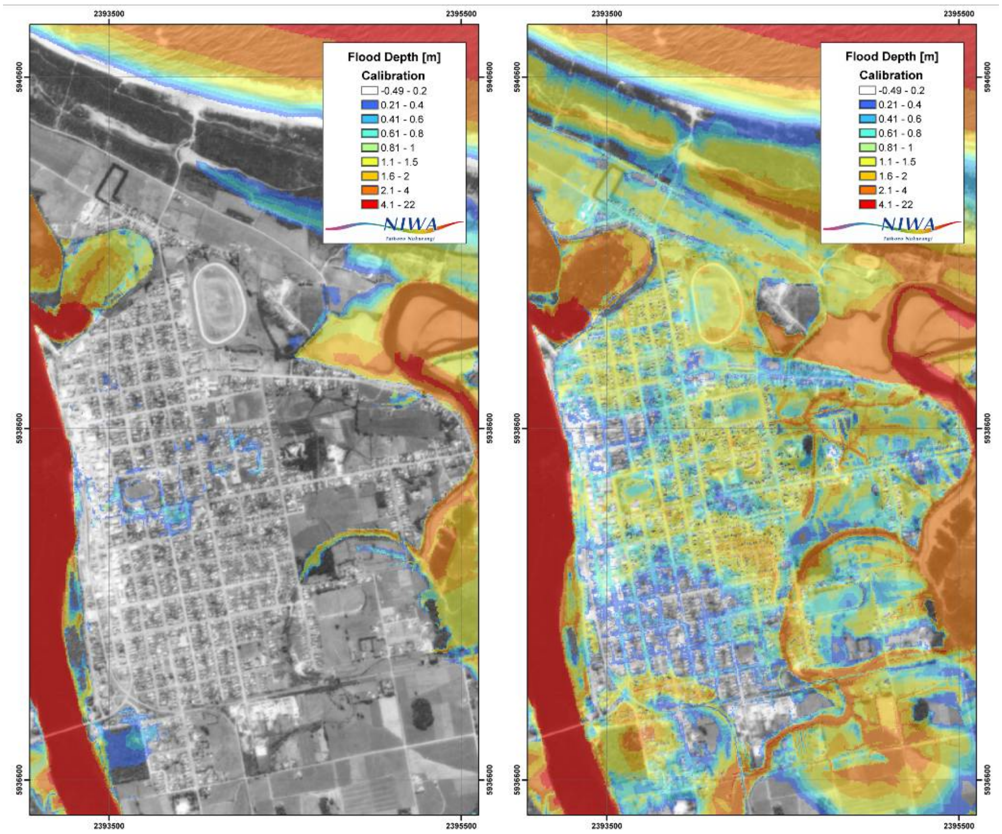
Scenario	Temperature rise °C	Rainfall enhancement %	Flow enhancement %	Peak flow (m^3/s)	Water-level rise (m)	Peak sea level (m)	Inundation extent: % Westport
Base case	0	0	0	8,785	0	1.24	4.3
Mid-low 2030s	0.5	3	3.9	9,180	0.065	1.27	12.8
Mid-high 2030s	1	5	9.7	9,692	0.15	1.35	29.6
Mid-low 2080s							
Mid-high 2080s	2.7	33	37.5	12,198	0.49	1.69	79.1

Source: Gray et al, 2005

Table 10 indicates that under the base case (current climate, flood protection works as at 2005), 4.3 per cent of Westport has a 1-in-50 chance of being inundated each year. Under the mid-low 2030s climate scenario, 12.8 per cent of Westport has a 1-in-50 chance of being inundated each year; this assumes that flood protection works and other relevant hydraulic features do not change. Similar interpretations can be made for the other rows in the table. There are many combinations of river flood and sea level that could cause the same flooding: the combination shown in each row of table 10 is the most likely of the many river–sea-level combinations that can cause the same inundation.

The potential impact of the mid-high scenario for the 2080s is graphically illustrated in figure 10.

Figure 10: 1-in-50-year inundation areas in downtown Westport, with the present climate (left) and a mid-high scenario for 2080 (right)



Note: Both scenarios assume flood protection works as at 2005.

6.4.3 Notes

The Westport study required a number of simplifying assumptions to make it tractable.

- The effect of climate change on the frequency of extreme events was ignored, even though extreme events can be expected to occur more frequently.
- The relative humidity of the initial conditions has been assumed to be unchanged from the base case. This limits the potential of the atmosphere to hold water and could lead to an underestimation of rainfall.
- The effects of climate change on land use were ignored.
- The effects of changes in temperature on freezing levels, and hence snow melt and soil permeability, were ignored.
- It was assumed that river beds would scour in a predictable manner, and so random factors such as a debris jam on the bridge were ignored.
- The rise in river-bed level near the coast that would accompany a general sea-level rise (see section 5.1) was not included.

These factors are in addition to the uncertainties inherent in the climate change-induced rainfall scenarios, related to both the model and the input data, and to natural changes in things such as the El Niño / La Niña pattern.

Despite these limitations, the study has shown that climate change can be expected to exacerbate the inundation of parts of Westport. The study provides guidance on how potential future inundation can be reduced by showing where inundation is likely to occur and where it will be greatest. Serious consideration must be given to how best to reduce the effects of the increasing flooding that could occur in future due to the climate-induced changes in river flooding and sea-level rise. The consequences of a mean sea-level rise of at least 0.8 metres (as recommended in the *Coastal Hazards and Climate Change* manual, Ministry for the Environment, 2008b) have not been investigated.

6.5 Leith Lindsay's flood protection scheme, North Dunedin

The Leith Stream and its tributary, Lindsay's Creek, pose a flood hazard in the reaches that flow through the urban area of North Dunedin. Damaging floods occurred in 1877, 1923 and 1929, and since then flood channel enhancement and flood protection works have been undertaken to reduce potential flood damage. The Otago Regional Council has been undertaking a programme of reviewing and enhancing the flood protection works, particularly in the vicinity of the iconic river reaches in the grounds of Otago University.

To allow for climate change effects, a study was undertaken to look at the possible changes in flood risk as a consequence of temperature increases. The approach was to assemble records of storm rainfalls and flood flows for recent events recorded over the Leith catchment. A rainfall-losses/run-off routing model, calibrated for recent storms, was used to assess the expected increase in peak flood flow resulting from expected increases in design storm rainfall intensities. Finally, both laboratory and mathematical hydraulic models were used to assess an expected increase in water levels and therefore the increase in flood hazard.

6.5.1 Estimate rainfall

The study used expected annual mean temperature changes by the 2080s in the range 0.4 to 3.1 degrees, as recommended for the Otago area in the 2004 *Climate Change Effects* manual, to increase design storm rainfall intensities. These changes suggested, for example, that 12-hour duration, 1-in-100 annual exceedance probability (AEP) rainfall intensities should be expected to increase by between 3 and 21 per cent.

Note that the revision of the 2004 manual (published in 2008) altered the expected temperature change for Otago by 2090 to 2.0 degrees average and a range of 0.8 to 4.6 degrees, based on the six SRES scenarios in table 3. It also suggested the 12-hour duration, 1-in-100 AEP rainfall intensities should be expected to increase by between 6 and 37 per cent, with an average value of 16 per cent.

6.5.2 Convert rainfall to flow

The study used the upper limit percentage increases in storm rainfalls (21 per cent) with a calibrated rainfall-losses/run-off routing model for the Leith Lindsay catchment to estimate that the 1-in-100 AEP flood peak for the Leith Stream above the tidal limits could increase from the present-day value of 171 cubic metres per second to 200 cubic metres per second – a 17 per cent increase. This is in contrast to the Westport example, where smaller percentage increases in rainfall led to larger percentage increases in flow.

6.5.3 Inundation aspects of the study

The design flood estimates were used with laboratory and mathematical models to assess the performance of the proposed works. The results showed the scheme would perform safely during floods of increased magnitude. Accordingly, it was concluded the proposed scheme would perform safely under the extreme and long-range climate change scenarios developed using the Ministry for the Environment's (2004a) guidelines.

6.5.4 Notes

In the context of the Leith flood protection works, the council has recognised the flood magnitude for a given standard of protection is expected to increase, but also that there is considerable uncertainty about the magnitude of the increase. The works have been designed to allow for enhancement to maintain the protection standard, if that proves necessary in the future. The council's strategy to allow for climate change was one of a number of concerns about the scheme that were the subject of an unsuccessful appeal to the Environment Court (*Gillies and Johnstone v Otago Regional Council 2008*).[14] In summing up the reasons for dismissing the appeal, the Court concluded that if the level of protection is considered inadequate in the future, there is the potential for further works to be undertaken.

[14] *Gillies and Johnstone v Otago Regional Council*, unreported (23 May 2008) ENVC, Christchurch, C 060/08.

7 Issues for Engineering Design

Incorporating climate change estimates into flow estimation can reveal various issues pertinent to engineering design. Some of these issues are discussed here.

7.1 Appropriate use of historical records

Gradual shifts in climate and flood risk have important implications for engineering design. An essential element of a design flood study is the prediction of the future risk of extreme floods. As the climate changes, however, historical observations will be less and less indicative of future events. In other words, future flood statistics will diverge from the past's. Statistical flood data analysis methods, and their applications, will need to change to reflect this (see Milly et al, 2008).

This is not to say that historical data is useless. It will remain invaluable as a means to calibrate hydrological models and to observe how flooding is indeed changing under climate change, as well as being useful in certain screening and advanced techniques discussed in this manual. Furthermore, because flood risk will change as climate changes, it will be necessary to identify the future time period for which a design is required and then determine the flood risk for that period.

For example, living with climate change means it is no longer meaningful to simply define a single value for the 50-year average recurrence interval (ARI) flood peak for a river. Instead, there will be several 50-year ARI flood peaks defined for time windows of practical interest (eg, for the 'current' climate, for a 'short' lifetime 2010–2040, and for a 'long' lifetime 2010–2090). Design studies will need to consider the lifetime of the structure being planned and select the appropriate flood peak that goes with that design lifetime. It is worth noting here that many assets still in use today have far outlived their design lifetimes.

For the quantitative estimation of flow, information is available for changes in seasonal rainfall, rainfall intensity, temperature, sea level and evapotranspiration. At the time of producing this manual, there are only qualitative assessments of the impacts of climate change on storminess, including impacts on storm surge and waves. This is an active area of research, and more quantitative information is expected to be released over the next few years.

7.2 Reporting the estimates

It is important when giving rainfall, flow and inundation estimates to comment clearly on what has been considered and what was beyond the scope of the project. This includes the scenarios chosen, the assumptions made, and the basis for the choices of parameters chosen in the modelling. This is particularly true when providing estimates of freeboard. The main impacts of climate change (eg, through rainfall changes) should be incorporated in the main flow estimation. Freeboard should then allow for some of the uncertainties in these climate change estimates, especially where they are likely to be greater (eg, with higher sea-level rise).

7.3 Dealing with uncertainty in estimates

There may be significant uncertainties in the estimates of rainfall, flow and inundation. These arise through uncertainties in rainfall inputs, parameter choices in modelling, errors in modelling, and assumptions about antecedent conditions. The errors from these uncertainties could be as large as the expected climate change impacts. Where possible, the error bounds of the calculations should be estimated. However, because climate change is likely to have a significant impact on flow, and much of that impact is able to be estimated, these broader uncertainties should not prevent efforts to include climate change in flow estimation. More confidence in the estimates can be given through replication. In other words, uncertainty can be reduced if the results from two screening methods and a more complex physical modelling method for the same catchment all point in the same direction.

7.4 Professional judgement

Professional judgement will often form an important part of the process of flow estimation. This judgement could be applied to the emission scenario choice, the choice of modelling parameters, the interpretation of past data, and in estimating confidence in the final results. Indeed, judgement may be most important when considering issues that have yet to be quantified, such as the effect of climate change on antecedent conditions, snow, aggradation, erosion and coastal outflow conditions.

7.5 Scenario choice

The estimates of rainfall, flow and inundation developed by the procedures outlined in this manual are likely to be used as the primary input into the risk assessment of future flooding. To help in this risk assessment process it will be necessary to choose a number of climate change scenarios to span the future possibilities. The *Climate Change Effects* manual suggests choosing a mid-low and a mid-high scenario. Given the current global emissions, and the likely emission paths, it may be more appropriate to choose a 'middle of the pack' emissions scenario such as A1B to represent a mid-low estimate, and a higher scenario such as A1FI to represent a mid-high estimate. These scenarios correspond to temperature changes for New Zealand of around 2ºC and 3ºC by 2100 respectively.

To help in your risk assessment you need to choose a number of climate change scenarios to span the possible future possibilities. For example, you might examine the consequences of a base level of temperature rise of 2ºC by 2100 but also consider the consequences of at least 3ºC rise.

7.6 Research

Significant climate change research is being undertaken at the time of writing, targeted at providing information that will aid flow estimation and engineering design. This includes detailed information on changes to:

- extremes in temperature, wind and rainfall
- offshore waves and storm surge
- storm paths and intensity
- snowfall and accumulation.

Much of this research is due to provide the first results within the next few years (2010–2013). Planners and engineers will need to be alert to the arrival of this information and the implications it has for their work. It is also clear that the science will continue to provide new information. Decisions will need to be made now, on the best information available, but where possible these decisions should not lock in options that minimise the ability to adapt at a later date.

Glossary

Analogue	a method of forecasting weather by identifying climate records for places or times where there is a similar climate to that predicted for the place of interest. For example, if climate projections indicated stronger westerlies across New Zealand in future, then possible analogues of future South Island rainfall patterns could be drawn from a historical sample of warmer and stronger westerly days of the past record.
Average recurrence interval (ARI)	same as *return period*.
Catchment	the land area drained by a river network.
Climate	the 'average weather' over a period of time, ranging from months to thousands or millions of years. The classic period for calculating a 'climate normal' is 30 years.
Climate change	a statistically significant variation in either the mean state of the climate or its variability, persisting for an extended period (typically decades or longer).
Climate model	a numerical representation (typically a set of equations programmed into a computer) of the climate system. The most complex and complete climate models are known as *general circulation models*.
Climate projection	a potential future evolution of the climate in response to an emission or concentration *scenario* of *greenhouse gases* and aerosols. A climate projection is often based on a simulation by a *climate model*.
Climate variability	variations of the *climate* (eg, of the mean state, standard deviations and extremes) on all temporal and spatial scales beyond those of individual weather events.
CLIMPACTS	an integrated assessment model for conducting analyses of the sensitivity of New Zealand's managed environments to climate variability and change. Both spatial and temporal variations can be examined. For further information, see: http://www.climsystems.com/site/home/ (3 April 2008).
Consequence (or impact)	the outcome (of an event), often expressed qualitatively in terms of the level of impact. Consequences can be measured in terms of economic, social, environmental or other impacts.
Design flood	the flood that is expected to result from a hypothetical storm of specific storm duration and recurrence interval. For example, a 25-year/24-hour design storm means that the storm duration is 24 hours and the recurrence interval is 25 years. The total rainfall depth and its time distribution are two elements characterising a design storm. The total rainfall depth of a design storm is usually estimated by hydrological frequency analysis using historic rainfall records. For areas without

	historic rainfall records, design storm depths are often estimated using design storm data from adjacent sites.
Digital elevation model	a topographic map expressed as elevations on a regular grid and available in electronic form.
Downscaling	deriving estimates of local climate elements (eg, temperature, wind, rainfall) from the coarse resolution output of *global climate models*. Statistical downscaling uses present relationships between large-scale climate variables and local variables. Nested regional climate modelling uses the coarse resolution output from a global climate model to drive a high-resolution *regional climate model*.
El Niño	a significant increase in sea surface temperature over the eastern and central equatorial Pacific that occurs at irregular intervals, generally ranging between two and seven years. Associated changes occur in atmospheric pressure patterns and wind systems across the Pacific. These can lead to changes in seasonal rainfall and temperature in parts of Australia and New Zealand.
El Niño–Southern Oscillation (ENSO)	a term coined in the early 1980s in recognition of the intimate link between *El Niño* events and the *Southern Oscillation*, which, prior to the late 1960s, had been viewed as two unrelated phenomena. The interactive global ocean–atmosphere cycle comprising El Niño and La Niña is often called the 'ENSO cycle'.
Evapotranspiration	the combined process of evaporation from the Earth's surface and transpiration from vegetation.
Event	in this context, an incident that is induced or significantly exacerbated by climate change and that occurs in a particular place during a particular interval of time. Examples of events are floods, very high winds and droughts.
Extra-tropics	the mid-latitudes (~ 30°S–50°S).
Extreme weather event	an event that is rare at a particular place. 'Rare' would normally be defined as being as rare as, or rarer than, the 10th or 90th percentile.
Flood run-off	the amount of rainfall that runs into rivers.
Freeboard	an allowance made to incorporate uncertainty in the water level due to one or more extreme meteorological, fluvial or oceanographic effects. Quoted design flood levels should include this safety factor.
General circulation model (GCM)	a global, three-dimensional computer model of the climate system, which can be used to simulate the general circulation and climate of the atmosphere and ocean, and particularly human-induced climate change. General circulation models are highly complex and represent the effects of such factors as the reflective and absorptive properties of atmospheric water vapour, greenhouse gas concentrations, clouds, annual and daily solar heating, ocean temperatures, and ice boundaries. General

	circulation models include global representations of the atmosphere, oceans and land surface.
Global climate model (GCM)	the same as a *general circulation model*.
Global warming	generally used to refer to the rise in the Earth's surface temperature predicted to occur as a result of increased emissions of *greenhouse gases*.
Greenhouse effect	an increase in the temperature of the Earth's surface and the lowest 8 kilometres or so of the atmosphere, caused by the trapping of heat by *greenhouse gases*. Naturally occurring greenhouse gases cause a greenhouse effect at the Earth's surface of about 30 degrees Celsius. Further temperature increases caused by anthropogenic emissions are termed the 'enhanced greenhouse effect'.
Greenhouse gases	gases in the Earth's atmosphere that absorb and re-emit infra-red (heat) radiation. Many greenhouse gases occur naturally in the atmosphere, but concentrations of some (such as carbon dioxide, methane and nitrous oxide) have increased above natural levels because of anthropogenic emissions.
Hazard	a source of potential harm to people or property. Examples are erosion and inundation.
High Intensity Rainfall Design System (HIRDS)	a software package that estimates the frequency of extreme rainfall at a large number of sites across New Zealand. HIRDS is currently being updated (March 2010), with a new feature being added that will enable the climate change rainfall adjustment factor to be included automatically.
Hydrograph	a chart showing how river flow changes with time. Inundation maps are based on a specific or implicit flood hydrograph.
Hyetograph	a graphical representation of the distribution of rainfall over time.
Interdecadal Pacific Oscillation (IPO)	a long time-scale oscillation in the Pacific Ocean–atmosphere system that shifts climate every one to three decades. The IPO has positive (warm) and negative (cool) phases. Positive phases tend to be associated with an increase in *El Niño* events and negative phases with an increase in *La Niña* events.
Intergovernmental Panel on Climate Change (IPCC)	the body established in 1988 by the World Meteorological Organization and the United Nations Environment Programme to objectively assess scientific, technical and socio-economic information relevant to understanding the scientific basis of the risk of human-induced climate change, its potential impacts and options for adaptation and mitigation.
La Niña	a significant decrease in sea surface temperature in the central and eastern equatorial Pacific that occurs at irregular intervals, generally ranging between two and seven years. La Niña is the cool counterpart to the *El Niño* warm event, and its spatial and temporal evolution in the equatorial Pacific is, to a considerable extent, the mirror image of El Niño. Like El Niño, there are

	associated changes in atmospheric pressures and wind systems across the Pacific, and related changes can occur in temperature and rainfall in parts of Australia and New Zealand.
Likelihood	the probability or chance of something happening (can be a qualitative or quantitative measure).
Mesoscale weather model	a numerical weather prediction model designed to simulate phenomena with horizontal scales between a few kilometres and several hundred kilometres. These include thunderstorms, squall lines, fronts, cyclone precipitation bands, and topographically generated weather systems such as mountain lee waves and sea breezes.
Monte Carlo	a technique that uses a large number of simulations which are run using random quantities for uncertain variables to determine the sensitivity associated with particular variables and to find which outcomes are most likely.
Natural variability	non-anthropogenic climate variability that may be irregular or quasi-cyclic. The *El Niño–Southern Oscillation* is probably the best-known example of a natural oscillation of the climate system, but there are many others. Changes caused by volcanic eruptions and solar variations can also be considered natural.
Precipitation	rainfall, plus any contributions from snow (or other frozen forms). It is standard practice for climate models to further distinguish between convective and large-scale rainfall and/or snowfall.
Rating curve	a relationship between river water levels and the corresponding river flows at a specific location.
Regional climate model (RCM)	a *climate model* that is run at high resolution over a 'region' (eg, the eastern part of Australia, Tasman Sea plus New Zealand) to describe climate at the regional scale. RCMs are typically driven with data from *global climate models,* which run at lower resolution and therefore do not accurately simulate, for example, the effects of the Southern Alps on New Zealand's climate.
Return period	the average time between repetition of extreme weather events, such as heavy rainfall or flooding, in a stationary climate (that is, a climate without global warming or other trends). By definition, a 50-year return period event has one chance in 50 of occurring in any one year. In the case of rainfall, a return period is always related to a specific duration (eg, a 50-year return period of 24-hour extreme rainfall).
Risk	the concept of the likely loss or gain from an event that may impact upon people or the things they value. Risk is measured in terms of consequence and likelihood. Climate change is likely to exacerbate flooding risk.
Run-off	flow per unit catchment area, expressed as a depth for comparison with rainfall data.

Scenario	a plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about key driving forces.
Screening assessment	an initial risk assessment that involves identifying current sensitivity to climate and possible future sensitivity to climate change, and the likely duration and extent of effects that may arise as a consequence of climate change.
Southern Oscillation	a multi-year, low-latitude seesaw in sea-level pressure, with one pole in the eastern Pacific and the other in the western Pacific / Indian Ocean region. This pressure seesaw is associated with a global pattern of atmospheric anomalies in circulation, temperature, and precipitation. Its opposite extremes are the *El Niño* and *La Niña* events.
Southern Oscillation Index (SOI)	an index calculated from *anomalies* in the pressure difference between Tahiti and Darwin. Low negative values of this index correspond to *El Niño* conditions, and high positive SOI values coincide with *La Niña* episodes.
SRES scenarios	a set of *greenhouse gas* and aerosol emissions *scenarios* developed in 2000 by Working Group III of the IPCC and used, among other things, as a basis for the climate projections in the IPCC's Third Assessment Report.
Storm surge	the excess above the sea level expected from tidal variation alone at a given time and place. The temporary increase in the height of the sea is caused by extreme meteorological conditions such as low atmospheric pressure and/or strong winds.
Stochastic model	a tool for estimating probability distributions of potential outcomes by allowing for random variation in one or more inputs over time. The random variation is usually based on fluctuations observed in historical data for a selected period using standard time-series techniques. Distributions of potential outcomes are derived from a large number of simulations (stochastic projections) which reflect the random variation in the input(s).
Time-series	a collection of measurements (eg, rainfall), arranged in order of time of occurrence.
Weather generator	a computer programme that produces multiple time-series of numbers with statistical properties that resemble those of historical weather records. The most common weather generators produce outputs representing daily time-series of maximum and minimum temperature, rainfall and solar radiation. The numbers preserve observed characteristics such as persistence of temperature (eg, one hot day is often followed by another), as well as inter-relationships (eg, wet days tend to have lower solar radiation and lower maximum temperature, but higher minimum temperature).

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