# Flood Risk Under Climate Change:

## A framework for assessing the impacts of climate change on river flow and floods, using dynamically-downscaled climate scenarios

### A Case Study for the Uawa (East Cape) and Waihou (Northland) catchments

**NIWA Client Report: CHC2010-033**
**March 2010**

**NIWA Project: SLCC095**

# Flood Risk Under Climate Change

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# Executive Summary

Increasingly complex information is becoming available on likely future changes in New Zealand's climate. The challenge for hydrologists is to use this information to make predictions about changes to water resources and water hazards. This report describes research carried out under the MAF initiative 'Sustainable Land Management Mitigation and Adaptation to Climate Change'. The project developed a framework to use dynamically-downscaled climate scenarios, together with precipitation and hydrological modelling, to predict changes in frequency and magnitude of floods under climate change. The project is intended as a pilot study to design and test the framework for use in New Zealand. Results are presented from two case study catchments: the Uawa River which flows into Tolaga Bay north of Gisborne, and the Waihou River in Northland.

The framework is designed to bring together climate scenarios, rainfall models and hydrological models which simulate as closely as possible the physical processes occurring in the catchment. NIWA's Regional Climate Model (RCM) provides climate simulations (precipitation and temperature) at daily timescales and grid resolution of 30km, for both current climate (1970-2000) and for IPCC climate scenarios A2 and B2 (2070-2100). The framework first uses measured rainfall data to correct any persistent biases in the RCM. The second step extrapolates from the 30 years of predicted climate data, to more extreme rainfall events, using precipitation modelling. This uses the spatial and temporal characteristics of the 30-year rainfall to create 1000-year periods of 'simulated rainfall'. The third step uses these rainfall series (30-year and 1000-year) to drive a hydrological model, which simulates river flow. Testing was performed on the hydrological model to ensure consistency with field data from the catchment. Flood frequency curves were constructed directly from the model output: this technique of 'continuous simulation' directly incorporates effects such as rainstorms occurring when the catchment is already saturated. The 30-year data gives more confident predictions for low return period flood events; the 1000-year data gives predictions for extreme events, but with greater uncertainty.

During this 1-year study, the framework was successfully implemented and trialled at the two case-study catchments. Recommendations for further development of the framework are also given. Results for these two catchments showed similar predictions: annual and seasonal rainfall totals were reduced but daily rainfall extremes and hence flood magnitudes were increased. In Uawa catchment, change in annual rainfall total between 1970-2000 and 2070-2100 was estimated at -10% to -15% (A2) or 0% to -5% (B2). Summer rainfall extremes are projected to increase by up to 100% at the 30-year return period resulting in floods up to 1.8 times (A2) or 1.2 times (B2) current discharge. Floods at 500-year return period are projected to increase from 1800 $m^3s^{-1}$ currently to 2000-3100 $m^3s^{-1}$ (B2) or 2900-4000 $m^3s^{-1}$ (A2). In Waihou catchment, a larger decrease in annual rainfall total is predicted between 1970-2000 and 2070-2100, estimated at -15% to -20% (A2) or -10% to -15% (B2). Summer rainfall extremes are projected to increase by up to 100% at the 30-year return period, resulting in floods up to 1.4 times (A2) or 2 times (B2) current discharge. Floods at 500-year return period are projected to rise from 900 $m^3s^{-1}$ to 1000-1500 $m^3s^{-1}$ (A2/B2). Uncertainties are large for extreme flood predictions due to extrapolation from short timeseries and uncertainty in the rainfall and hydrological models.

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# 1. Introduction

The climate in New Zealand is changing: the IPCC Fourth Assessment Report (2007) found that increased temperatures are "virtually certain". An important consequence of this finding is that floods in New Zealand are "very likely" to become more frequent and intense, resulting in increased risk to major infrastructure including failure of flood protection measures. The pattern of rainfall over New Zealand will also change, with Eastern areas expected to become drier leading to greater pressures on water resources. As well as new risks, the changing climate will also bring opportunities, and early uptake of adaptation measures can have immediate benefits for land managers. It is therefore critical that the best information on the likely impacts of a changing climate is available, especially in terms of changes in magnitude and frequency of extreme events.

This paper describes how, for the first time, a framework has been set up to assess the effects of climate change on river flow and floods in New Zealand, using Global Climate Model (GCM) results dynamically downscaled to the regional scale. Our aim is to demonstrate how the latest advances in climatological and hydrological modelling can be combined to create a framework which simulates the physical changes in the atmosphere and hydrological cycle under climate change, and hence can be confidently used to plan for the future. NIWA's Regional Climate Model (RCM) provides dynamic downscaling from GCM predictions to high-resolution climate simulations over New Zealand. These 30-year climate series for A2 and B2 IPCC emissions scenarios are corrected for bias and then used to drive NIWA's hydrological model (TopNet) in order to predict changes in flood frequency under climate change. To make predictions for more extreme events, a rainfall generator is used to simulate rainfall series up to 1000 years long with the same statistical characteristics as those of the current, A2 and B2 rainfall series. These long rainfall series are also used to drive the hydrological model and simulate changes in the magnitude and frequency of extreme flood events. The uncertainty in the predictions is considered at each stage.

The remainder of this report is organised as follows. In Section 1 the techniques used to build the framework are introduced, including GCM downscaling (1.1), bias correction (1.2), rainfall simulation (1.3) and hydrological modelling (1.4). A review of previous studies in the field is also included (1.5). In Section 2, the catchments used in the case study are described, including physical characteristics of the catchment and weather-related hazards faced in each area. Section 3 describes in detail the methods used. Section 4 presents the results for both catchments, in terms of changes in climate and flood risk under A2 and B2 emissions scenarios. Section 5 concludes the report, summarising the results and making recommendations for future research.

### 1.1. Global climate modelling and downscaling

Extensive research has demonstrated that precipitation in New Zealand is intrinsically linked to Southern Hemisphere circulation patterns and their modes of variability such as the southern annular mode (SAM) and the El Nino-Southern Oscillation (ENSO) via mechanisms such as a strengthening and southward movement of the subpolar westerly wind maximum (e.g. Salinger and Mullan, 1999; Ummenhofer *et al.*, 2009; Renwick and Thompson, 2006). The SAM and ENSO modes are in turn influenced by atmospheric greenhouse gases as well as other factors such as ozone depletion (e.g. Kushner *et al.*, 2001; Cai *et al.*, 2003; 2005; Arlbaster and Meehl, 2006; Fyfe *et al.*, 1999). In order to understand how New Zealand precipitation patterns and depths will evolve under climate changes, it is therefore essential to use a Global Climate Model which can model such shifts in atmospheric circulation in the future.

Global Climate Model predictions cannot, however, be used directly in climate impact studies. GCM output is typically at a grid scale of 100-200 km which is too coarse, and does not represent topography on land with sufficient accuracy, to reproduce orographic effects and other local-scale rainfall patterns (Figure 1). For example, for New Zealand many of the closest GCM grid points are located in the ocean and hence are representative of oceanic rather than continental weather. Predictions from GCMs must therefore be downscaled to the relevant local spatial scale for the physical processes involved in the hydrological cycle.

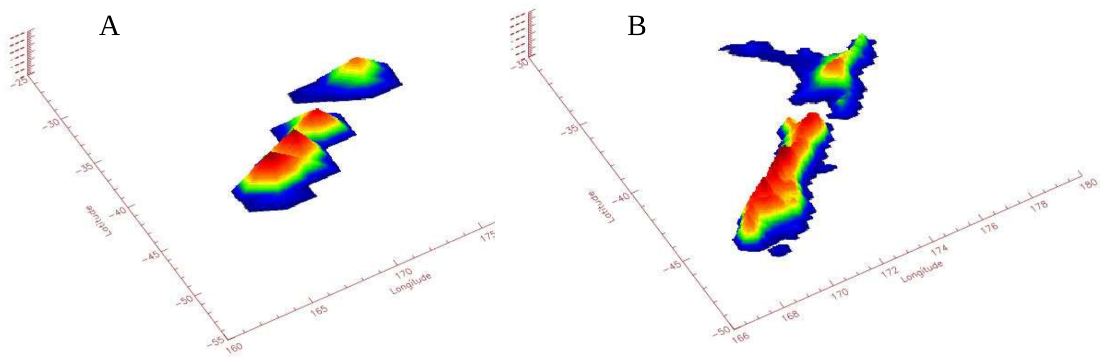



**Figure 1: Representation of NZ topography by (A) Global Climate Model at resolution of 140km and (B) Regional Climate Model at resolution of 30km. Colours show the land surface elevation used in the model.**

There are two families of downscaling method: statistical and dynamic. Statistical downscaling has previously been the most popular method as it is computationally inexpensive, and can therefore be used relatively easily for ensemble simulations. It consists of the formulation of regression equations to link GCM predictions to local observations of precipitation and temperature. The method which has been used in New Zealand is described in more detail in the Climate Change Effects and Impacts

Assessment Guidance Manual (MfE, 2009), also Mullan *et al.* (2001). Pseudo-observation data is used from a gridded dataset that covers all of New Zealand with 0.05° latitude–longitude boxes. There are approximately 11,500 grid points over the New Zealand land mass. The gridded data were developed by interpolating observed daily rainfall plus maximum and minimum temperatures from some hundreds of daily reporting sites (Tait et al, 2006)

The main theoretical disadvantage for statistical downscaling is that it is based on an empirical relationship, derived from the present climate, which may not hold true in the future as physical processes that control rainfall and temperature may change (Boé *et al*, 2009). Instead, the second approach of dynamical downscaling may be used, in which a Regional Climate Model running at higher resolution (30 km in New Zealand) is forced at the boundaries with GCM predictions. The RCM runs at a scale commensurate with the climate processes of interest and hence is able to simulate them directly (Durman *et al*., 2001). An RCM, nested within a GCM, has been developed for New Zealand (Drost *et al*., 2007) based on the UK Met Office Unified Model framework (Cullen, 1993). Regional-scale modelling has previously been shown to improve climate simulations for the New Zealand area (Renwick *et* al., 1998).

Regional Climate Model output can be used for future climate simulation in two ways. It can be used directly (with bias-correction if necessary) or via the delta-change method. In the latter method, mean monthly changes in precipitation and temperature are derived from RCM simulations of present and future climate, and then applied to recorded data series. This method is frequently used with GCM data, and can be extended to match changes in daily rainfall intensity as well as monthly means, which is important for predictions of changes in extreme events (Kay *et al*., 2009). However due to the reliance on the recorded data series, this method does not allow for more complex changes in spatial and temporal variability which may be observed in the RCM output. For this reason, it was preferred to use the RCM output directly in this study.

## 1.2. Bias correction

RCMs still have significant biases that must be corrected prior to use in impact studies (Boe *et al.*, 2009). The bias may be due to different causes such as small-scale topographic variations which are not fully represented at the 30 km RCM scale; or the limited area for which the RCM runs meaning that small scale weather events do not fully develop. There are various techniques that can be used to correct the biases. Some studies using a relatively simple linear ‘change factor’ approach to correct mean precipitation (e.g. Fowler and Kilsby, 2007). Other studies (e.g. Leander and Buishand, 2007; Shabalova *et al.*, 2003) use a power transformation to correct the coefficient of variation as well as the mean. Alternatively, a quantile-mapping correction may be used which corrects the entire distribution of precipitation (e.g. Boe *et al.*, 2007; Déqué *et al.*, 2007; Wood *et al.*, 2004; Segua *et al.*, 2009). The last is chosen here for its ability to correct the extremes of the distribution which are critical for flood risk assessment. The approach is described in detail in Section 3.1.2.

## 1.3. Climatic variability

The climate system has natural internal variability: the simulation of current or future climate provides only one possible representation of the system, and if the simulation were run again with different initial conditions or GCM forcing then a different result would be produced. Some studies have addressed this problem by resampling the rainfall series to create many different climate realisations (e.g. Kay *et al.*, 2009; Leander and Buishand, 2007), however this method does not allow for variation in short-term extremes from those in the original modelled series. Instead, natural climatic variability may be assessed more fully by using a stochastic rainfall model which uses the spatial and temporal statistical properties of the modelled rainfall series to produce multiple alternative series with the same properties. This approach has been used successfully in previous studies (e.g. Cameron, 2006; Kilsby *et al.*, 2007). Although this method incurs significant model set-up costs, in New Zealand we can benefit from a multisite stochastic rainfall model previously developed by NIWA (Thompson *et al.*, 2007) as a generalisation to the model proposed by Wilks (1998). The NIWA model allows the simulation of daily rainfall values at a network of locations, retaining the spatial and temporal characteristics of the original series. Use of this model allows both investigation of climate variability, and estimation of flood magnitudes of longer return periods: for example by simulation of 1000 realisations of a one-year rainfall series, and using a hydrological model to transform these into river flow series, the 1-in-1000 year flood may be directly estimated. Further details of the method are given in Section 3.2.

## 1.4. Flood risk

Future flood risk cannot be reliably estimated from current records of river flows, due to changes in New Zealand's precipitation under climate change. This means past flood frequency is not a good predictor of future flood frequency. This is highlighted by the MfE report *Meeting the Challenges of Future Flooding in New Zealand* (MfE, 2008) under the key question "What is the flood risk in our regions given the likely consequences of landuse and climate change, especially in light of the short hydrologic records that are common in New Zealand?" Instead, flood risk can be estimated using the climate projections described above as input to a hydrological model and simulating future river flows.

The underpinning method we use is that of *continuous simulation* whereby a rainfall series (direct from the RCM or output from a stochastic rainfall model) is input into the hydrological model in its entirety to produce the corresponding discharge series, from which extreme event frequencies may be calculated explicitly. An important strength of the method is that it provides continuous soil moisture accounting which gives implicit consideration of antecedent wetness conditions in the catchment, and hence allows for floods caused by extended periods of high rainfall (e.g. a wet winter following a wet autumn). This is a significant advantage over the simpler method of *event-based simulation* where rainfall events are considered in isolation. Continuous simulation is a standard technique for forecasting the discharge magnitude of extreme floods and has been used in a wide variety of studies (Cameron *et al*., 1999; Chetty and Smithers, 2005; Franchini et al., 2000; Hashemi et al., 2000; Maskey et al., 2004; Onof et al., 1996; Pandit and Gopalakrishnan, 1996). The method is flexible and may if required be extended to flood inundation mapping (Hsieh et al., 2006; Faulkner and Wass, 2005; McMillan and Brasington, 2008).

A further advantage of using a stochastic rainfall model to drive the hydrological model is that it removes the necessity of extrapolation of flood frequency curves from short series of measured or simulated flow data. This can introduce large errors or uncertainties into the estimates of flood risk, as there are many different extreme-value distributions which can be used for extrapolation (including Log Normal, Gumbel, Pearson, Generalised Pareto and Generalised Logistic distributions) which are often chosen empirically with no process-based strategy for choice of distribution (Kidson, 2004; Vogel et al., 1993).

## 1.5. Review of previous studies in New Zealand

This study builds on a strong foundation of previous research into impacts of climate change in New Zealand. Predictions from Global and Regional Climate Models have been developed by NIWA under the FRST-funded Adaptation to Climate Variability and Change programme (C01X0701). That programme uses a global climate model (GCM) developed at the UK Met Office, known as HadCM3, to generate boundary conditions in the New Zealand region (Bhaskaran et al., 2001; Dean et al, 2006), and hence to run a regional climate model . The FRST 2007/08 programme Understanding and Adapting to Global Process and Change is currently enabling NIWA to build on these results, exploiting the new AR4 global data set.

Statistically downscaled rainfall and temperature predictions from GCM output have been used to drive a hydrological model in the Buller catchment (MfE, 2005b); and hydrological and irrigation models in Canterbury catchments under the programme 'Projected Effects of Climate Change on Water Supply Reliability in Mid-Canterbury' undertaken for MAF by NIWA and Aqualinc and funded by the Sustainable Farming

Fund. Similarly, GCM predictions are being used by NIWA to model climate change impacts in major snow-influenced catchments in the South Island under FRST programme 'Regional climate modelling to develop probabilistic scenarios of future New Zealand climate'.

The study presented here will not only benefit from previous research, but the results will also be used within current and future studies, ensuring that it provides ongoing benefit to climate impacts modelling in NZ. The results will be used to inform methods of using RCM in addition to GCM output for impacts modelling within the Regional Climate Modelling FRST programme described above. The results will also be used to form the framework of a Flood Risk Assessment method in the FRST programme 'Science-based processes for Central and Local Government to identify opportunities and reduce impacts of climate change on the urban and built environment/infrastructure'.

## 2. Case study locations

Two pilot study catchments in New Zealand have been chosen to test the suggested framework. These are the Uawa River flowing into Tolaga Bay (Gisborne DC) and the Waihou River flowing into Hokianga Estuary (Northland RC) (Figure 2). These catchments were suggested by the respective regional councils after a discussion at the River Manager's Forum meeting in Wellington in March 2009. A brief description of the catchments and review of the weather hazards associated with these regions is provided below, in order to put the climate change predictions into context. The Uawa catchment was used as the main case-study catchment where development work on the impacts assessment framework was undertaken and field studies carried out to verify functioning of the catchment model. The Waihou was used as a secondary location to test the completed framework.

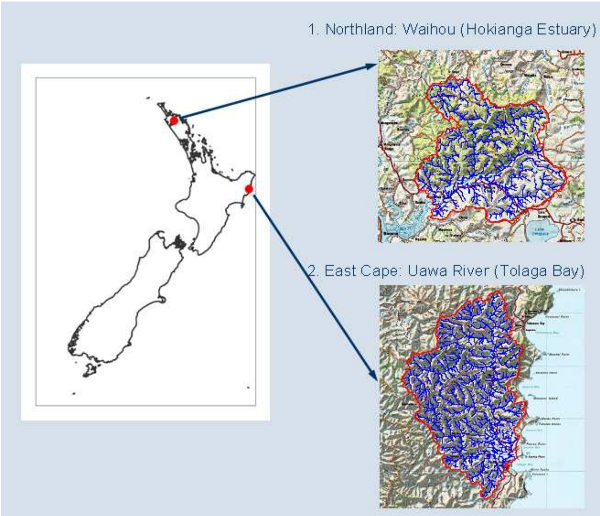



**Figure 2: Locations of Catchments used in the Pilot Study**

### 2.1. Catchment land use

The two catchments have a mixture of land uses (Figure 3; data derived from the New Zealand Land Cover Database). Waihou catchment is dominated by native forest in its Northern half (the Omahuta and Puketi Forests). In the Southern half of the catchment (South of State Highway 1 and Puketi Road), the land cover comprises grassland (farmland) interspersed with stands of native bush. The Uawa catchment is split between exotic forest (pine) in the Western uplands, and grassland in the East. Interspersed throughout are areas of Manuka/Kanuka scrub.

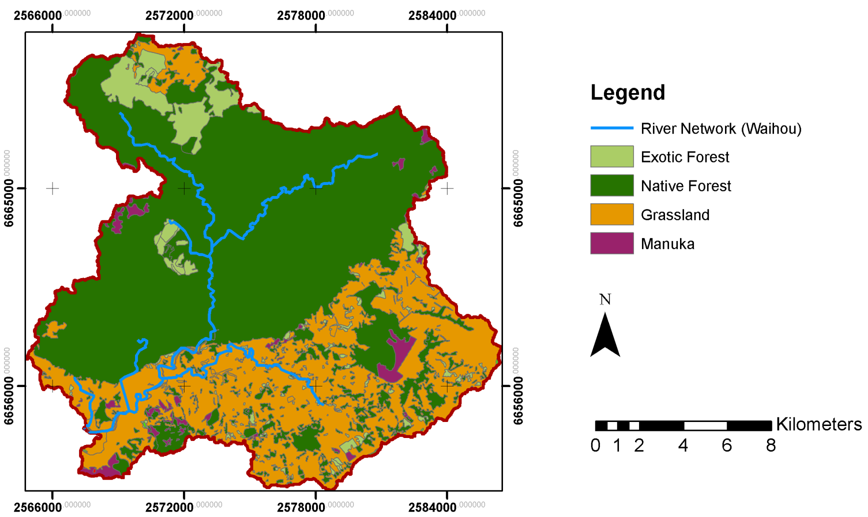



**Figure 3a: Land cover in Waihou Catchment**

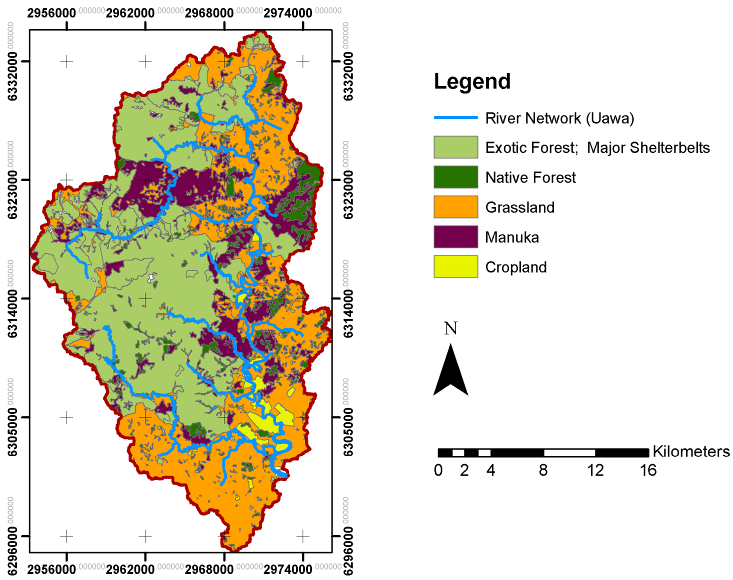


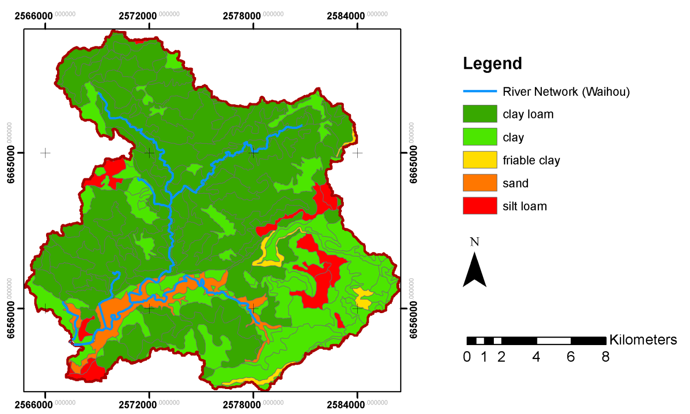

**Figure 3b: Land cover in Uawa Catchment**

## 2.2. Catchment soils

### 2.2.1. Soil texture

Soil textural information is important because it can be used to estimate hydraulic properties of the soil which are needed as input to the hydrological model. Together with measures of organic carbon and bulk density where available, measurements of %sand, %silt and %clay are used to determine the hydraulic conductivity of the soil (i.e. the rate at which water can move through pore spaces or fractures) using pedo-transfer relationships (Saxton and Rawls, 2006).

Mapped soil textural information is available for the Waihou catchment (Figure 4a; data derived from the New Zealand Land Resource Inventory (LRI; Newsome *et al.*, 2000)). This shows that in general the river valleys are dominated by sandier soils, whereas the uplands have a higher clay content, with clay loam the most frequent soil type. The pasture areas in the Southern part of the catchment have higher clay content than the forested areas in the Northern part of the catchment.




[Mapped Soil Texture information not currently available for the Uawa catchment]

**Figure 4a. Soil texture in Waihou Catchment**

Mapped soil textural information is not available for the Uawa catchment, but soil textural analysis for selected sites in the Uawa catchment was available from a Victoria University experimental programme, which sampled soils under seven different soil/land use classes which are representative of the catchment, and included particle size analysis. Sample results are shown in Table 1 below. Samples were taken at two depths in order to measure the characteristics of both surface soils and those of the buried clay-rich layer which occurs in this catchment.

**Table 1: Soil textural analysis for three locations and two depths in the Willowbank catchment of the Uawa River.**

| | Lowland Pasture | | Gorse-covered hillslope | | High pasture | |
|---|---|---|---|---|---|---|
| | 5-10cm | 30-50cm | 5-10cm | 30-50cm | 5-10cm | 30-50cm |
| % Sand | 60.19 | 60.77 | 66.51 | 62.77 | 56.02 | 43.35 |
| % Silt | 38.76 | 36.41 | 33.32 | 35.66 | 42.82 | 39.25 |
| % Clay | 0.64 | 2.82 | 0.17 | 1.57 | 1.16 | 17.40 |

### 2.2.2. Soil type

Mapped soil type information is available for both the Waihou (Figure 5a) and Uawa (Figure 5b) catchments. Both catchments are similar in their soils types. Both are dominated by Yellow-Brown Earths, with some areas of Brown Loam or Yellow-Brown Loam. Both have areas of Recent Soils on the valley flats.

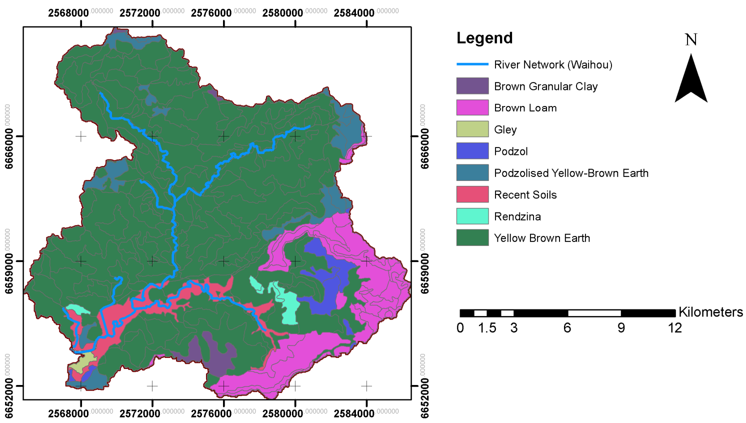



**Figure 5a: Soil type in Waihou Catchment**

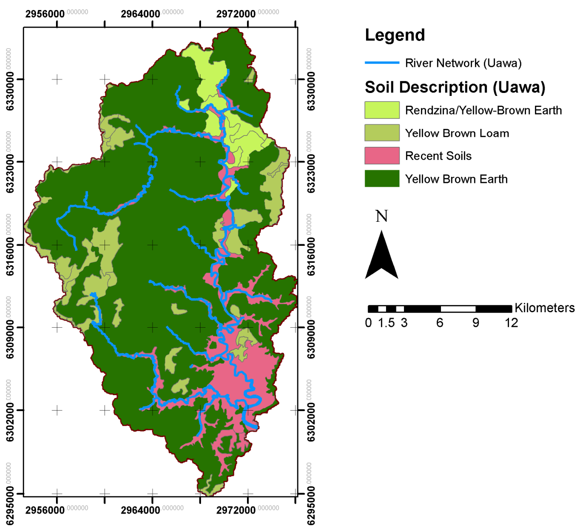



**Figure 5b: Soil Type in Uawa Catchment**

## 2.3. Catchment geology

The geology of a catchment is critical to its hydrologic behaviour, both indirectly through control of soil type, and directly by controlling groundwater flow in the catchment. Mapped geological information is available for both catchments (Figure 6a and Figure 6b; data extracted from the LRI), and is used to derive model parameters which control the subsurface flow regime of the catchments.

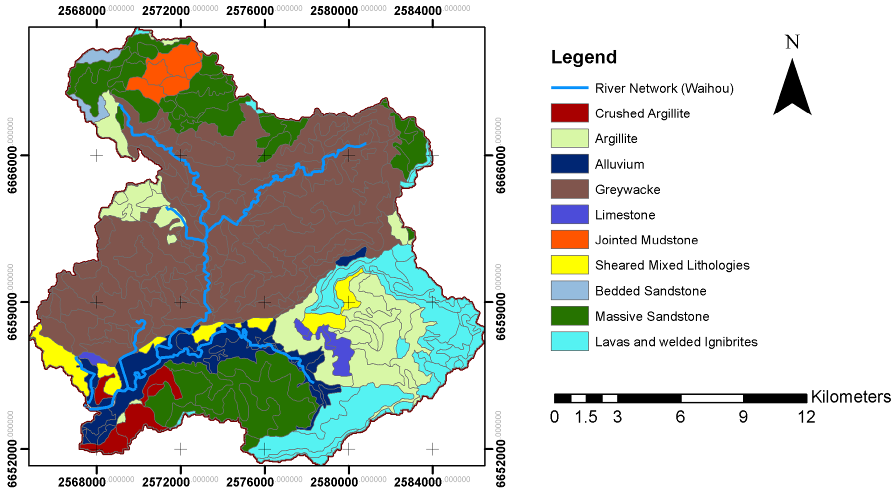



**Figure 6a: Geology of Waihou Catchment**

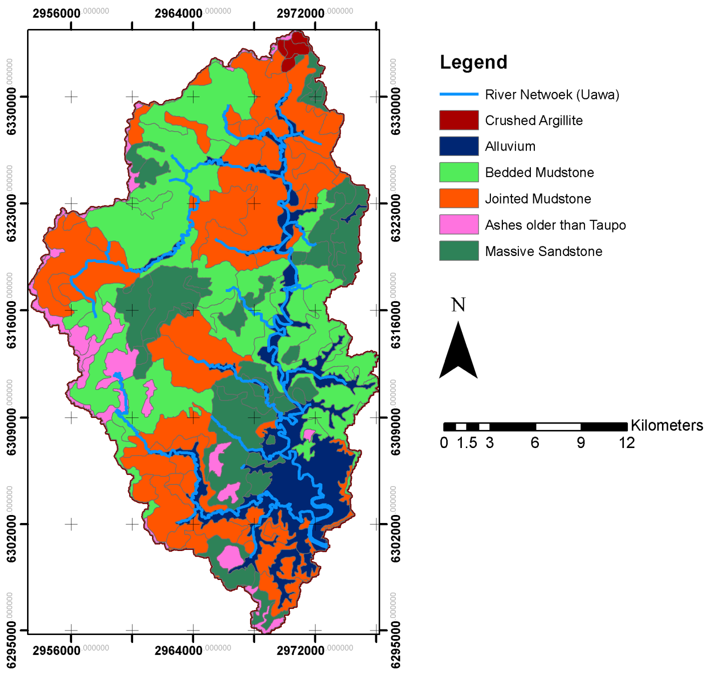



**Figure 6b: Geology of Uawa Catchment**

The Waihou catchment is split between the Northern uplands which lie predominantly on Greywacke, and the Southern area which has a mix of geology including Massive Sandstone, Argillite and Welded Ignibrites. All these rock types have typically low hydraulic conductivity/permeability and the rivers of the Waihou catchment therefore respond quickly to rain events.

The Uawa catchment consists mainly of bedded and jointed Mudstones, with some more limited outcrops of Massive Sandstone. Therefore we would expect greater infiltration into the bedrock and greater influence of groundwater in the Uawa. This may lead to a slower response of rivers to rainfall events.

## 2.4. Natural hazards

### 2.4.1. Uawa (East Cape)

The East Cape region around the Uawa River is a dry part of New Zealand; however interannual variability in rainfall is high. Rainfall totals are highest in Winter and lowest in Spring. The region is at risk from tropical cyclones and ex-tropical cyclones: in 1988 when cyclone Bola hit, a peak rainfall of 916 millimetres over the three days was recorded inland from Tolaga Bay (see Figure 7 description). In severe events such as Cyclone Bola, the Stat Highway in the Mangatuna basin around the Uawa River mouth becomes a flood-way and cannot be used, cutting access along the coast (Gisborne District Council, 2009). The Tolaga Bay flats are subject to relatively frequent flooding and, given their economic importance for a wide range of farming activities. GDC recently undertook a feasibility study for flood mitigation measures (Gisborne District Council, 2007).

The Uawa and Tolaga Bay regions are at risk from drought in addition to flood hazard. The East Cape is one of the regions of New Zealand of highest risk of drought when measured via the Potential Evaporation Deficit (MfE, 2005). Drought hazard is also affected by the ENSO cycle with severe drought conditions in the East Cape region more likely during the El Nino phase when south-westerly airflows are more common, such as the 1997-1998 year.

### 2.4.2. Waihou (Northland)

Northland is at significant risk from weather hazards, from several sources. These include tropical cycles, ex-tropical cycles, North Tasman Lows (such as the 2002 ‘weather bomb’), and intense convective activity. These weather hazards readily cause flood hazard, due to the steep hills of Northland quickly feeding storm runoff to the surrounding low-gradient rivers which are slow to disperse flood waters (Gray, 2003).

At high tides, water in the estuaries may further hold back flood waters and increase flood heights. The hazard may be made worse by high silt loads in flooded rivers due to steep terrain with high erosion rates.


**Figure 7:** **The flood gauge on the Hikowai branch of the Uawa River (Willow Flat) provides a reminder of the power of the Uawa River in flood. When the river stage reaches the top of the old bridge pillar shown (12 m) the council activates its evacuation plan for the lower flats; during Cyclone Bola the stage reached 3 m above the pillar (15 m).** **Photo: H.K. McMillan**

Weather hazards in Northland are affected by the ENSO cycle (El-Nino Southern Oscillation). During the La Nina phase, North-Easterly winds are more common, bringing higher rainfalls to Northland, and increased numbers of ex-tropical cyclones pass close to New Zealand.

Flood events have caused significant damage in Northland in recent years, particularly the March/July 2007 and July 2008 floods. In response to this hazard, the Northland Regional Council has set up the Priority Rivers Flood Risk Reduction Project, which has identified 27 rivers in Northland where flooding poses a high risk to lives, buildings, road access, infrastructure and agriculture. The Waihou river chosen as a case-study for this project is one of the Priority Rivers due to the flood risk particularly in the Rahiri-Rangiahua reach.

# 3. Methods

## 3.1. Climate scenarios

### 3.1.1. Regional Climate Model

The climate scenarios considered in this project are derived from the UK Met Office HadCM3 Global Climate Model; one of the models used for the IPCC Fourth Assessment Report to simulate future climate. This model has been coupled to the HadRM3 Regional Climate Model, also from the UK Met Office in order to provide dynamically downscaled climate predictions for the New Zealand region at a grid scale of 30km. Three simulations are used: firstly a control experiment is available for the years 1970-2000. In this model run, the RCM is forced by a free-running GCM (that is, one that is not constrained by real observations), and provides simulations of current atmospheric and climate conditions which are directly comparable with the future climate scenarios.

Two future experiments are used to simulate climate conditions in the years 2070-2100. These model runs are driven by two different forcing emissions scenarios, as the model predictions are sensitive to the choice of emissions scenario. The IPCC SRES B2 scenario represents a moderately low emissions future; the IPCC SRES A2 represents moderately high emissions (IPCC, 2007). Comparisons of results from these two scenarios will hence allow us some understanding of the uncertainty in changes in flood risk due to uncertainty in future emissions.

### 3.1.2. Bias correction

As explained in Section 1.2, quantile-mapping bias correction is used to correct any persistent bias in regional climate model rainfall volumes when compared to observed rainfall data. The method is as follows. Regional Climate Model output from the current climate scenario and the two future scenarios are extracted for the grid points surrounding the chosen catchment. The location of the relevant points in comparison to the (A) Uawa and (B) Waihou catchments is shown in Figure 8.

Next the observed rainfall series for the same locations (one per grid point) is extracted from the Virtual Climate Network (VCN; Tait *et al*., 2006). The VCN rainfall surface is derived from rainfall totals measured at rain-gauges using spline interpolation. The VCN is on a high resolution grid of 0.05° Lat/Lon and hence locations can be matched very closely.

For each location, the cumulative density function (CDF) of daily rainfall amount was calculated for both the observed (VCN) and modelled 'current climate' data. The mapping between the two CDFs was then used to correct each modelled daily rainfall amount. This is done in two parts: first the percentage of days where rain was observed is corrected, and second the CDF of those rain days is corrected. To adjust the modelled ‘future climate’ data in the same way, although there is no ‘observed future climate’ data for comparison, we assume that the same multiplicative biases are present as those in the current climate.

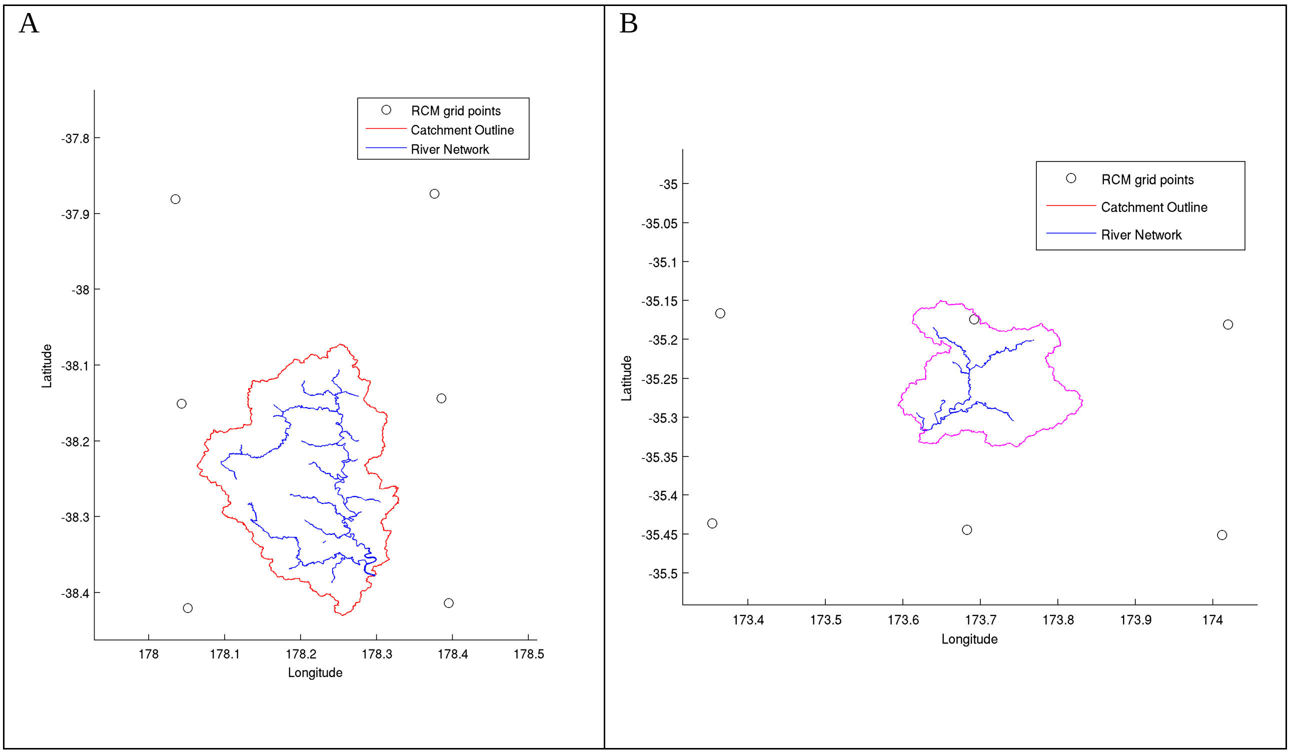



**Figure 8: Locations of the Regional Climate Model grid points surrounding the (A) Uawa and (B) Waihou catchments.**

The temperature series produced by each model run also require bias correction. Minimum and maximum daily temperature data are extracted from the VCN and used for quantile-mapping bias correction of the modelled daily minimum/maximum temperatures. The only difference is that the temperature biases are treated as additive rather than multiplicative, as is standard in climate change applications.

## 3.2. Rainfall generator

### 3.2.1. Description

A multisite daily rainfall generation model has been developed for New Zealand conditions under the FRST ‘Climpacts’ programme, and was tested using a network of raingauges in Canterbury (Thompson *et al.*, 2006; 2007). Stochastic models for rainfall occurrence and amounts are used to understand rainfall variation over space and time, within a localised area affected by regional-scale weather patterns. The rainfall generator takes as input concurrent rainfall series for multiple locations and generates further rainfall series as required which have the same rainfall volume and pattern characteristics. The rainfall generator fits statistical distributions of daily rainfall volume to the observed data, and then samples from these distributions to generate new data. It is therefore possible for the generator to simulate rainfall heavier than that occurring in the original series, because the extreme tail of the fitted distribution could be sampled. This would happen only as a rare event with high return period, and is consistent with the possibility of more extreme events occurring when a longer rainfall series is modelled.

The NIWA multisite rainfall generator is of the 'Hidden Markov Model' type, which first simulates a series of days divided into dry, light rain and heavy rain states, for each location, and for each month of the year separately. These rain states are then used to generate individual daily rainfall totals. Both the rain states and daily totals are generated so that simulated rainfall displays the same correlation in time and between sites as the original observed rainfall series. This type of rainfall simulation model was assessed as suitable for use in New Zealand by Thompson and Mullan (2002).

### 3.2.2. Set-up

Initial work had to be done to tailor the rainfall generator to receive climate model output rather than measured rainfall. This included adapting the rainfall generator to the more highly correlated and smoother patterns of rainfall that are typical of a regional climate model.

The bias-corrected 30-year rainfall series from the six RCM output grid points and for each scenario (current climate, A2, B2) were then input into the rainfall generator together with information of the location of each point. The rainfall generator was then run to produce 1000-year rainfall series for each scenario.

### 3.2.3. Temperature simulation

Temperature, minimum and maximum, daily values are also required as input into the hydrological model to be run for the 1000-year series, as temperature controls potential evapotranspiration and hence catchment water balance. The temperature values are represented as a first-order auto-regressive moving average model, using the method described by Mullan *et al.* (2003).

$$T'(t) = [A] \cdot T'(t-1) + [B] \cdot \varepsilon(t) \qquad \text{[Eq. 1]}$$

Where $t$ is time, $T'$ is the transformed temperature min/max vector, $A$ and $B$ are matrices representing the serial and cross-correlation of the temperatures, and $\varepsilon$ are independent normal variates. The temperature vectors are residuals from the average annual cycle, which are normalised by mean and variance, separately for wet and dry days, i.e.:

$$T'(t) = ((T(t) - Y(t)) - \mu)/\sigma \qquad \text{[Eq. 2]}$$

Where $T$ is the original temperature measurement, $Y$ is the yearly cycle component, $\mu$ is the mean and $\sigma$ is the standard deviation.

This temperature model is fitted to temperature minimum and maximum data from each of the 30-year series output from the RCM, and then used to generate typical temperature data for the 1000-year series, separately fitted to wet and dry days as determined by the rainfall generator.

## 3.3. Hydrological model

### 3.3.1. Model set up

For this research we used a distributed hydrological model, TopNet (for a complete model description see Clark *et al.*, 2008). The stream network is divided into first order subcatchments, and for each subcatchment an underlying spatial data file contains information about soil cover, soil depth, hydraulic conductivity, elevation (distribution), etc, as well as information about the river network, for example stream width, roughness, etc. The main sources of spatial data used for New Zealand applications of Topnet are the New Zealand River Environment Classification (Snelder & Biggs, 2002), supplemented with additional analyses of topographic data, the Land Resources Inventory (Newsome et al. 2000), and the New Zealand Land Cover Data Base (Willoughby et al., 2001). Examples of information used for the Uawa and Waihou catchments is shown in Figure 9, 10 and 11.

For each timestep and each sub-basin a water balance is calculated (precipitation, evaporation, baseflow, overland flow, etc). Then the baseflow and overland flow are added to the stream network, and the water in the rivers is routed down through the stream network. Figure 12 shows the main state variables and fluxes in TopNet. Further information on the model equations is given in Appendix B. For each subcatchment and each timestep we get output for all state variables and fluxes of the hydrological model.

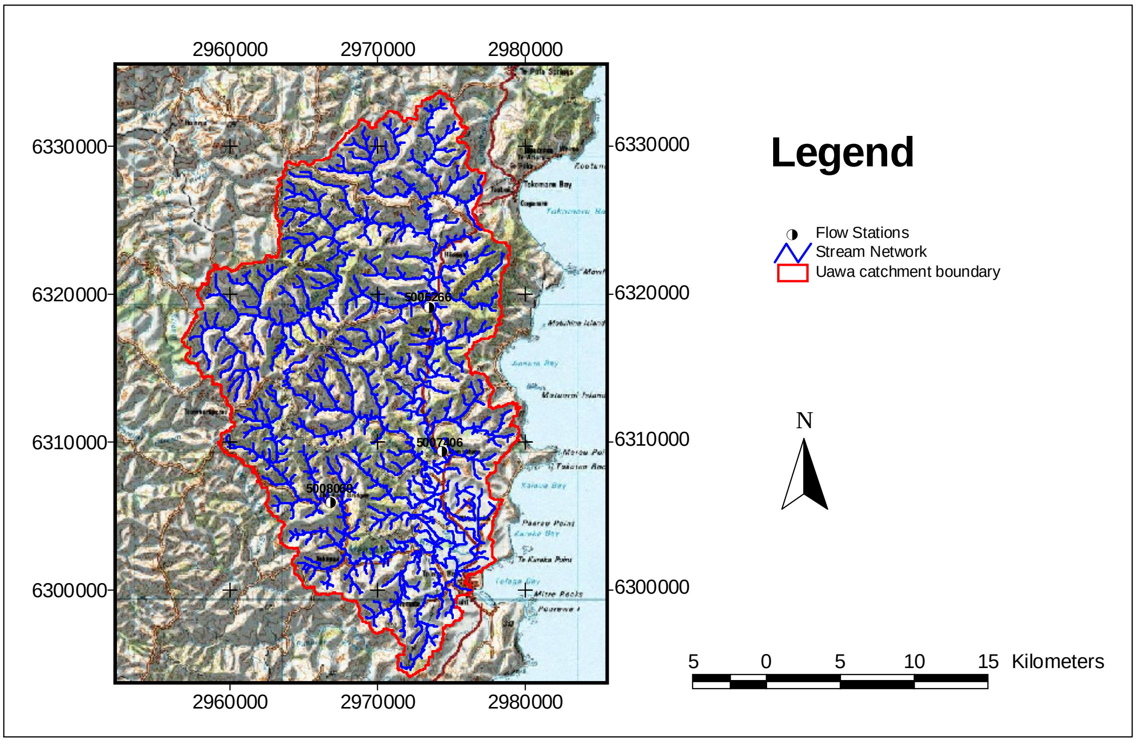



**Figure 9:** **Uawa catchment outline, stream network and flow station locations.**

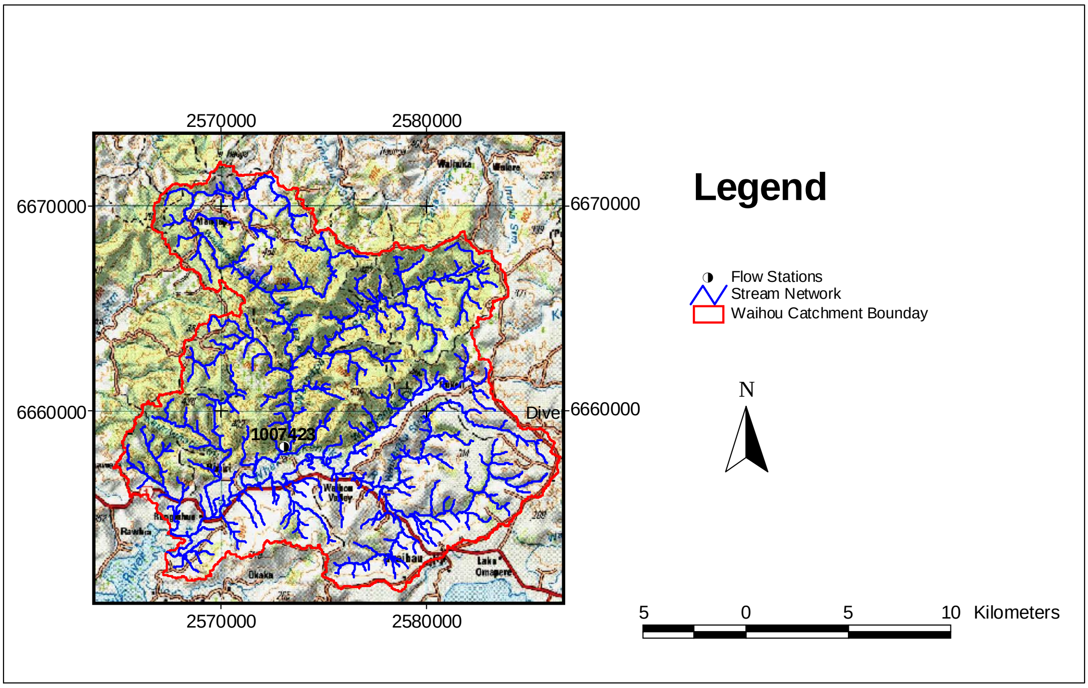



**Figure 10:** **Waihou catchment outline, stream network and flow station locations.**

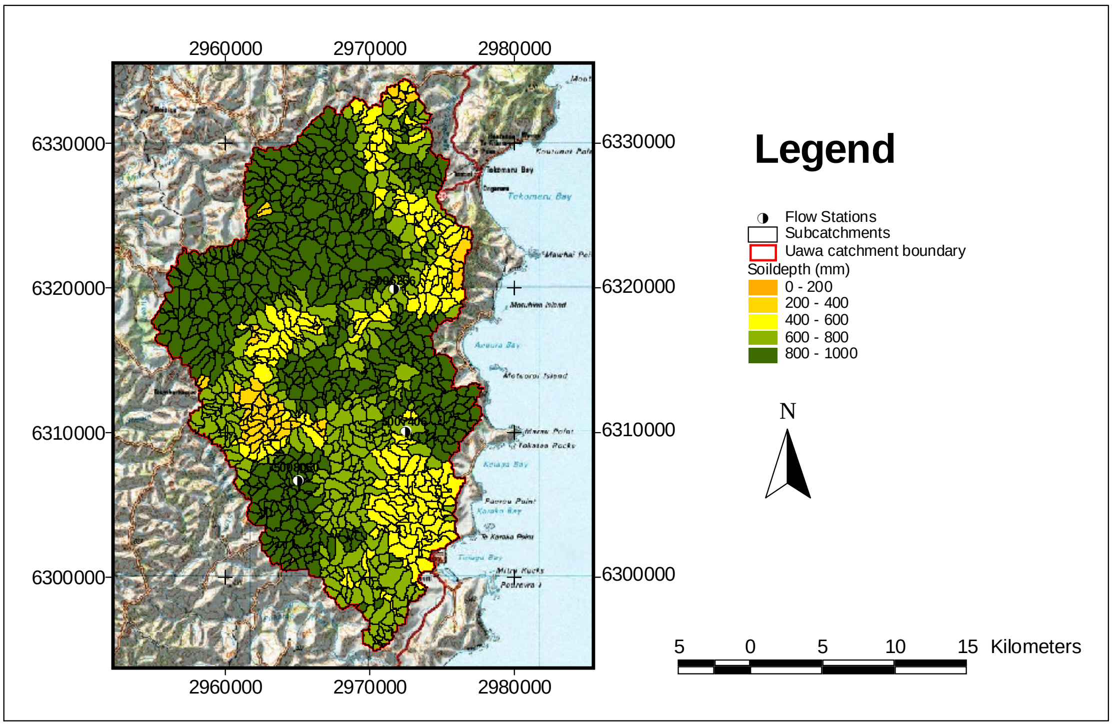



**Figure 11:** **Soil depth of Uawa subcatchments (source: LRI)**

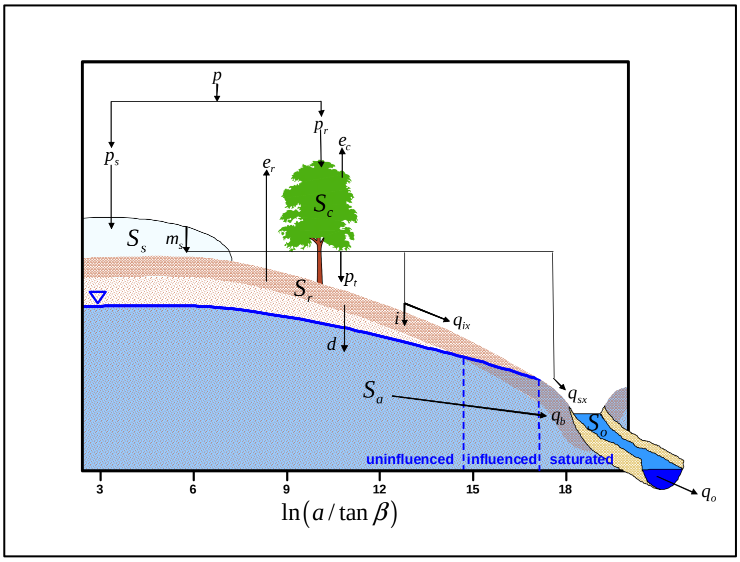



**Figure 12:** **Main state variables and fluxes in TopNet: State variables are canopy storage ($S_c$), snowpack storage ($S_s$), soil, or root zone, storage ($S_r$), aquifer storage ($S_a$), and overland flow storage ($S_o$). Fluxes are precipitation rate (p), throughfall ($p_t$), canopy evaporation ($e_c$), snow melt ($m_s$), soil evaporation ($e_s$), infiltration (i), drainage (d), aquifer discharge ($q_b$), infiltration-excess runoff ($q_{ix}$), saturation-excess runoff ($q_{sx}$), basin outflow ($q_0$). The wetness index ln(a/tan β), where a is upstream area and β is slope, divides the catchment into saturated and unsaturated zones.**

Input data are precipitation and temperature, and output variables are, amongst others, evaporation, infiltration, overland flow, baseflow, streamflow. TopNet was run on an hourly timestep. However, the precipitation and temperature data that comes into TopNet is on a daily basis (daily sums for precipitation, daily minimum/maximum for temperature). The daily precipitation was therefore (stochastically) disaggregated to hourly timesteps by TopNet. The temperature was disaggregated using a sine curve, fitted through the daily minimum and maximum temperature.

The rainfall and temperature input was provided on a grid, and for each basin the nearest grid point on the rainfall/temperature surface was used as the basin value (nearest grid point to the centroid of the basin), taking into account elevation differences in the case of temperature using a standard lapse rate.

For the future scenarios the climate information used for TopNet is as described in the Climate section of this report (Section 3.1). This means that temperature and rainfall are available at six RCM grid point locations, surrounding the catchment. Temperature was spatially disaggregated in the same way as described before, i.e. nearest neighbour, corrected for differences in elevation between station and basin location. For rainfall, we used the inverse distance method, taking the weighted average of the surrounding stations, which we corrected for the pre-existing knowledge of the difference between the mean annual rainfall at the station location and the basin (centre) location.

### 3.3.2. Model calibration

The hydrological model was calibrated based on measured streamflow series for one year (2005; chosen because it included a large flood). In the Uawa we had three measurement locations; in the Waihou, one (see Figure 9 and Figure 10). The calibration was done via manual optimisation, i.e. a range of different parameter sets were tested, and the parameters were also adjusted manually to ensure a good fit between measured and modelled streamflow series. The fit was assessed using both time series of measured and modelled flow (to ensure flood peaks and timing were properly represented), and cumulative flow and precipitation series (to ensure correct water balance). Example calibration results are shown below (Figure 13, 14 15 and 16) with time series of flow data shown in the upper figures and cumulative plots shown in the lower figures. Verification of the model parameters was also undertaken using a different year of precipitation and flow data (2001). The best three parameter sets identified for each catchment were chosen for the future climate simulations – using multiple parameter sets allows us to assess the uncertainty in the final results due to the choice of hydrological model parameters.

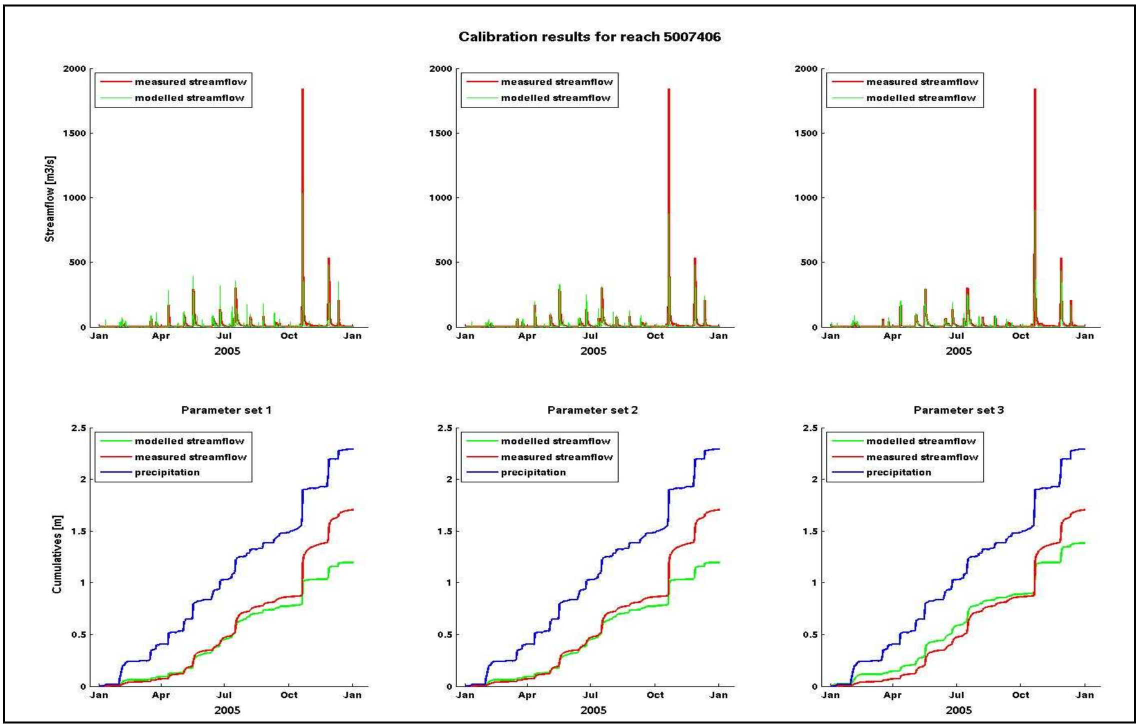



**Figure 13:** **Calibration results for year 2005 for flow station at Willow Flat on the Uawa River (reach 5007406; see Figure 9).**

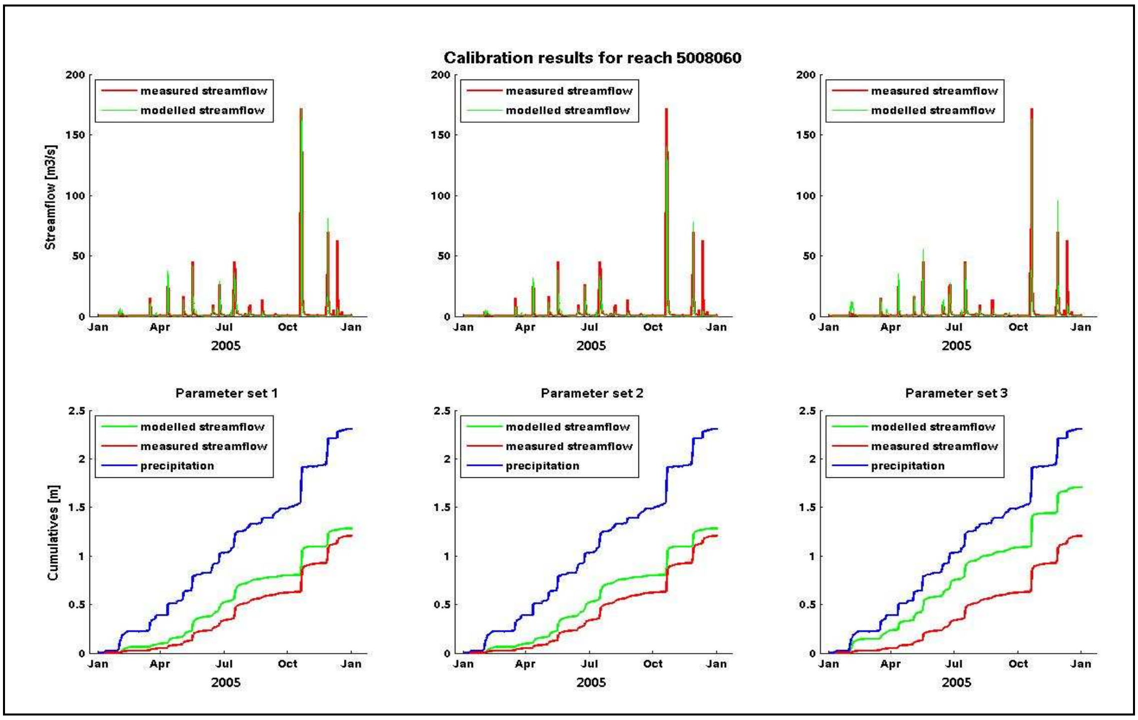



**Figure 14:** **Calibration results for year 2005, for flow station at Willow Bank on the Mangaheia River (Uawa tributary) (reach 5008060; see Figure 9).**

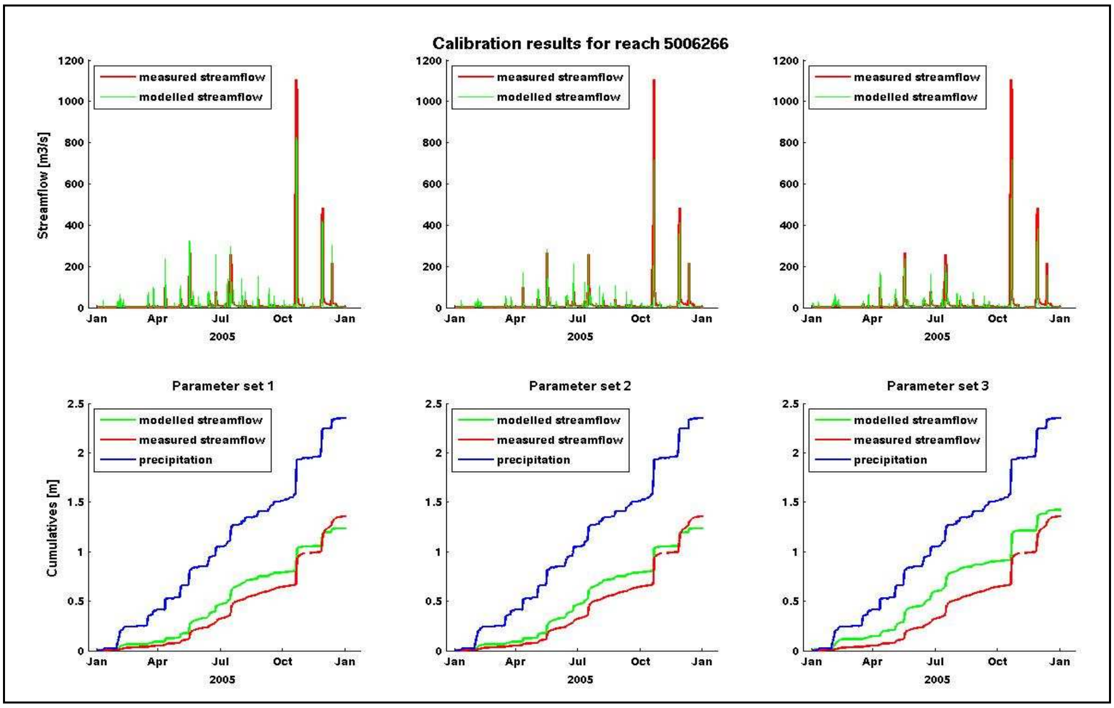



**Figure 15:** **Calibration results for year 2005 at flow station at Hikowai No. 4 Bridge on the Uawa River (reach 5006266; see Figure 9).**

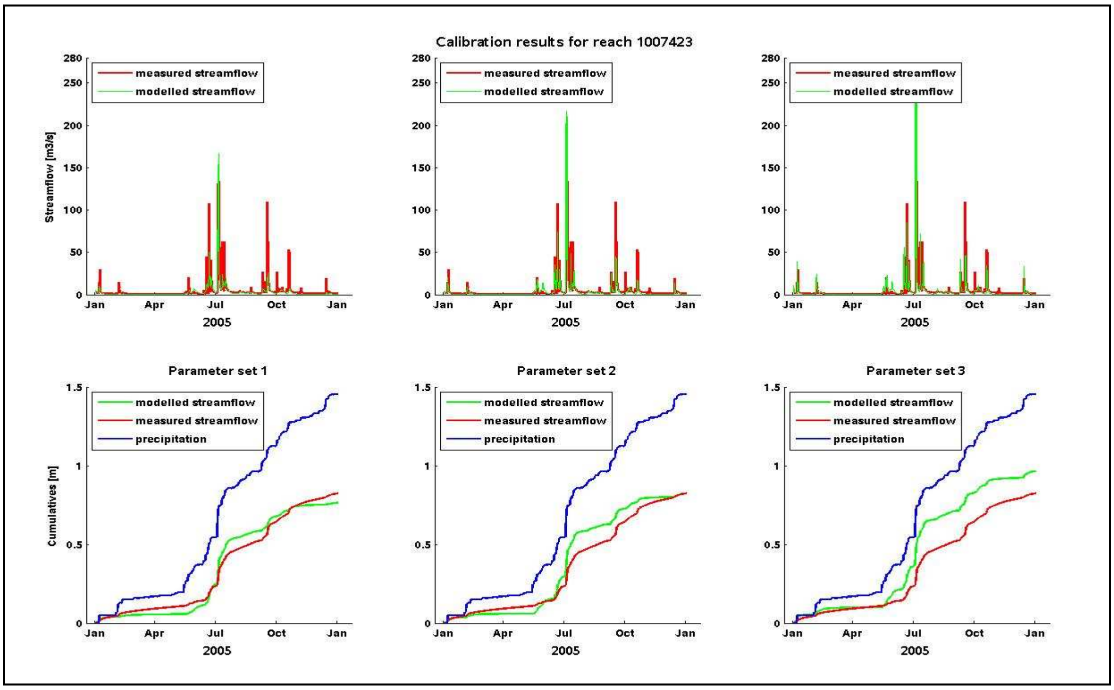



**Figure 16:** **Calibration results for flow station on Waihou River (reach 1007423; see Figure 10). (NOTE: parameter sets were different for the two catchments).**

### 3.3.3. Model and field comparison for verification of small-scale soil water dynamics

#### 3.3.3.1 Model to model comparison

*Introduction*

A difficulty with calibrating a model with measured data is that you can never be sure if the chosen parameter set will also be the best for future, unknown situations. In the future there might be events with different rainfall and runoff dynamics to those we have measured to date, so we want to be confident that we can “extend” the catchment behaviour to these possibly more extreme events. We must therefore be sure that the model is representing the right processes. One of the most determining processes governing the catchment’s rainfall runoff behaviour is the capacity of the soil to infiltrate, store, and transport water. To gain confidence that we are representing the dominant processes appropriately here, we carried out a small-scale comparison of the soil water dynamics of our hydrological model, TopNet, and a 3D physically based model, SPW (Butler and Jackson, 2003).

TopNet soil moisture and water table calculations are based on the TOPMODEL concept (Beven and Kirkby, 1979; Beven, 1997). A description of the governing equations can be found in Appendix B. For a more detailed description of the equations, see Clark et al., 2008. A figure of the main storages and fluxes can be seen in Figure 12.

SPW is a three-dimensional model, based on Richard’s equation (Equation 3), which is the commonly accepted equation describing flow in variably saturated soils (Hillel, 1992). Richard’s equation for soil water flow in multiple space dimensions can be written as:

$$\frac{d\theta}{d\psi}\frac{\partial\psi}{\partial t} = -\nabla\cdot(-K(\theta)\nabla(\psi+z)) - u_w, \qquad \text{[Eq. 3]}$$

where:

$K$ is the hydraulic conductivity,

$\psi$ is the pressure head,

$z$ is the elevation above a vertical datum,

$\theta$ is the water content,

$u_w$ is root uptake,

$t$ is time.

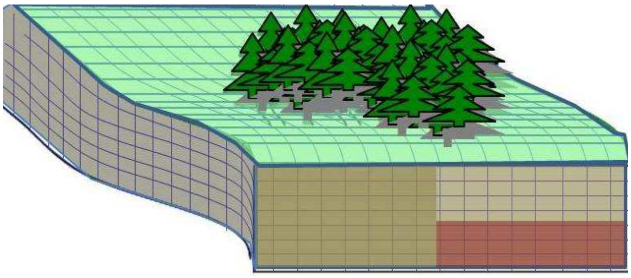


**Figure 17: Schematic layout of SPW showing 3D representation of the soil zone. Colours represent percentage volumes of the soil column corresponding to different textural classes. The model includes a vegetation layer which can be adjusted for different plant characteristics and can include forest cover.**

SPW provides a physically consistent and volumetrically explicit representation (and understanding) of soil moisture fluxes. However, model simulations are computationally intensive and solutions break down if the grid sizes used in applications are too large. Therefore 3D Richard's equation models such as SPW cannot be applied credibly at full catchment scale except perhaps at great computational expense to very small catchments. As it was not possible to run the model for either of the full catchments, due to runtime, we instead applied the model comparison to a single subcatchment represented as one unit within the Uawa TopNet setup, and using a 1m by 1m (lateral) by 1cm (vertical) grid within SPW.

*Results*

Individual state variables and fluxes within TopNet were matched as closely as possible to the spatially explicit volumes and fluxes produced by SPW. In some cases, the comparison had to be adjusted to take into account indirectly coupled processes in TopNet. For example, in TopNet the drainage is corrected for the evaporation demand unsatisfied in the canopy and upper soil layer, without storing both original fluxes separately. In such cases we could not isolate individual fluxes, but were able to compare and closely match the additive combinations between the two models. We therefore ensured that total water balance and overall fluxes from catchment to river were respected in TopNet. For a more detailed explanation of all our specific findings, see Appendix A.

Figure 18 shows the results for the comparison of streamflow between TopNet and SPW, where the storage and conductivity relationships between the models are matched. As can be seen in Figure 18, the overall streamflow, predicted by TopNet and SPW, matches well. The timing and extent of peaks are approximately equal, although SPW predicts a slightly longer recession period after a flood.

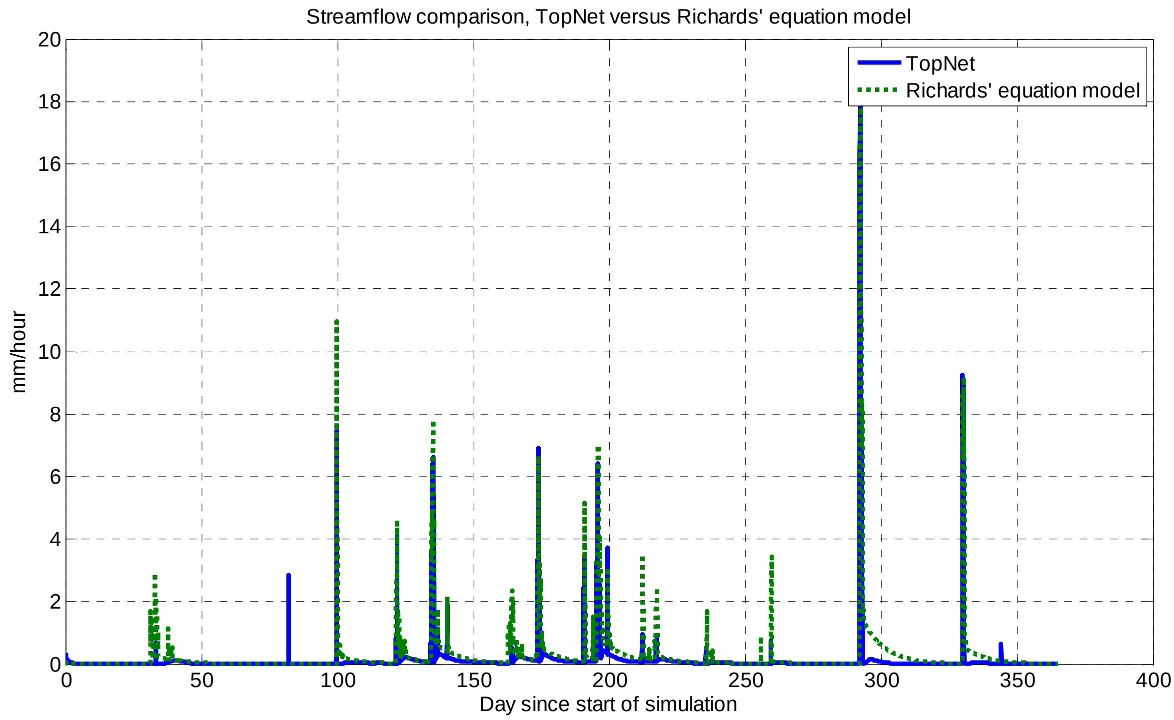



**Figure 18:** **Results for streamflow comparison, TopNet versus SPW**

In conclusion, the flow prediction behaviour that is important for TopNet streamflow forecasts is consistent with the physics-based model outputs in flood conditions. We were able to relate conceptual storages and fluxes to spatially explicit volumes and transfers between states, and also able to put physical constraints on model parameters such as saturated hydraulic conductivity and soil depth. We therefore have increased confidence that TopNet correctly models water movement through the soil zone and will have good predictive power in the study catchment.

#### 3.3.3.2 Model to field comparison

*Introduction*

To further verify the output of TopNet, as well as the (calibrated) model parameters, we undertook field investigations at the Willow Bank farm, which lies in the catchment where the model-to-model comparison was carried out. In this catchment we have a streamflow gauge, and soil moisture measurements and samples were taken for a soil textural classification.

To supplement the quantitative investigation of the site, we made a qualitative inspection of the catchments behaviour, during a site visit which coincided with a medium rainfall event. We assessed the wetness of the catchment at different locations (using hand-held TDR probes), soil texture across the site and dominating processes of rainfall runoff (e.g. infiltration vs. saturation excess runoff; overland vs. subsurface flow).

*Results*

Results from the calibrated Uawa TopNet model implied that a substantial part of the streamflow was generated by overland flow. Specifically, the model results showed that most of this overland flow was infiltration excess overland flow (as opposed to saturation excess overland flow). Our field assessment showed that the behaviour in these model simulations was consistent with observed processes. We saw a significant amount of overland flow (e.g. see Figure 19). A small part of the catchment, close to the river, was saturated (i.e. the water table had risen to the land surface) and showed saturation excess runoff, but the major part of the catchment was subject to overland flow without the soil being saturated. This finding was confirmed by measuring soil volumetric moisture content at a range of depths: the soil moisture readings we performed approximately 15 m away from the river channel showed a decrease of soil moisture with depth for the first 10-20 cm of the soil (see Table 2).

Organic carbon, particle size analysis and bulk density were measured at a variety of depths, and related to soil hydraulic properties through the Saxton and Rawls (2006) pedo-transfer relationships (statistically relating bulk density, %sand, %silt, %clay, & organic matter to saturated hydraulic conductivity and plant available water, among other quantities). We compared the hydraulic conductivity and plant available water inferred through these pedo-transfer relationships to the values within the TopNet simulations (the latter were fixed by calibration to streamflow).

The pedo-transfer relationships suggested plant available water of the order of 0.11 – 0.18 cm $cm^{-1}$, consistent with the values we derived from the TopNet parameters. The pedo-transfer derived hydraulic conductivities were around 60-150mm $h^{-1}$ at the surface, dropping to 8.9-70mm $h^{-1}$ at 40cm below the surface (low values associated with grassland and high values with trees/shrubs). The TopModel calibration assumed a more severe decline in hydraulic conductivity with depth, but the most important “bottleneck” conductivity at depth was not obviously inconsistent with that inferred from the textural data. Some caution is needed, as the imposed declining hydraulic conductivity relationship with depth does lead to drainage being very sensitive to the soil depth parameter, which might at times impact on storage and hence accuracy of flood predictions. Overall however, the pedo-transfer results further supported our general finding that, within the Uawa TopNet simulations, significant subsurface water storage volumes and rates of water flow within these stores are consistent with the physical environment.

**Figure 19:** **(a) Overland flow observed in the catchment. (b) Pits dug for soil moisture sampling**

**Table 2:** **Volumetric soil moisture content measured using a hand-held Campbell Scientific TDR probe at a pasture location at 15 m .distance from the river channel.**

| Depth (cm) | Soil Moisture % (Individual readings) | | | | Mean % moisture content |
|---|---|---|---|---|---|
| 5 | 44 | 42 | 35 | 46 | 41.75 |
| 10 | 43 | 42 | 35 | 32 | 38 |
| 15 | 35 | 34 | 33 | 34 | 34 |
| 20 | 36 | 34 | 35 | 33 | 34.5 |
| 30 | 47 | 46 | 46 | 47 | 46.5 |
| 40 | 54 | 53 | 51 | 47 | 51.25 |
| 50 | 61 | 60 | 61 | 60 | 60.5 |

# 4. Results

## 4.1. Uawa catchment

### 4.1.1. Climate

This section shows the results of data extracted from the Regional Climate Model for the Uawa catchment, after bias correction. In order to compare differences in the climate between current conditions and future conditions, the average daily rainfall is compared per month (Figure 20). The results show that the extended high-rainfall winter period observed in the current climate (May-October) is expected to be shortened under both future scenarios (typically lasting only June-September). Although mean daily rainfalls during the wettest months of July and August are expected to be maintained under the B2 scenario, the A2 scenario results suggest that the mean daily rainfall will be reduced by 10-20% during the winter months.

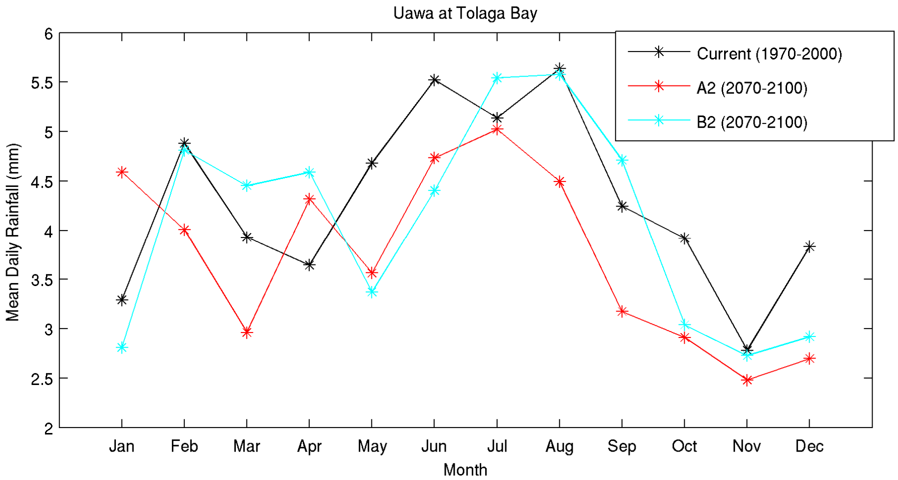



**Figure 20:** **Mean daily rainfall for each month, calculated from the 30-year bias-corrected RCM output for the Uawa catchment. Figure shows current climate compared with future climate under A2 and B2 IPCC emissions scenarios.**

In addition to examining mean rainfall behaviour under climate change scenarios, this project focuses on high-rainfall extremes which cause floods in the Uawa catchment. We therefore use the Regional Model output to compare extremes of daily rainfall totals between current and future scenarios, for each month. The results are shown in Figure 21. The figure shows that extremes in rainfall change little over the autumn, winter and spring months (Apr – Dec), but during the summer period (Jan – Mar) we expect significant increases in the extremes under both A2 and B2 scenarios. However, it is also clear that these extreme rainfalls are rare events, especially in the case of the B2 scenario, often occurring only once in the 30-year simulation period. For example in January, the highest daily rainfall under the B2 scenario was 400mm, but the second highest was only 153mm. The uncertainty in the extreme rainfall is therefore high and repeat model runs may yield noticeably different extreme values. NIWA plans to run repeated RCM simulations using alternative GCM boundary conditions as part of the Regional Climate Modelling programme, so in the future it will be possible to quantify this uncertainty in extremes using model ensembles.

### 4.1.2. Changes in flood risk (30-year return period)

In order to assess the changes in flood risk under climate change, the rainfall and temperature series from the Regional Climate Model (current climate, A2 and B2 climate change scenarios) are used to drive the hydrological model set up for each catchment. The output from the hydrological model is a continuous 30-year flow record which reflects the daily, seasonal and multi-year patterns in catchment wetness which could be expected under each scenario. Flow is calculated hourly by the model. In order to estimate flood frequency under each scenario, the largest flood from each year of simulated record are used to develop the flood frequency curve. There is uncertainty in the hydrological model because different sets of parameters can give similarly good results during the calibration period, but produce different predictions during a future period. In the Uawa catchment, three parameter sets were chosen as equally good. Hence the model is run with each parameter set in turn, giving three different flood frequency records.

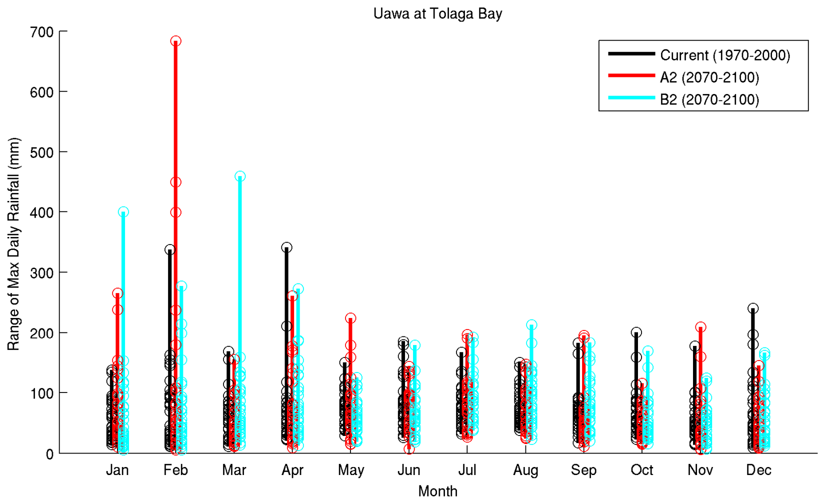
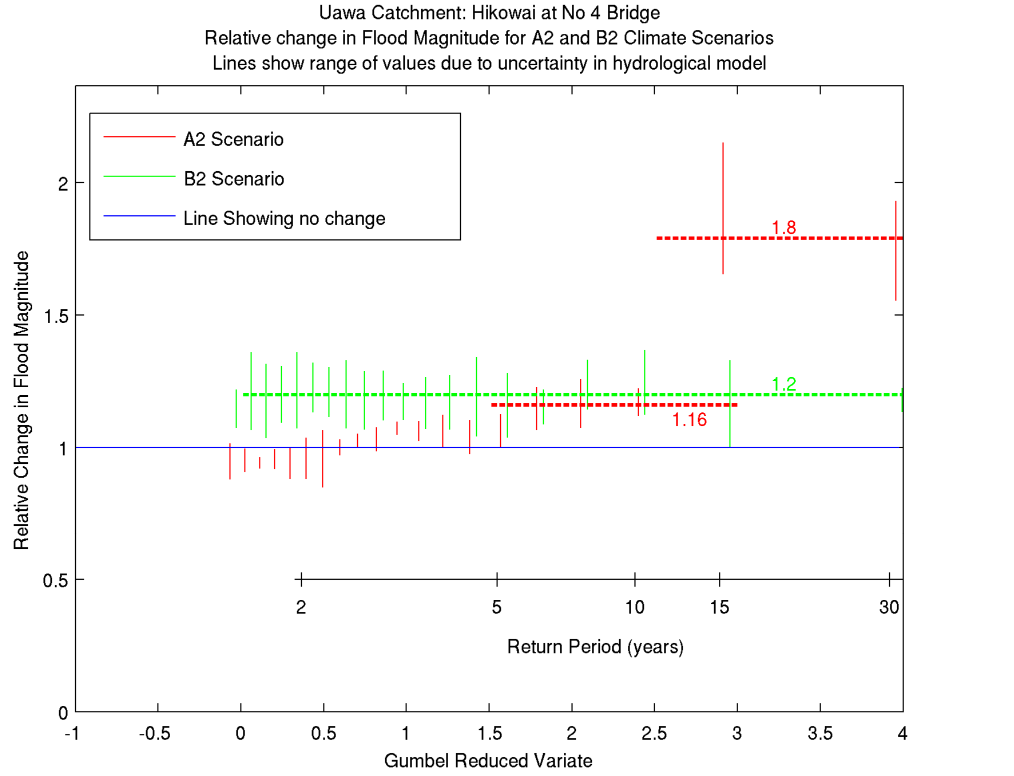


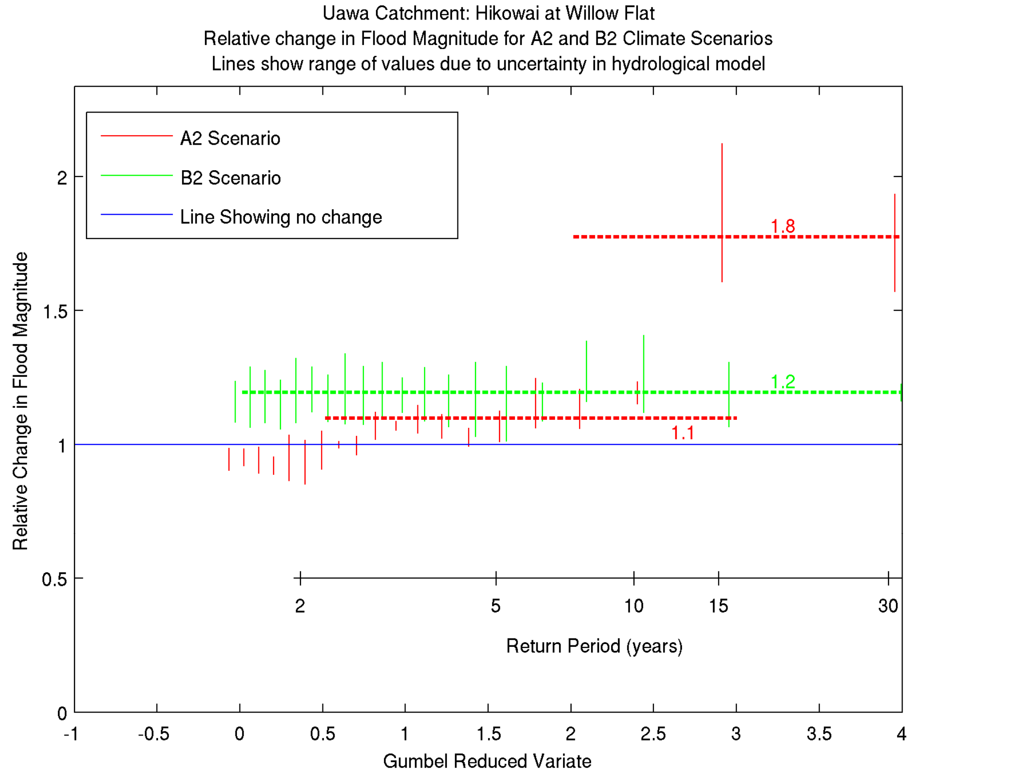

**Figure 21: Ranges of daily rainfall maxima for each month, calculated from the 30-year bias-corrected RCM output for the Uawa catchment. Figure shows current climate (black) compared with future climate under A2 (Red) and B2 (Blue) IPCC emissions scenarios. Lines give range of values, circles show values from individual years of the RCM output.**

We can then assess the changes in flood frequency under climate change scenarios. For each return period up to 30 years, the percent change in flood magnitude under the A2 and B2 scenarios is calculated. These values are shown in Figure 22, for the three gauging stations in the Uawa catchment. The range of values is shown using an error bars, rather than as points, to show the uncertainty due to the hydrological model parameter set.

The figures show clear differences between the A2 and B2 climate scenarios. Under the B2 scenario (moderate emissions), floods at all return periods and all gauging locations are expected to be larger, having approximately 1.2 times the discharge seen under current conditions. Under the A2 scenario, floods at less than two years return periods (e.g. the annual flood) are expected to decrease slightly (approximately 0.9 times current discharge); floods at 2- to10- year return period will be little changed (0.9 – 1.1 times current discharge); but floods at the 15 – 30 year return period may become significantly larger, up to 1.8 times current discharge for the two sites on the Hikowai. The results suggest that the Mangaheia branch will be worst affected under this scenario, with the 30-year return period up to 2.5 times current volume, although this result is highly uncertain as it relies on the most extreme event predicted by the models. The Mangaheia is likely to be worst affected due to the steep upland country in the headwaters which can cause high-discharge, short-duration flood events.


Uawa Catchment: Hikowai at No 4 Bridge
Relative change in Flood Magnitude for A2 and B2 Climate Scenarios
Lines show range of values due to uncertainty in hydrological model
A2 Scenario
B2 Scenario
Line Showing no change
Relative Change in Flood Magnitude
1.8
1.2
1.16
2
5
10
15
30
Return Period (years)
Gumbel Reduced Variate

A


Uawa Catchment: Hikowai at Willow Flat
Relative change in Flood Magnitude for A2 and B2 Climate Scenarios
Lines show range of values due to uncertainty in hydrological model
A2 Scenario
B2 Scenario
Line Showing no change
Relative Change in Flood Magnitude
1.8
1.2
1.1
2
5
10
15
30
Return Period (years)
Gumbel Reduced Variate

B

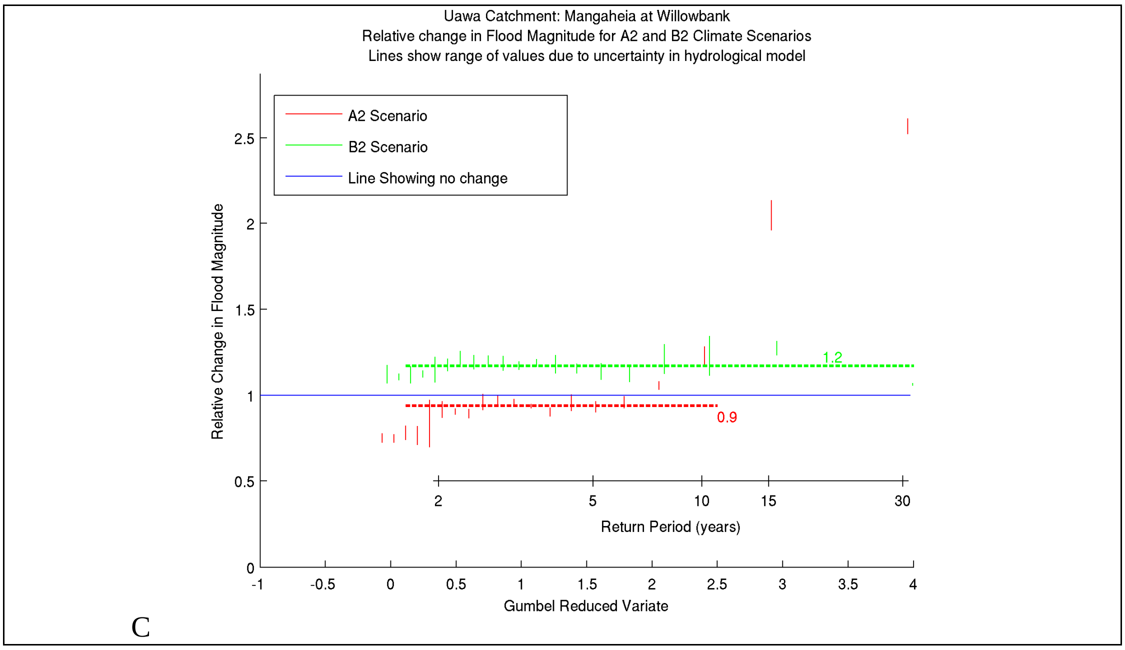


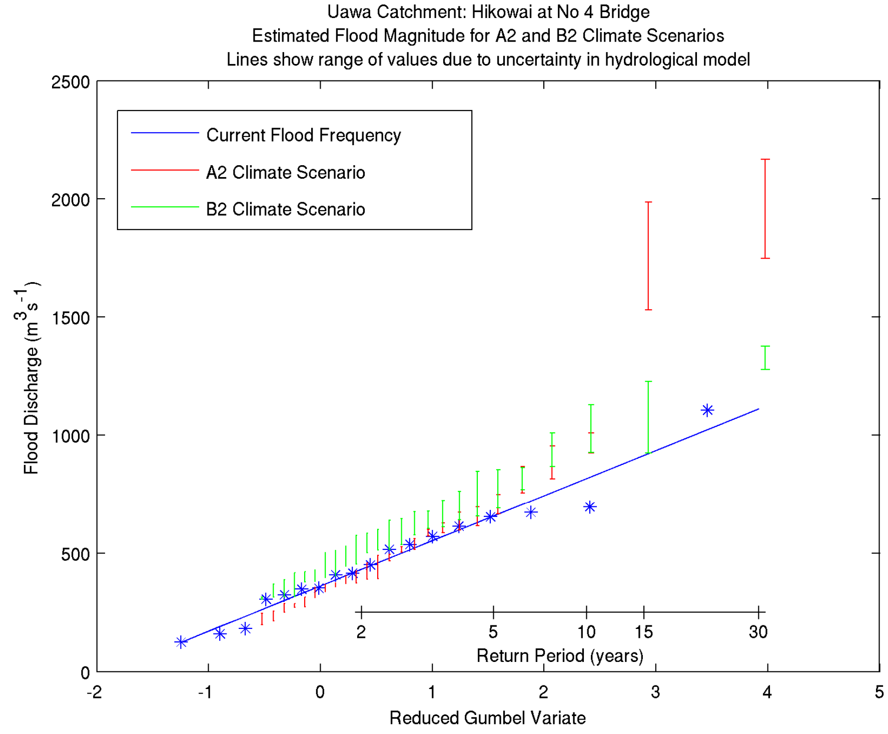

**Figure 22: Percent changes in flood frequency expected under A2 and B2 climate change scenarios for three gauging stations in the Uawa catchment: (A) Hikowai at No. 4 Bridge (B) Hikowai at Willow Flat (C) Mangaheia at Willowbank**

Figure 23 shows the changes in flood frequency in terms of discharge rather percentage change, to aid understanding of the data.

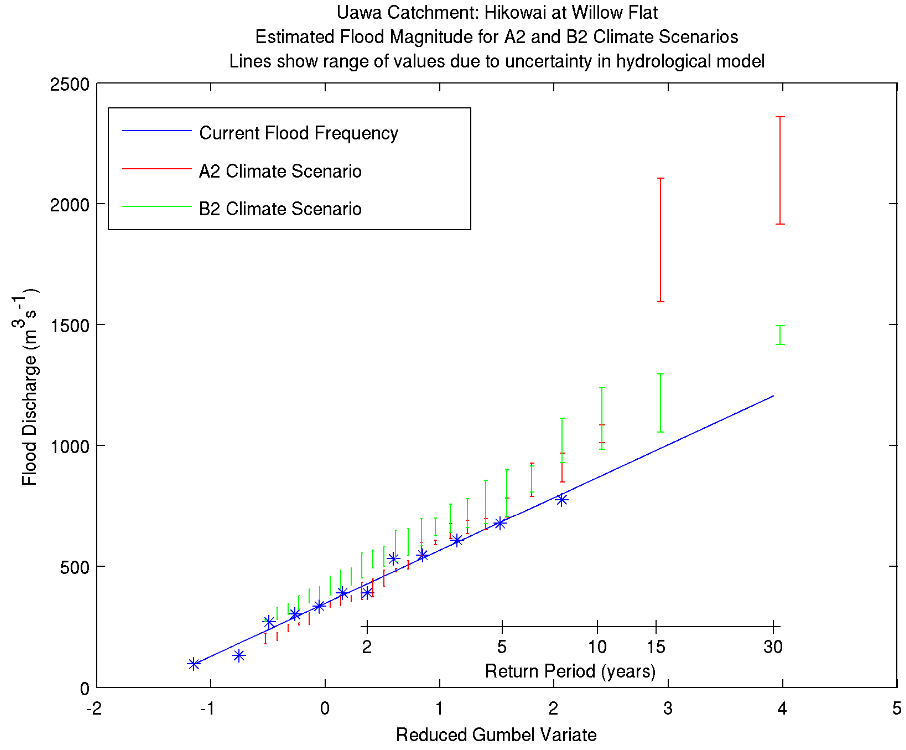
### 4.1.3. Rainfall generator results

In order to make predictions of flood discharge under climate change for floods of return period great than 30 years, the rainfall generator (described in Section 3.2) was used to generate rainfall series of 1000 years with the same statistical properties as the 30 year sequence. In order to check that the rainfall generator is working correctly, the rainfall values produced are compared with the original Regional Climate Model rainfall values for each scenario. The comparison is made by splitting the 1000-year series into 30-year sections, and comparing the range of values with the RCM value (Figure 24).

Figure 25 shows that the rainfall generator is working reasonably well, with the range of rainfall maxima from the rainfall generator surrounding the recorded RCM output rainfalls in most cases. At the 1-day timescale, the rainfall maxima for a 3-year return period or more extreme are higher under both future climate scenarios. This demonstrates how the rainfall has become more variable under climate change, with higher extremes and hence greater flood risk. However, at the 28-day timescale, the rainfall maxima are forecast to be lower in the future. This shows how long-term rainfall will decrease (leading to more common droughts), despite occasional heavy rainstorms giving high 1-day totals.


Uawa Catchment: Hikowai at No 4 Bridge
Estimated Flood Magnitude for A2 and B2 Climate Scenarios
Lines show range of values due to uncertainty in hydrological model
Current Flood Frequency
A2 Climate Scenario
B2 Climate Scenario
Flood Discharge (m3s-1)
Return Period (years)
Reduced Gumbel Variate

A


Uawa Catchment: Hikowai at Willow Flat
Estimated Flood Magnitude for A2 and B2 Climate Scenarios
Lines show range of values due to uncertainty in hydrological model
Current Flood Frequency
A2 Climate Scenario
B2 Climate Scenario
Flood Discharge (m3s-1)
Return Period (years)
Reduced Gumbel Variate

B

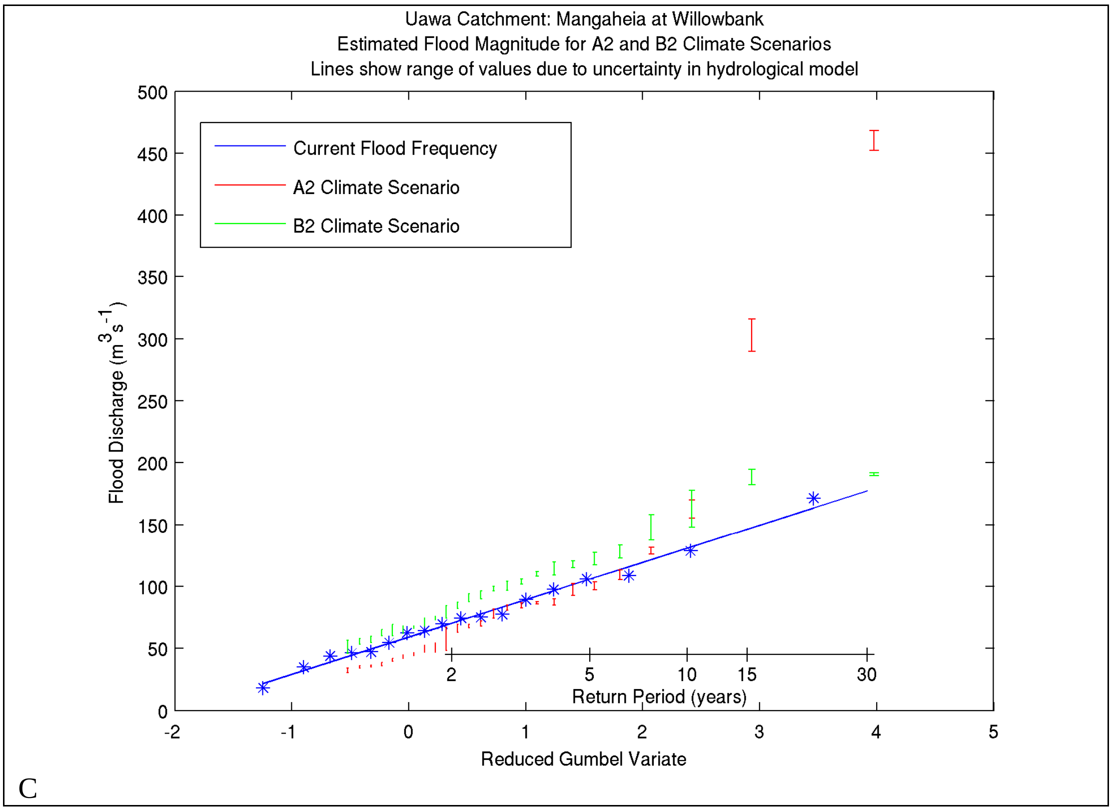



**Figure 23: Absolute changes in flood frequency expected under A2 and B2 climate change scenarios for three gauging stations in the Uawa catchment: (A) Hikowai at No. 4 Bridge (B) Hikowai at Willow Flat (C) Mangaheia at Willowbank**

However, we also note that in some cases (typically in the range of return periods 3-10 years), the rainfall generator produces lower values than the original RCM rainfall. This discrepancy may be due to the type of statistical distributions fitted in the rainfall generator (mixture of exponentials light-tailed distribution) which restricts the range of extreme values it is able to produce. In the future, NIWA aims to diversify the range of distributions able to be fitted by the rainfall generator.

The figure also shows the variability inherent in the climate system (refer to the uncertainty bounds shown from the simulated rainfall series). We should therefore expect that although sometimes there will be dry years or multi-year periods without damaging floods; in general the flood risk will be greater under both A2 and B2 scenarios.

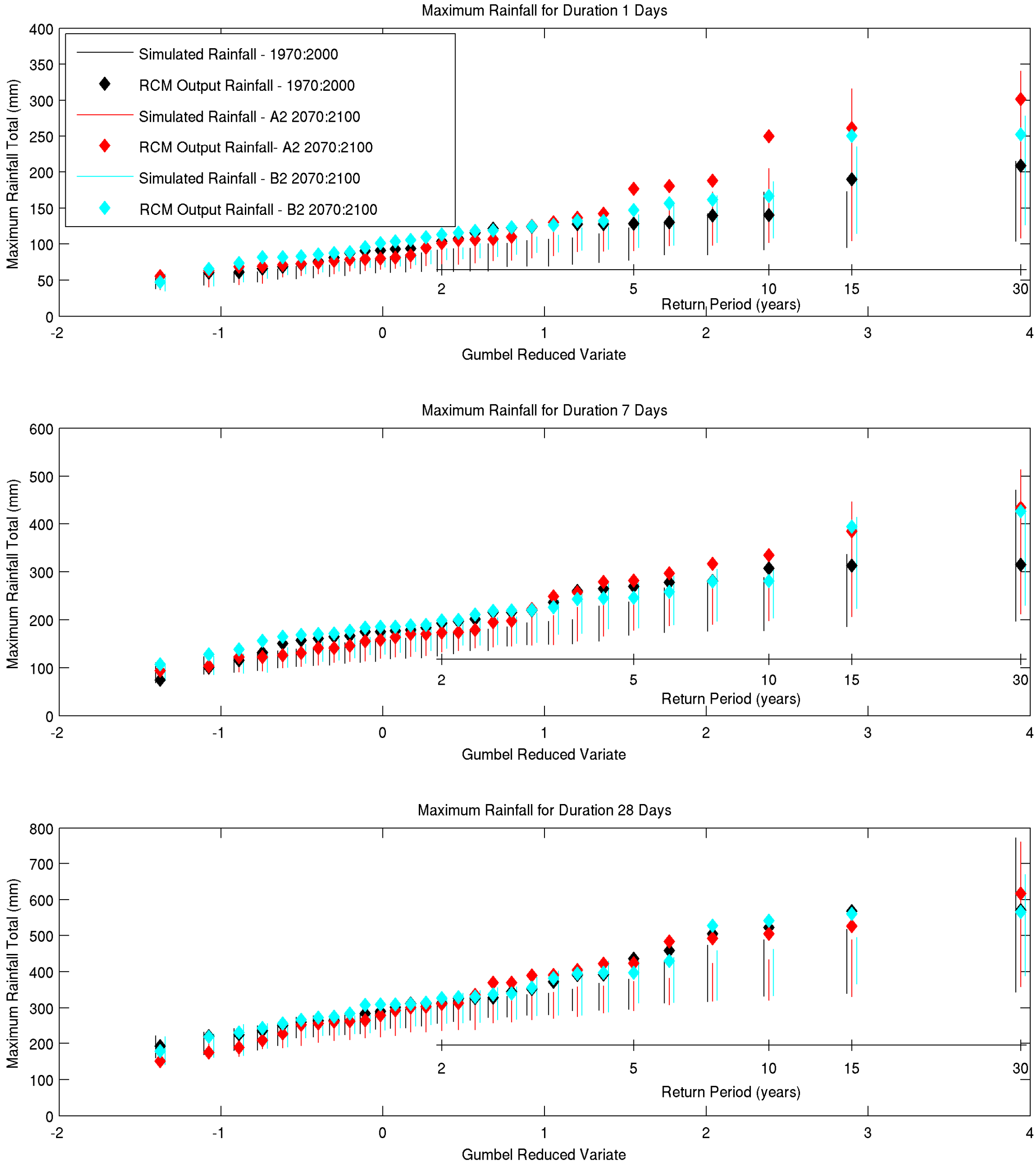
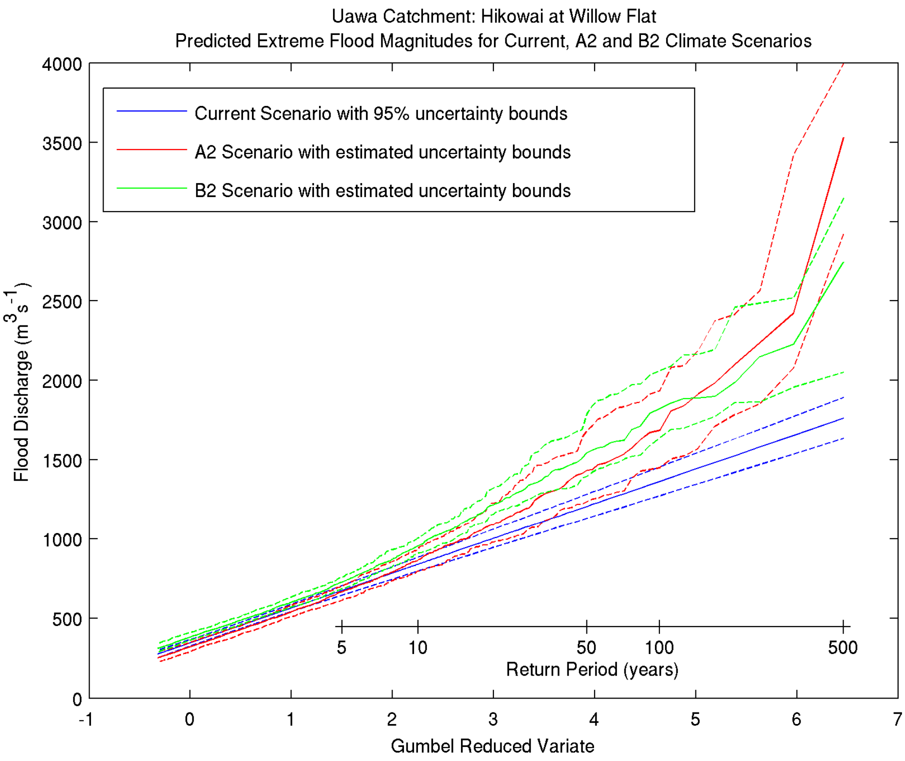
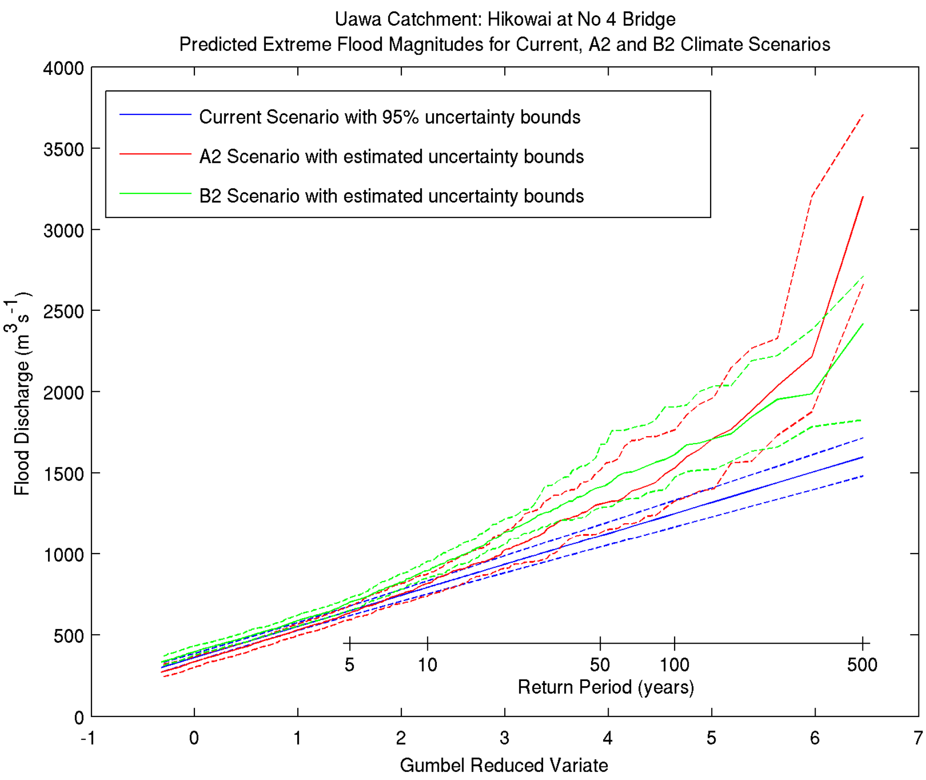



**Figure 24:** **Maximum rainfall at different durations, compared between RCM output and rainfall generator output, for current and future (A2/B2) RCM scenarios.**

A.


Uawa Catchment: Hikowai at Willow Flat
Predicted Extreme Flood Magnitudes for Current, A2 and B2 Climate Scenarios
Current Scenario with 95% uncertainty bounds
A2 Scenario with estimated uncertainty bounds
B2 Scenario with estimated uncertainty bounds
Flood Discharge (m3s-1)
4000
3500
3000
2500
2000
1500
1000
500
0
5
10
50
100
500
Return Period (years)
-1
0
1
2
3
4
5
6
7
Gumbel Reduced Variate

B


Uawa Catchment: Hikowai at No 4 Bridge
Predicted Extreme Flood Magnitudes for Current, A2 and B2 Climate Scenarios
Current Scenario with 95% uncertainty bounds
A2 Scenario with estimated uncertainty bounds
B2 Scenario with estimated uncertainty bounds
Flood Discharge (m3s-1)
4000
3500
3000
2500
2000
1500
1000
500
0
5
10
50
100
500
Return Period (years)
-1
0
1
2
3
4
5
6
7
Gumbel Reduced Variate

C

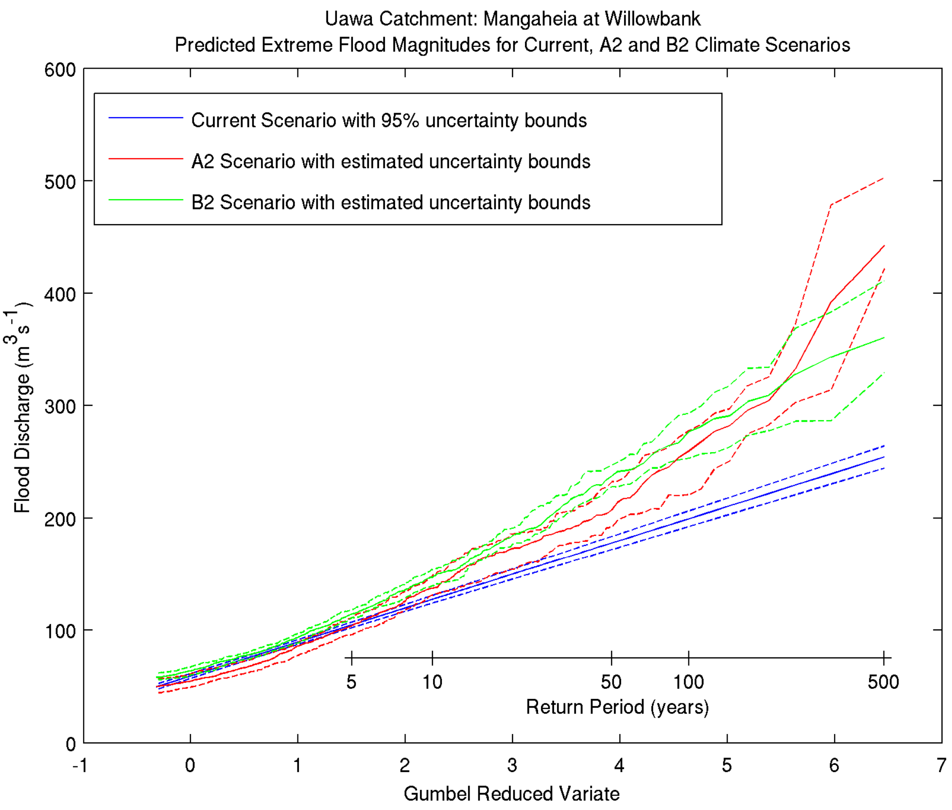



**Figure 25:** **Absolute changes in flood frequency for return periods up to 500 years, under A2 and B2 climate change scenarios for three gauging stations in the Uawa catchment: (A) Hikowai at Willow Flat (B) Hikowai at No. 4 Bridge (C) Mangaheia at Willowbank. Solid lines show median predicted values; dashed lines show uncertainty bounds.**

### 4.1.4. Changes in flood risk (500-year return period)

Using the 1000-year rainfall series produced by the rainfall generator, the hydrological model is run for a 1000-year period to simulate the extreme floods possible in the Uawa catchment, under Current (1970-2000), A2 (2070-2100) and B2 (2070-2100) scenarios. The procedure is exactly the same as for the 30-year model runs described in Section 4.1.2. In order to estimate flood frequency under each scenario, the largest flood in each year of simulated record is noted, and these values are used to form a flood frequency curve. The three plausible hydrological model parameter sets used give uncertainty in the flood frequency curve. The procedure is then repeated for a second independent 1000-year series produced by the rainfall generator (the series are produced using random sampling from statistical distributions fitted to observed rainfall data, and therefore re-running the rainfall generator produces a different series). This allows us to further account for uncertainty caused by the stochastic nature of the rainfall generator; although typically this uncertainty is small compared with that caused by the choice of hydrological model parameters.

The results are used to calculate the flood discharge for return periods up to 500 years (it is good practice to estimate return periods only up to one half of the length of series available: an estimate of the 1000-year flood would be considered too unreliable due to high errors). The results are shown in Figure 25. The flood discharges in the current climate are also shown with uncertainty bounds in this case, as these values also are estimates derived from extrapolation of the measured record. The extrapolation was done by fitting a Gumbel extreme value distribution to the record which gave a good fit to the data.

The projections show that floods up to approximately 3500 cumecs at a 500-year return period are possible at the Willow Flat gauge location on the Uawa under the A2 climate change scenario, compared with 2800 cumecs under the B2 climate change scenario and 1800 cumecs under current conditions. As with the 30-year data, a complex picture emerges where any increases in flood discharge are controlled by both emissions scenario and return period. Results from the A2 scenario show the most extreme floods at the 500-year return period which may indicate increased instability and intensification of weather systems under a high emissions scenario. However the moderate-emissions B2 scenario shows the highest floods at lower returnperiods. The uncertainties are very large for such extreme return periods due to both uncertainty in the climate change projections and uncertainty in the rainfall generator and hydrological model: the error bounds are typically ± 500 cumecs. Where estimates are required for floods of lower return period, the 30-year results should be used in preference as they have lower uncertainty. However the results presented here give an indication of changes in flood discharge under climate change and may assist Regional Councils needing information on a ‘worst-case scenario’.

## 4.2. Waihou

In order to further test the flood frequency assessment method developed for the Uawa catchment, the same analyses are repeated for the Waihou catchment. This enables us to compare the method in a different location which may undergo different changes in rainfall patterns under climate change, and to assess the consistency of the method. To reduce the computational burden for this catchment, only a single 1000-year rainfall series was used to drive the hydrological model, so the uncertainty in the rainfall generator 1000-year results is not assessed in this case. Three parameter sets for the hydrological model are used, as before.

### 4.2.1. Climate

This section shows the results of data extracted from the Regional Climate Model for the Waihou catchment, after bias correction. The same analyses are carried out as for the Uawa catchment. In order to compare differences in the climate between current conditions and future conditions, the average daily rainfall is compared per month (Figure 26). The model results show a similar pattern to the Uawa, where the extended high-rainfall winter period observed in the current climate (May-October) is shortened under both future scenarios (typically lasting only June-September). Mean daily rainfalls during the winter months are reduced under both A2 and B2 climate scenarios, with the reduction being more extreme under the A2 scenario.

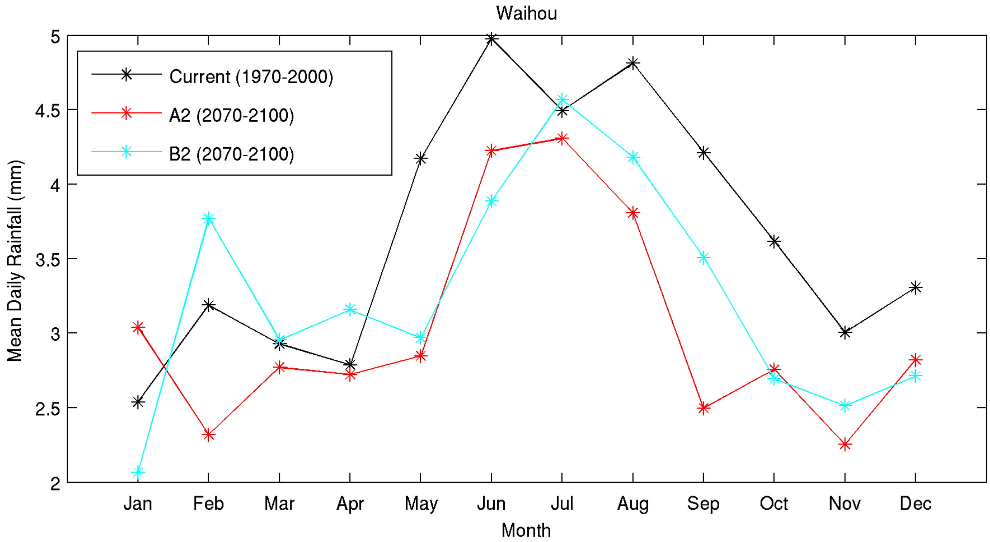



**Figure 26: Mean daily rainfall for each month, calculated from the 30-year bias-corrected RCM output for the Waihou catchment. Figure shows current climate compared with future climate under A2 and B2 IPCC emissions scenarios.**

The extremes of daily rainfall totals between current and future scenarios, for each month, are also examined for the Waihou catchment. The results are shown in Figure 27. The figure shows that extremes in rainfall are increased throughout the year, under both A2 and B2 climate scenarios, although the increase is the most pronounced during the summer period (Dec – Mar).

Unlike the simulations for the Uawa catchment where the A2 scenario gave the highest extreme rainfalls, in the Waihou catchment it is the B2 scenario produces the highest daily rainfall values. This demonstrates the complex nature of climate changes, under different emissions scenarios and in different locations. The results suggest that in the Waihou, a limited increase in greenhouse gases may give rise to decreased average rainfall but increased rainfall extremes, whereas under greater greenhouse gas increases, the increase in rainfall extremes is lower as total rainfall volumes fall. However as commented with the Uawa results, the uncertainties relating to these modelling results are high, and further model runs will be essential to confirm the conclusions.

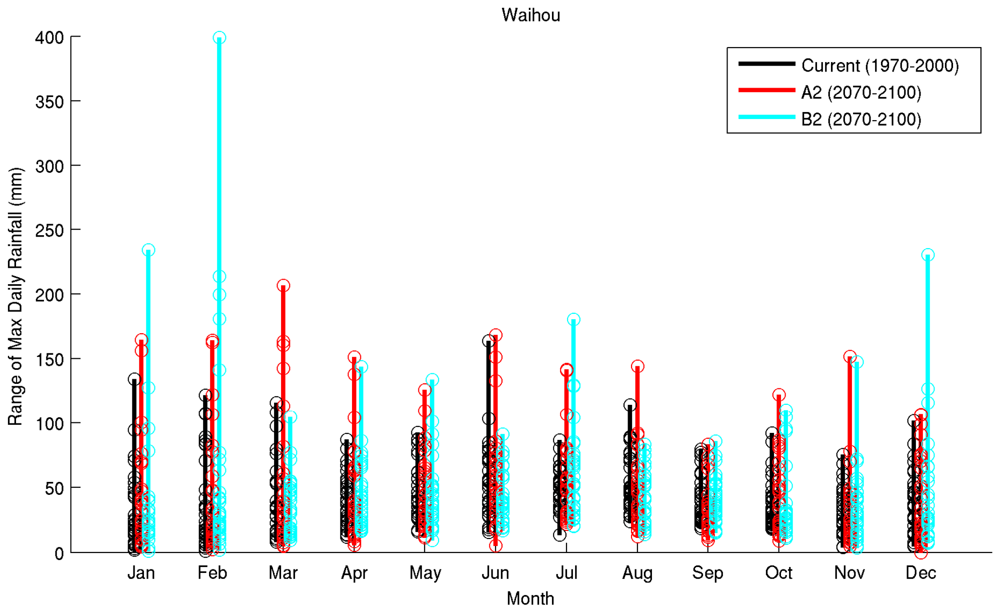



**Figure 27: Ranges of daily rainfall maxima for each month, calculated from the 30-year bias-corrected RCM output for the Waihou catchment. Figure shows current climate (black) compared with future climate under A2 and B2 IPCC emissions scenarios. Lines give range of values, circles show values from individual years of the RCM output.**

### 4.2.2. Changes in flood risk (30-year return period)

In order to assess the changes in flood risk under climate change, the 30-year rainfall and temperature series from the RCM (current climate, A2 and B2 climate change scenarios) were used to drive the hydrological model set up for the Waihou. In the Waihou catchment, three parameter sets were chosen as equally good. Hence the model is run with each parameter set in turn, giving three different flood frequency records. The flood frequency curve is calculated as before.

We can then assess the changes in flood frequency which are possible under climate change. For each return period up to 30 years, the percent change in flood magnitude under the A2 and B2 scenarios is calculated. These values are shown in Figure 28 below, for the gauging station in the Waihou catchment. The values are shown as error bars (ranges of values) rather than points to show the uncertainty due to the hydrological model parameter set.

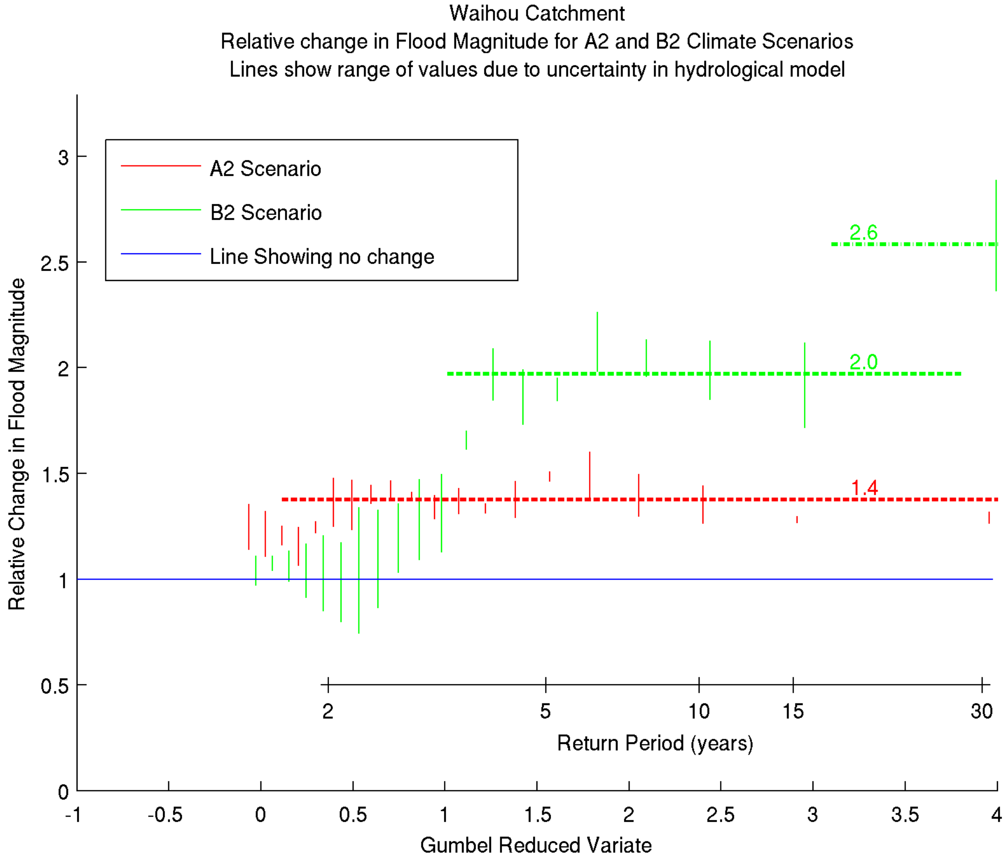



**Figure 28: Percent Changes in Flood Frequency expected under A2 and B2 Climate Change Scenarios for the gauging station in the Waihou catchment**

Figure 28 shows clear differences between flood frequency under the A2 and B2 climate scenarios in the Waihou catchment. Under the A2 scenario (high emissions), floods at all return periods are expected to be larger, approximately 1.4 times the discharge for current conditions. Under the B2 scenario (moderate emissions), floods at less than 3-year return periods are similar to current conditions; and floods at 4- to 15-year return period will increase to approximately twice the current discharge. Floods at the extreme 30 year return period are shown to become up to 2.6 times current discharge; however, this result is highly uncertain as it relies on the most extreme event predicted by the models. As commented for the rainfall values, in the Waihou it the B2 climate scenario which is predicted to give the most increase in flood discharges. For the A2 scenario, floods are still expected to be larger than in the current climate, but the increase will not be as severe.

The following Figure 29 shows the changes in flood frequency in terms of discharge rather percentage change, to aid understanding of the data.

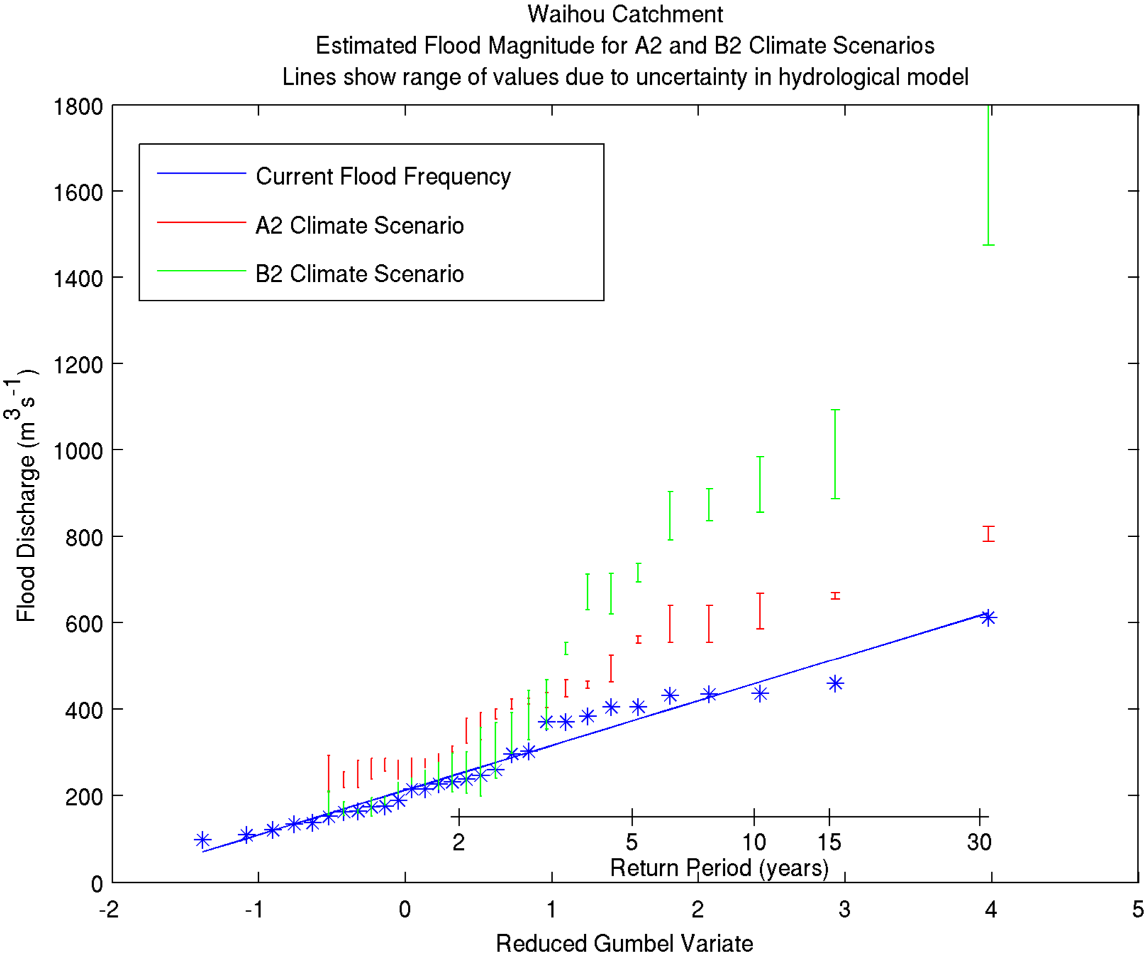



**Figure 29: Absolute changes in flood frequency expected under A2 and B2 climate change scenarios for the gauging station in the Waihou catchment**

### 4.2.3. Rainfall generator results

In order to make predictions of flood discharge under climate change for floods of return period great than 30 years in the Waihou, the rainfall generator (described in Section 3.2) was used to generate rainfall series of 1000 years with the same statistical properties as the 30 year sequence. As with the Uawa catchment, the rainfall generator series are checked by comparison with the original RCM output (Figure 31).

Figure 30 shows that as in the Uawa catchment, the rainfall generator is working reasonably well in the Waihou, with the range of rainfall maxima from the rainfall generator surrounding the recorded RCM output rainfalls in most cases. At the 1-day timescale, the rainfall maxima for a 2-year return period or more extreme are higher under both future climate scenarios, with the B2 scenario producing the highest rainfall totals.

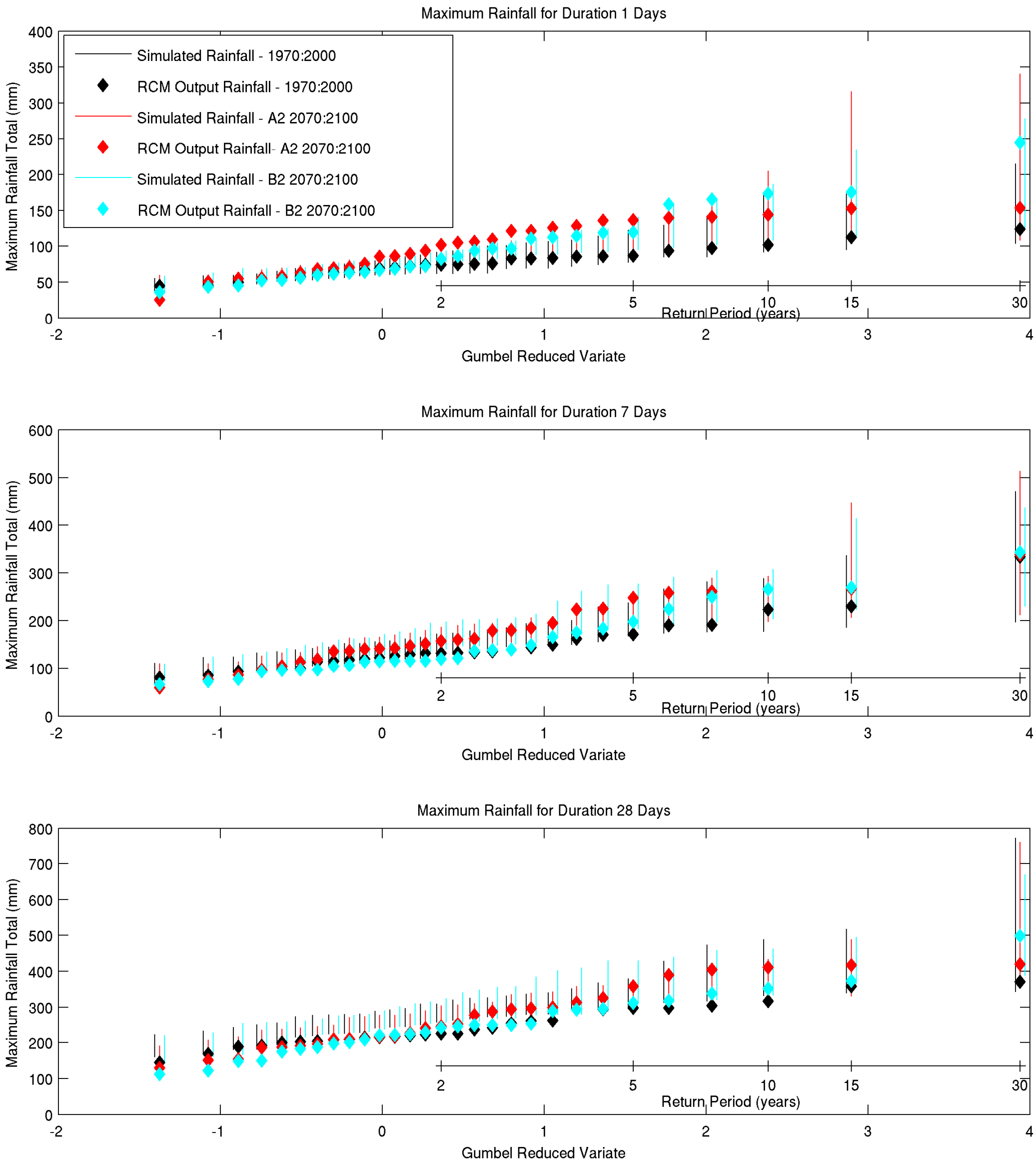



**Figure 30: Maximum rainfall at different durations for the Waihou catchment, compared between RCM output and rainfall generator output, for current and future (A2/B2) RCM scenarios.**

### 4.2.4. Changes in flood risk (500-year-return period)

Using the 1000-year rainfall series produced by the rainfall generator, the Waihou hydrological model is run for a 1000-year period to simulate the extreme floods possible in the Waihou catchment, under Current (1970-2000), A2 (2070-2100) and B2 (2070-2100) scenarios. The procedure to form the flood frequency curve is the same as for the Uawa catchment. The three plausible hydrological model parameter sets used give uncertainty in the flood frequency curve.

The results are used to calculate the flood discharge for return periods up to 500 years. The results are shown in Figure 31. Floods up to 1200 cumecs at a 500-year return period are predicted in the Waihou under the climate change scenarios. At this extreme return period both A2 and B2 scenarios give similar ranges of values. This discharge compares with 880 cumecs for the 500-year flood under current conditions, extrapolated from measured data. It is also important to note that the climate change uncertainties become very large for such extreme return periods, and therefore the results can only be used to give an indication of flood discharge.

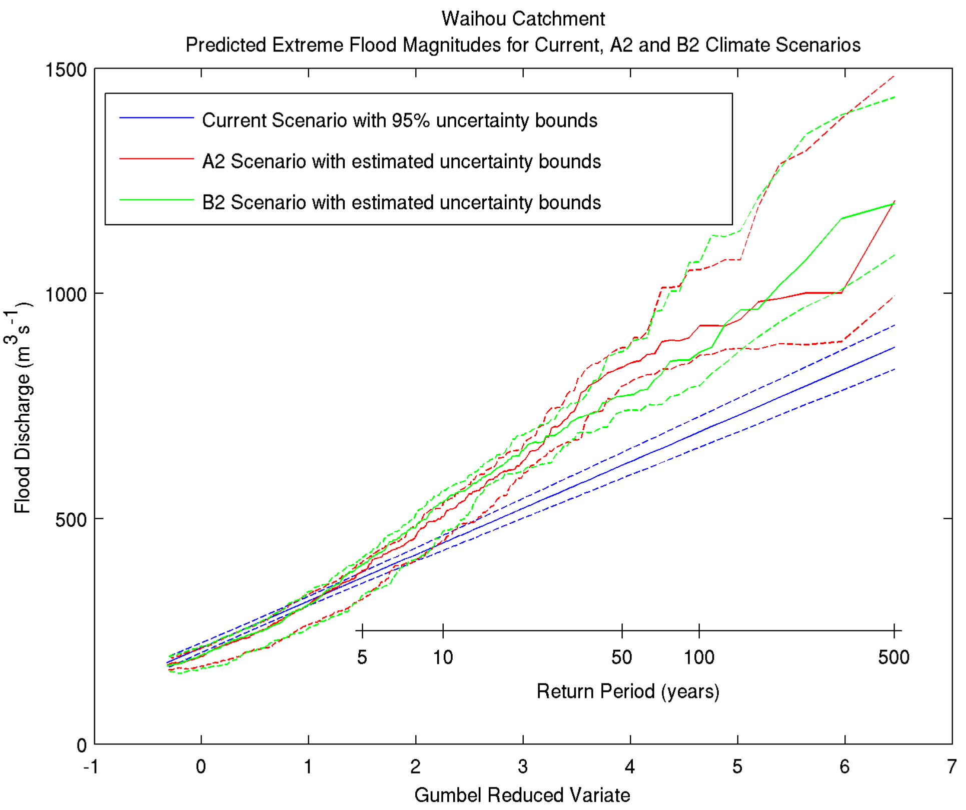



**Figure 31: Absolute changes in Flood Frequency up to 500-year return period under A2 and B2 Climate Change Scenarios for the gauging station in the Waihou catchment. Solid lines show median predicted values; dashed lines show uncertainty bounds.**

## 4.3. Seasonal impacts of climate change in the Uawa and Waihou

A brief comparison of the differing impacts of climate change on seasonal precipitation in the two case-study catchments in shown below (Figure 32). This figure shows that the climate change scenarios can have significantly different effects in different locations in NZ, dependent on predicted changes in local weather patterns. In this case the reduction in seasonal precipitation totals by 2070-2100 is most severe in the projections for the Waihou catchment where it is expected to decrease across all seasons for both A2 and B2 scenarios. In the Uawa the changes are less certain with totals under the B2 scenario, not greatly reduced from current levels. By season, spring rainfalls are predicted to be most severely reduced; which has implications for pasture growth and requirements for irrigation at this critical time of year. Rainfalls during autumn and winter are predicted to be less severely affected.

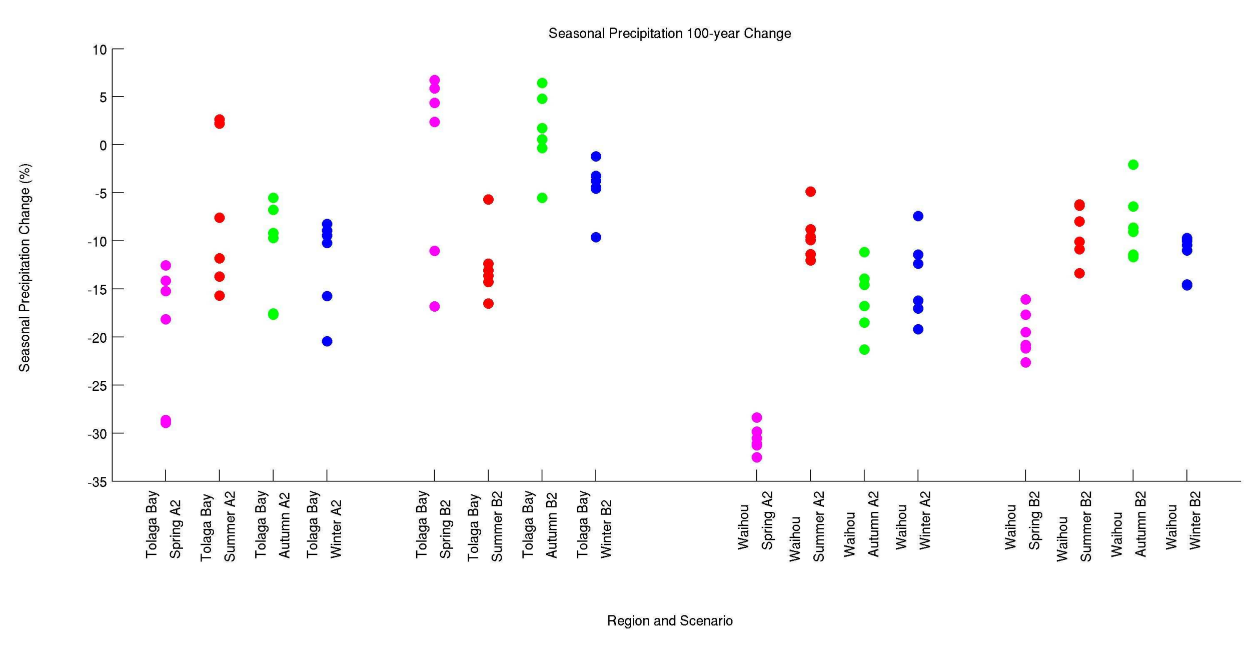



**Figure 32:** **A comparison of seasonal precipitation change under IPCC climate change scenarios A2 and B2 for the Uawa at Tolaga Bay and the Waihou. Results are split by season.**

# 5. Conclusions

## 5.1. Development of the flood risk assessment framework

The flood risk assessment framework developed in this study has been shown to be able to produce projections of climate change impacts on rainfall patterns and totals; and river flow and floods – at annual, seasonal and daily scales. The framework differs from previous methods used to assess climate change impacts because it is 'process-based' – i.e. it explicitly models the water cycle through rainfall, catchment water balance and flow processes, and the changes in the water cycle under different climate scenarios. This enables us not only to predict future changes in river flows, but to understand the reasons behind the changes and the effects on the wider water resource, and hence provides opportunities for improved integrated catchment management under climate change.

This process-based framework allows us to draw a wide range of conclusions and understand changes to a wide range of processes by collecting information from the models at the appropriate point. For example: rainfall totals and peaks can be analysed for different areas of the catchment, flow can be analysed at different locations in the river network giving detailed projections for sites of interest. Feedback from end-users in response to the presentation of results at the NZ Hydrological Society conference in Whangerei (McMillan *et al.*, 2009) was very positive; in particular the ability to make projections of river flows at known gauging sites was welcomed.

The results presented in the two case-study catchments chosen for this study show that flood frequency changes under climate change are highly dependent on location and underline the importance of high-resolution modelling of climate and hydrological processes, tailored for the individual river or catchment.

## 5.2. Limitations, extensions and recommendations

The development of the Flood Risk Assessment framework was designed as a short-term (1-year) pilot study and has identified various areas where further work is appropriate before the framework can be rolled out to provide national projections of climate change impacts.

1. The Regional Climate Model simulations underpinning this study are currently being updated under FRST programme C01X0804 with new emissions scenarios, GCM boundary conditions and an enlarged model domain. Once these simulation results are available, the bias in model simulations compared to measured climate data will be reduced and the hydrological model simulations should be re-run to provide improved predictions.

2. The rainfall generator used in this study performed reasonably well for producing daily rainfall simulations over long time series. However the following improvements are suggested as necessary before further work is undertaken: (i) The range of extreme-value distributions able to be fitted should be increased, in particular to include heavy-tailed statistical distribution types. (ii) Rainfall generator feasibility for application over large catchments with high numbers of RCM grid points should be ensured. (iii) Alternative downscaling methods from 30km grid to appropriate scales for small catchments should be investigated: currently the long-term mean rainfall surface is used but the use of different rainfall surfaces for storm event types would also be beneficial.

3. During this study, the uncertainty in the climate change impact projections due to the IPCC climate scenario, the stochasticity of the rainfall generator, and the uncertainty in hydrological model parameters were all taken into

account to produce error bounds for the predicted flood discharge values. However it would be desirable to additionally include the uncertainty due to which Global Climate Model is used to provide the Regional Climate Model boundary conditions. In a concurrent FRST programme (C01X0804) the RCM simulations will be placed in the wider context of the range of 12 GCM simulations currently used by NIWA, and the results of this analysis should be included in future work.

This study has also identified opportunities for the development of climate change impact scenarios to provide additional information to NZ water resource and hazard management practitioners. Due to the process-based nature of the Flood Risk Assessment Framework which models the complete water cycle, statistics on changes in soil moisture and soil water processes were also collected. Further analyses of these statistics to provide information on changes in agricultural conditions under climate change would be expected to be highly beneficial. In addition, the ability of the rainfall generator to quantify rainfall patterns in terms of mixtures of statistical distributions has the potential to provide an improved method to quantify changes in mean and extreme rainfall behaviour predicted by the Regional Climate Model over the whole of NZ.

## 5.3. Summary of climate and hydrological modelling results

This section gives a brief summary of the climate modelling results for the two case-study catchments (Uawa and Waihou). These results are taken from the statistical analysis of the Regional Climate Model simulations, comparisons of current (1970-2000) and future (2070-2100) climate projections, and hydrological model output. As highlighted in the previous section, these results are based on A2 and B2 scenarios from a single Global Climate Model (HadCM3 from the UK Meteorological Office), and there is a need for further research to understand how the scenarios studied fit into the range of alternative climate scenarios and GCMs.

### 5.3.1. Seasonal and Annual Rainfall Trends

In the Northland and East Cape locations studied here, annual and seasonal rainfall totals are expected to decrease under climate change: typical changes are between -5% and -20% of current rainfall totals. Spring rainfalls are predicted to be most severely reduced; while rainfalls during autumn and winter are predicted to be less severely affected. The decrease is predicted to be more severe for the A2 scenario (high emissions) than the B2 scenario (moderate emissions); and more severe for Northland than for East Cape. In Northland, approximate predicted change in annual total is -15% to -20% (A2) or -10% to -15% (B2). In East Cape, approximate predicted change in annual total is -10% to -15% (A2) or 0% to -5% (B2). Exact values depend on which location in the region is used.

### 5.3.2. Changes in Seasonal Extreme Rainfalls

The extreme rainfall values which can cause floods show different patterns under climate change than the changes seen in seasonal or annual totals. In the Uawa catchment the overall pattern seen is a drier climate but with more severe storms and flood events. Again there are differences according to season: rainfall extremes change little over the autumn, winter and spring months (Apr – Dec), but during the summer period (Jan – Mar) there are significant increases in rainfall extremes in the 30-year future scenario under both A2 and B2 scenarios, with the highest projected daily rainfall totals up to double those measured in the current climate.

In the Waihou catchment, the picture is more complex. A moderate carbon emissions scenario (B2) is projected to have similar effects to those in the Uawa: drier winters but more extreme rainfall in the summers (Dec – Mar), with 30-year daily extreme values simulated to double. However under the more extreme climate change scenario (A2), increases in the daily rainfall extremes are less severe, which we hypothesise may be due to the overall decrease in rainfall.

### 5.3.3. Changes in Flood Frequency (30-year data)

By using the simulated rainfall data for different emissions scenarios to drive the TopNet hydrological model, the changes in rainfall extremes and patterns can be used to model changes in flood frequency.

In the Uawa catchment, under the B2 scenario, floods for return periods up to 30 years are expected to be larger, having approximately 1.2 times the discharge seen in current conditions. Under the A2 scenario, floods for return periods up to 10 years will be little changed (0.9 – 1.1 times current discharge); but floods at the 15 – 30 year return period may become significantly larger, up to 1.8 times current discharge. For example, the current 10-year flood of 800 $m^3s^{-1}$ is projected to increase to 900-1100 $m^3s^{-1}$; the current 30-year flood of 1100 $m^3s^{-1}$ is projected to increase to 1300-1400 $m^3s^{-1}$ (B2 scenario) or 1700-2200 $m^3s^{-1}$ (A2 scenario).

In the Waihou catchment, under the A2 scenario, floods at return periods between 2 and 30 years are expected to be larger, having approximately 1.4 times the discharge seen in current conditions. Under the B2 scenario, floods at less than three years return periods are little changed; but floods at 4 – 30 years return period may increase to twice the current discharge or even higher. For example, the current measured 10-year flood discharge is approximately 400 $m^3s^{-1}$; this is projected to increase to 600-700 $m^3s^{-1}$ (A2 scenario) or 850-900 $m^3s^{-1}$ (B2 scenario).

### 5.3.4. Changes in Flood Frequency (1000-year data)

The hydrological model was also used to simulate flood characteristics during a 1000-year simulation, using input data from the rainfall generator. This information gives an indication about the magnitude of extreme floods under climate change, but is highly uncertain due to the high level of extrapolation needed.

In the Uawa catchment at the Willowbank gauge on the Hikowai branch, the 500-year flood under current climate conditions is predicted to be 1650-1900 $m^3s^{-1}$, calculated by extrapolation using standard extreme value theory. Under climate change scenarios, this discharge is simulated to increase to 2000-3100 $m^3s^{-1}$ (B2 scenario) or up to 2900-4000 $m^3s^{-1}$ (A2 scenario), with the higher emissions scenario therefore giving rise to more extreme flood events. In the Waihou catchment, the 500-year flood is currently estimated to be 830-930 $m^3s^{-1}$, which could increase to 1100-1400 $m^3s^{-1}$ (B2 scenario) or 1000-1500 $m^3s^{-1}$ (A2 scenario).

# 6. Summary of research outputs

Five presentations were made during the research programme. These are listed below:

| | |
|---|---|
| 1 | McMillan, H.K., Jackson B., Poyck, S.<br>Impacts of climate change on river flow and floods: summary of proposed research.<br>Presented at the New Zealand River Managers Forum, Wellington, March 2009. |
| 2 | McMillan, H.K., Jackson B., Poyck, S.<br>Impacts of Climate Change on River Flow and Floods. Presented at the New Zealand Climate Change Conference, Wellington, 2009. |
| 3 | B. M Jackson, H. K. McMillan, S. Poyck, B. O'Leary<br>Increasing confidence in model predictive capabilities under climate change through diagnosis of internal fluxes and storages<br>Poster presented at the American Geophysical Union Fall Meeting, San Francisco, 2009<br>Refer to Appendix A for full text of the poster. |
| 4 | McMillan H.K., Jackson B., Poyck, S.<br>A framework for assessing the impacts of climate change on river flow and floods, using dynamically-downscaled climate scenarios<br>Presented at the New Zealand Hydrological Society Conference, Whangerei, November 2009. |
| 5 | McMillan, H.K., Jackson B., Poyck, S.<br>Impacts of climate change on river flow and floods: review and findings of the 1-year research program.<br>Presented at the New Zealand River Managers Forum, Wellington, March 2010. |

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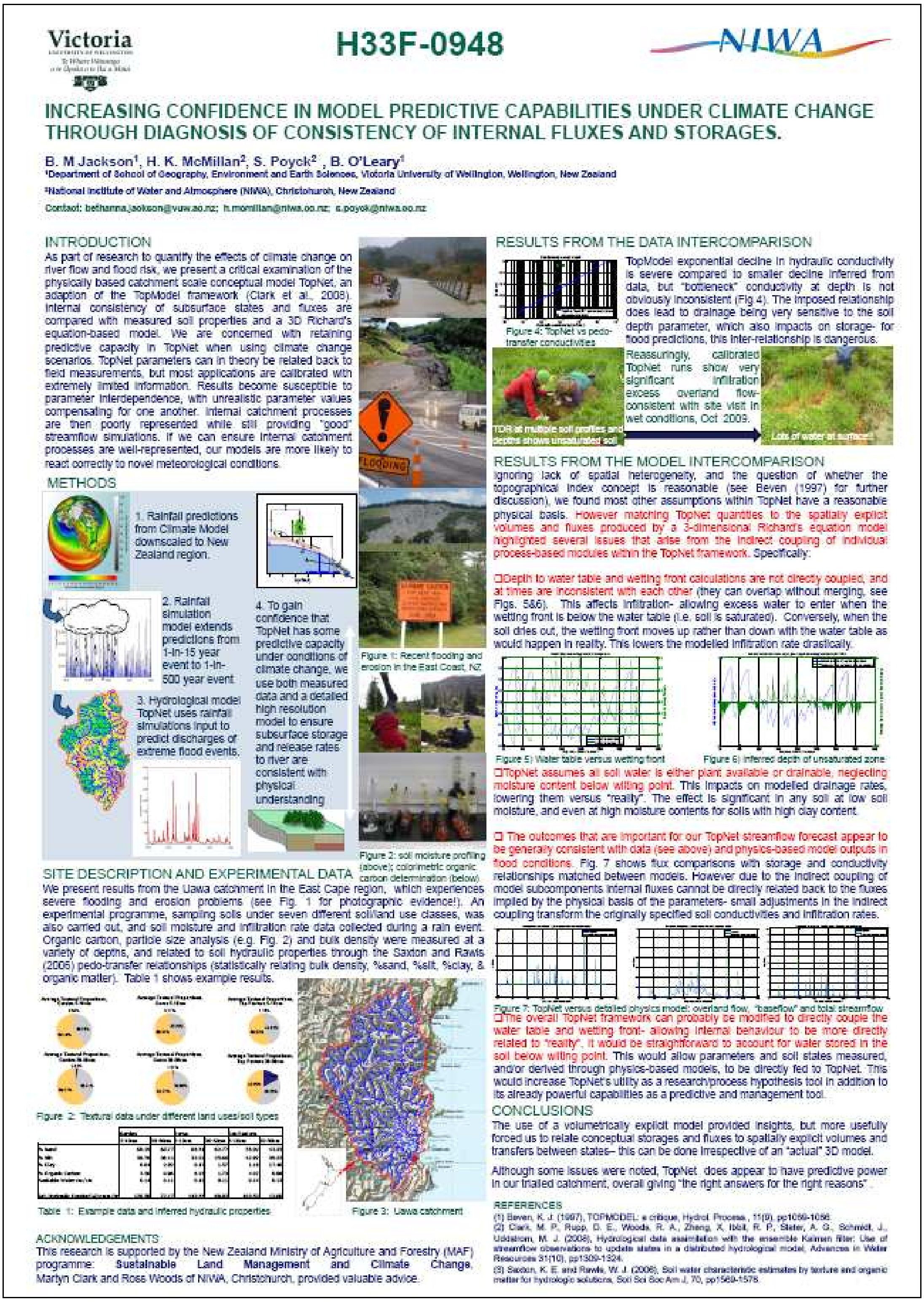
## Appendix A: Poster Presentation

The poster below describes results of the project objective to compare the TopNet catchment model to a 3D Richard's equation model and experimental data from the Uawa catchment. The poster was presented at the American Geophysical Union Fall Meeting, December 2009, San Francisco.



# Appendix B: State equations of TopNet

There are five components of storage of water in a sub-catchment. They are the canopy storage (Sc), snowpack storage (Ss), soil, or root zone, storage (Sr), aquifer storage (Sa), and overland flow storage (So). The movement of water in time t into and out of each of these storages is described by differential equations. The three that are relevant to this project are:

$$\frac{dS_r}{dt} = i - e_r - d \quad \text{[Eq. B1]}$$

where
$S_r$ is soil storage
$i$ is the infiltration rate
$e_r$ is the evaporation rate,
$d$ is the rate of drainage from the soil to the aquifer,
$t$ is time.

$$\frac{dS_a}{dt} = d - q_b \quad \text{[Eq. B2]}$$

where
$S_a$ is aquifer storage,
$d$ is the rate of drainage from the soil to the aquifer,
$q_b$ is the baseflow rate,
$t$ is time.

$$\frac{dS_o}{dt} = q_{ix} + q_{sx} + q_b - q_o \quad \text{[Eq. B3]}$$

where
$S_o$ is overland flow storage,
$q_{ix}$ is the infiltration excess overland flow rate,
$q_{sx}$ is the saturation excess overland flow rate,
$q_b$ is the subsurface runoff rate,
$q_o$ is the basin outflow rate from the surface storage to the river network,
$t$ is time.