The potential effects of climate change on flood frequency in the Hutt River

Prepared for the New Zealand Climate Change Research Institute
Victoria University Wellington

2011

John Ballinger [1],Bethanna Jackson[1], Andy Reisinger[2] and Kristin Stokes[1]
[1]School of Geography, Environment and Earth Sciences, Victoria University of Wellington, Wellington, New Zealand
[2]Climate Change Research Institute, Victoria University of Wellington, Wellington, New Zealand

School of Geography, Environment and Earth Sciences
Victoria University of Wellington
PO Box 600
Wellington
New Zealand

Contact: Bethanna Jackson
Phone: (04) 463 6116
Email: bethanna.jackson@vuw.ac.nz

Caveat

This work was undertaken as a small component within the overall project to illustrate a risk-based approach to decision making under climate change. The work is not intended to serve specific planning purposes. Although we believe there is some potential in the approach used, the illustrative results provided are limited by significant data deficiencies, parameters chosen, and assumptions and results that could not be appropriately examined or ground-truthed given the limited resources available.

This research was funded by the Foundation for Research, Science and Technology under contract VICX0805 *Community Vulnerability and Resilience.*

Contract: E1307

Vulnerability, Resilience, and Adaptation Objective 2 reports, October 2011	
NZCCRI-2011-01	Synthesis: Community vulnerability, resilience and adaptation to climate change in New Zealand
NZCCRI-2011-02	Vulnerability and adaptation to increased flood risk with climate change—Hutt Valley summary *(Case study: Flooding)*
NZCCRI-2011-03	**The potential effects of climate change on flood frequency in the Hutt River (SGEES client report) *(Case study: Flooding)***
NZCCRI-2011-04	Potential flooding and inundation on the Hutt River (SGEES client report) *(Case study: Flooding)*
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1 Introduction

The residents of the Hutt Valley face a significant flood hazard. In 2000 it was estimated that flood hazard in the Hutt Valley would affect 106,000 residents including 75,000 floodplain occupants, and up to $6 billion of public and private property (Wellington Regional Council 2001a). The onset of climate change and its predicted impacts on river flow and flooding will likely further increase the risk to those communities. With this in mind, the New Zealand Climate Change Research Institute (NZCCRI) of Victoria University Wellington has commissioned the authors to establish how much the current flood risk could alter under climate change based on the expected changes in rainfall intensity during storm events. An increase in temperature increases the water holding capacity of the atmosphere, which in turn contributes to larger more intense rainfall. This study uses global temperature increase scenarios from the International Panel on Climate Change's (IPCC) Fourth Assessment Report (2007b) to predict what climate might reasonably be like over the Wellington region out to 2040 and 2090. It uses three SRES emissions scenarios (B1, A1B, A2) based on 12 climate change models in addition to a baseline case. The baseline is a 40 year record (1 Jan 1970 to 1 Jan 2010) taken from the Hutt River. Downscaled climate patterns were used to generate perturbed rainfall scenarios based on alternative emissions scenarios and global climate models. The perturbed rainfall files were then used as input to NIWA's hydrological model TopNet, which was used to make predictions for changes in flood frequency.

This report is broken into four main sections after this introduction (Section 1). Section 2 provides some information on the flood risk to the Hutt Valley with background detail on the Hutt River characteristics, historical flooding and Hutt River Floodplain Management Plan (2001). Section 3 reviews and compares previous work addressing flood frequency and climate change on the Hutt River. Section 4 tests TopNet's validity compared to the baseline record, and then discusses the potential changes in flood frequency under the different climate change scenarios. Section 5 summarises the outcomes of this report.

2 Background

2.1 Hutt River characteristics

The Hutt catchment area is 655km^2 and starts in the Tararua Ranges ending where the Hutt River enters Wellington Harbour. The main channel is 54km and is generally aligned with the Wellington fault and is influenced by both tectonic activity and significant human modification (Wellington Regional Council 1995). Four main tributaries, the Akatarawa (116km^2), Mangaroa (104km^2), Pakuratahi (81km^2), and Whakatiki (82km^2) contribute flow. Land use in the catchment ranges from forest and scrubland in the upper hill and mountainous areas to agricultural, industrial, commercial and residential land uses in the lower portions. The Hutt River is hydraulically connected to the Hutt Aquifer and in the lower reaches flows across a broad alluvial flood plain formed during previous glacial periods (Wellington Regional Council 1995).

Precipitation varies across the catchment primarily due to orographic effects and is distributed relatively evenly throughout the year, but with a maximum in winter. Mean annual precipitation varies from about 1,200mm a year in low lying areas to 5,000 mm a year in some headwater areas in the Tararua Ranges (Wellington Regional Council 1995).

The Hutt River is gauged with flow recorders and meteorological stations throughout the catchment. Due to the high risk of flooding in the lower reaches a flood warning system has been established utilising rainfall-runoff models and telemeter recording stations. The catchment area is capable of producing an estimated *probable maximum flood* of 7000 cumecs, but with a return period of thousands of years is extremely unlikely (Wellington Regional Council 2001a).

2.2 History of flooding

The Hutt River has a long history of flooding. The first European/Pakeha settlers in the Wellington Region settled around Petone and Lower Hutt in the 1840s. Within two months of the arrival of the first New Zealand Company ships the Hutt River had burst its banks inundating the settlement. Over the next 50 years, 20 major floods were recorded within the Hutt Valley (Hutt City Council 2007). Further flooding in conjunction with earthquakes in 1855 caused many residents to move to Wellington. In 1898 the largest recorded flood in the valleys history (2000 cumecs) rose 900mm in 30 minutes and covered the entire valley floor (Hutt City Council 2007). This led to the construction of the first major stopbanks to protect Hutt residents. Over the next 150 years intensive settlement and land use cleared the nearby hill slopes of indigenous vegetation and urbanised the floodplain confining the river to its present path. This has created a significant flood hazard for the growing Hutt Valley community with a number of substantial historical floods (see Table 1). In response to these floods structural measures in the form of stopbanks, rock linings, bank edge works, gravel extraction, and bed and beach re-contouring have formed the basis of the Hutt flood protection system (Wellington Regional Council 2001a).

Table 1. Data sourced from (Pearson and McKerchar 1999; Wellington Regional Council 2001a)

Hutt River Historical Floods		
Date	Flow (m^3s^{-1})	Return period (year)
1855	-	-
1858	2000 approx	100
1878	-	-
1893	1550 & 1700	20 & 50
1898	2000 & 1500	100 & 20
1931	1400	20
1939	1600	50
1976	-	-
1998	1305 & 1540	10 & 20
2000	1245	10
2004	1067	5
2005	1527	20

All flows are provided as if measured at the Lower Hutt City centre (Taita Gorge)

2.3 Hutt River Floodplain Management Plan (2001)

The Hutt River Floodplain Management Plan (HRFMP) is the main document for managing flood risk on the Hutt River. It represents 10 years of work by Wellington Regional Council, the Upper Hutt and Hutt City councils, the Manawhenua, and the residents of the Hutt Valley. The HRFMP is a blueprint for protection works from the year 2000 to 2040 when works are due for completion. Over the 2000 to 2040 period, reviews have been scheduled every 10 years, with additional reviews planned after any major floods occur. This is to allow provision for change in response to needs that arise and refinement where new data and/or increasing scientific understanding allow. A review is currently pending. Concurrently there is ongoing work on implementing non-structural measures as part of the Hutt River Environmental Strategy (Wellington Regional Council 2001b)

2.4 Hutt floodplain hydraulic modelling

As part of the HRFMP process Hutt floodplain hydraulic modelling was required. For convenience, the Hutt floodplains were separated into five independent hydraulic units and flow simulated using separate models for each area. These were Lower Hutt (from Pomare to Seaview on the left bank of the Hutt River), Upper Hutt (from Maoribank to Silverstream on the left bank of the Hutt River), Petone (on the right bank of the Hutt River downstream of Melling bridge), Totara Park (on the right bank of the Hutt River opposite Maoribank), and Manor Park (on the right bank of the river upstream of Pomare bridge)(Barnett Consultants 1993:1). The Hutt River channel data is composed of cross sections with roughness (Manning's *n* values) specified. It was found that simulated flows in the Upper and Lower Hutt models significantly affected flow on the Hutt River, which was therefore included in these models. In the other models, the interaction between the floodplain and river flow were less important so they were mostly run disconnected from the Hutt River, and were driven by water level boundary conditions at overtopping points (Barnett Consultants 1993:1). The combined flow on the Hutt was calculated using a DHI one-dimensional hydraulic modelling package MIKE11. In addition, a bridge modelling package HYBRID was used to support MIKE11 simulations by providing a more sophisticated analysis of flow through bridge piers than was included in MIKE11. The brief for the investigation called for "(1) the simulation of a total of 5 stopbank breaches at plausible locations and times (near the peak of a large flood); (2) the flow over the floodplains due to overtopping of the stopbanks during two large floods (with peak flows of 3000 and 3500m^3/s) to be modelled; (3) the overtopping cases in (2) to be modelled with each exacerbated by a different scenario of debris blockage on the 10 Hutt River bridges within the urban area"(Barnett Consultants 1993:1). For detailed analysis and results see (Barnett Consultants 1993; 1999)

In 1999 a consultancy, Montgomery Watson, reviewed and updated MIKE11. The changes were in regard to the starting conditions of hydraulic factors, the way bridges were modelled, and boundary conditions. The model was then calibrated and different flood events modelled using three different channel configurations (existing, minimum, wide) with results available in Wellington Regional Council (1999).

2.5 Selecting the design standard

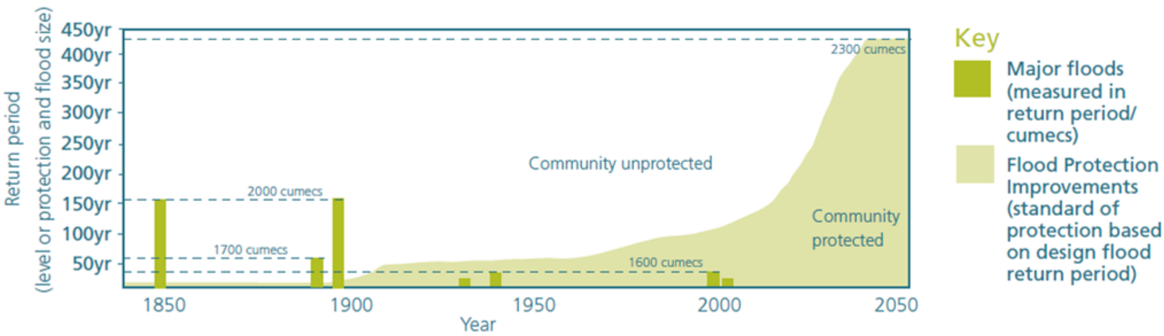
When selecting the design standard for the HRFMP, different policies were considered. Of note was Policy 3: Reinforcing the Selected Design Standard and Individual Measures where the issue of climate change specified an "accounting for potential climate change scenarios that predict an increased frequency of larger floods" (Wellington Regional Council 2001a:39).

An important part of the flood mitigation process is deciding on what level of protection to build to and in what areas. The degree of structural protection is a trade off between the level of protection and cost. In the Hutt River a design standard of 2300 cumecs (a 1 in 440-year flood) was chosen via a risk-based approach. This approach applies varying protection standards to different areas of the flood plain depending on how flood prone they are. The level of protection chosen for each flood-prone area is mainly based on potential damage costs, area and number of people affected, and the area's vulnerability to flooding and erosion (Wellington Regional Council 1999). The risk-based standard for the Hutt River provides a 2300 cumec standard of protection to all floodplain areas except for small urban areas. The Plan (2001a:32) lists its main features as:

- an emphasis on protecting existing urban floodplain areas;
- upgrading all major stopbanks to a 2800 cumec standard capacity (a rare flood), with remaining stopbank protection mostly to a 2300 standard (a 1 in 440-year flood);
- bank-edge and berm protection to a 1900 cumec standard (a 1 in 100-year flood) for isolated and small urban areas, and a 2300 cumec standard for main urban areas;
- assistance for house raising; replacing bridges at the end of their useful life, with new bridges and their associated floodways required to pass a 2800 cumec flood;
- developing appropriate risk-based non-structural measures to complement the structural measures for the different flood-prone areas of the Hutt Valley.

The flood hazard is complex and forever changing as either new protection works are completed, or existing works degrade. The Plan lists the capacity of the existing system as mixed. Bridges that span the Hutt influence the capacity of the system with all having varying abilities to allow flood flows beneath them. The HRFMP states that "the stopbanks upstream of Kennedy-Good Bridge, except for a few reaches, are adequate to contain a 2800 cumec flow. However, the mix of bank-edge protection, berm widths and stopbanks lack the combined strength necessary to hold such flows" (Wellington Regional Council 2001a:33) Indeed, a few individual properties on Gemstone Dr are susceptible to flooding in a 100 year event. The reaches of the river downstream from Kennedy-Good Bridge have a much lower capacity and security. If all goes to plan the entire length of the Hutt River downstream from Kennedy-Good Bridge should have a capacity of at least 2300 cumecs by 2021. However, the river mouth downstream of Ava Rail Bridge will only have protection to contain a 100 year event (Flanagan 2010). Figure 1 displays the major floods and flood protection improvements on the Hutt River. The grey area after 2001 shows the level of protection if planned flood protection works are completed.

Major Floods and Flood Protection Improvements on the Hutt River (1850 – 2050)



(Flood protection improvements and major flood events)

The bars on the graph show the major floods on the Hutt River since 1850.The dotted lines and the return periods on the left axis show the **size** of the floods. The flood protection improvements (which started in 1901) are shown as the blocked out area that increases over time. These improvements have already started to provide the community with a higher level of protection, and more improvements will continue until the Plan has been fully implemented. By 2040 these improvements will provide protection against a 440 year (2300 cumec) flood.

It is important to remember that this graph is only an indication of the varying level of protection provided to the community through flood protection improvements on the Hutt River. To find out more , get a copy of the Hutt River Floodplain Management Plan from the Greater Wellington website www.gw.govt.nz.

Figure 1. Flood protection improvements and community protection on the Hutt River Source: GWRC

3 Hutt River flood frequency and climate change

3.1 Effects of interannual and decadal variability

When evaluating the affects of climate change in New Zealand, regional climate oscillations such as the Interdecadal Pacific Oscillation (IPO) and El Niño Southern Oscillation (ENSO) must be considered. Both are Pacific wide natural climate variations, but operate over different time scales. ENSO functions on a yearly basis and is superimposed over the longer term decadal variability of the IPO.

3.1.1 El Niño Southern Oscillation (ENSO)

ENSO is a coupled natural climate fluctuation composed of an oceanic component (El Niño) and an atmospheric component (Southern Oscillation). El Niño involves warming of tropical Pacific surface waters to the west of South America which changes oceanic circulation. Its atmospheric counterpart, the Southern Oscillation involves changes in trade winds, tropical circulation and precipitation. Historically, El Niño events occur every 3 to 7 years and alternates with La Niña which lies at the opposite end of the ENSO cycle. When neither are present it is called neutral, or normal conditions (IPCC 2007b).

During El Niño New Zealand tends to experience stronger more frequent wind and rain in the west during summer, and drought in the east. During winter, the winds tend to be from the south, and cool the land and surrounding ocean. During spring and autumn there is a mixture of both summer and winter effects. La Niña has less of an effect on New Zealand's climate but can cause more north-easterly winds which bring warm rainy conditions to the north east of the north island, and reduced rainfall to the south and south-west of the South Island (Wratt *et al.* 2008). However, Wratt, Basher, and Renwick (2008) note that "although El Niño has an important influence on New Zealand's climate, it accounts for less than 25% of the year to year variance in seasonal rainfall and temperature at most New Zealand measurement sites".

Despite this, it is thought that ENSO may have contributed to a number of shifts in New Zealand climate in 1978. Pearson and McKerchar (1999) checked whether ENSO affected the Hutt catchment by using the Southern Oscillation Index (SOI). The SOI provides an index of the state of ENSO with negative values corresponding to El Niño conditions, and positive values to La Niña conditions. The effect of El Niño on annual maxima floods on the Hutt River was assessed by NIWA scientists Pearson and McKerchar (1999). They compared two river reaches; Kaitoke (1968-1998), and Birchville (1971–1998) against the SOI at the time of the flood peak and found "no obvious relationship between flood peak and SOI for either site" Pearson and McKerchar (1999:13).

3.1.2 Interdecadal Pacific Oscillation (IPO)

A second NIWA report by Tait et al., (2002) looked for evidence of the effects of the IPO on rainfall within the Hutt catchment. Tait et al., (2002) examined rainfall records from the Hutt catchment for the period 1961–1990 and found an increase in heavy rainfall in the west of the Wellington region (Wellington) and a decrease in the east (Masterton). However, Tait et al., (2002) note that there was no indication of a decrease in the number of very wet years in Masterton with at least 10 days above the 95-percentile. These changes did not coincide with the observed IPO shift around 1978 which was most pronounced in the South Island's West Coast and central Otago. This caused Tait et al., (2002) to conclude that the observed data did not suggest any strong correlation in decadal extremes with the IPO in the lower North Island and for this reason, the report concentrates on the changes in flood frequency due to climate change rather than decadal variability.

3.2 Previous work examining effects of climate change

3.2.1 Leong, Jordan et al., (1992)

Early work by Leong, Jordan et al., (1992) investigated climate change impacts on river protection for the Hutt River upstream of Birchville. To do this they used a rainfall-runoff catchment model, flood estimation and river channel cross section design techniques. Their model conceptualised the catchment into 12 hillslopes and a number of gutters and reaches. It simulated 19 maximum annual floods over the period 1971 to 1989 using both static and dynamic rainfall. For most of the 1970s only three or less automatic rain gauges were in operation. From 1981 to 1989 this was improved with records from 13 automatic rain gauges. However, Leong, Jordan et al., (1992) observed that the rain gauges were poorly positioned with respect to the centroid of any of the hillslope areas making it difficult to assign gauges to each hillslope. To try and mitigate this problem they applied a method based on Shaw and Lynn (1972) and Lee, Lynn, and Shaw (1974) to generate hourly isohyetal patterns over the entire Hutt catchment for individual rain events. A time series of the volume of rainfall for each sub-catchment was then determined at each time interval, from which an average hillslope rainfall could be achieved. The procedure was used to calculate a time series of areal rainfall totals over each of the 12 hillslopes during nine annual flood events for the period 1981 to 1989. In this way, each of the conceptual hillslopes had a unique rainfall record assigned to it. Prior to July 1980, the lower and central catchment rain gauges only recorded totals accumulated over 24 hours making it impossible to generate hourly rainfall records as input into the model. As a substitute, a rainfall pattern was used that assumed a stationary storm rainfall distribution. It was based on contours of rainfall intensity over the Hutt catchment prepared by Thompson and McGann (1990). Relative intensities based on this pattern were then used to calculate the amount of rainfall for each of the 12 hillslopes for individual storms. River flow data was used to validate the model. It was created by converting records of stage from water level recorders into flows using independently checked rating curves (Leong *et al.* 1992).

Leong, Jordan, and Ibbitt (1992) simulated 19 maximum annual floods over the period 1971 to 1989 at Birchville with increased rainfall intensifications of 5, 10, and 15%. This resulted in three sets of simulated peaks, one set corresponding to each rainfall scenario. Rather than using each set to calculate an extreme value analysis, they were used to calculate enhancement factors for recorded observed flow. The frequency analysis of annual maximum discharge was calculated using the EV1 distribution by the method of probability weighted moments. This resulted in annual peak flow increases averaging 6.7, 13 and 20% respectively. For 1 in 100-year floods the increases in peak flow were 6.5, 12.6 and 18.9% respectively. These results indicated a decreased level of protection to the inhabitants of the Hutt flood plain. An example is where a 15% increase in rainfall intensity will turn a 1 in 500-year flood into a 1 in 130-year flood, while a 1 in 100-year flood will become a 1 in 33-year flood (table 2) (Leong *et al.* 1992:34).

Leong, Jordan, and Ibbitt (1992) also estimated design flows for Taita Rock. Although a water level recorder was in operation at Taita Rock (site 29816) from 1974 to 1979, no stage/discharge rating curves exist. Therefore, a flow record was created by transposing adjusted flow from upstream sites Taita Gorge (site 29809) and Birchville (site 29818). The modified correlation accounted for differences in rainfall and catchment size between all three sites (Leong *et al.* 1992). The report lists the 100-year design flows at Taita Rock only (Table 3).

Table 2. Flood frequency estimates at Birchville under different rainfall intensification scenarios. Source (Leong, Jordan, and Ibbitt 1992)

Natural conditions			Estimated return period (years)		
Peak flow (m3/s-1)	Return period (years)	Annual exceedence probability	Rainfall intensification		
			5%	10%	15%
2210	1000	0.001	580	360	230
2040	500	0.002	300	190	130
1830	200	0.005	130	85	59
1660	100	0.01	66	46	33
1500	50	0.02	34	25	18
1280	20	0.05	14	11	9
1100	10	0.1	8	6	5
930	5	0.2	4	3.3	2.8

Table 3. 100-year design flows at Taita Rock. Source (Leong, Jordan, and Ibbitt 1992)

Scenarios:	Estimated 100-year return period flow (m3/s-1) at Taita Rock:
No change (natural)	1960
5% increase	2090
10% increase	2210
15% increase	2330

3.2.2 Pearson and McKerchar (1999)

Wellington Regional Council commissioned a NIWA report as part of investigations for setting a design standard for the Hutt River Floodplain Management Plan. The report by Pearson and McKerchar (1999) updated earlier work by Pearson (1990) by using an extra decade of flow data to cover the period 1968 to 1998, and considered the effects of potential detention reservoirs on the Hutt River flood peaks. The frequency analysis of annual maximum discharge was calculated using the TopNet model and the EV1 distribution at 17 Hutt River locations. Three of these, Taita Gorge, Birchville and Kaitoke had flow records spanning 20, 28 and 31 years respectively and were the focus of the study. Pearson and McKerchar (1999) provided flood frequency estimates using two methods. The first used continuous records only, and the second continuous records plus historical floods since 1840. Including the historical floods increased flood frequency by 1–2% on average compared to continuous records alone and was the adopted option for the report (Table 4).

Table 4. Return periods for Taita Gorge and Birchville under different flood frequency curves. Data sourced from (Pearson and McKerchar 1999)

	Hutt at Taita Gorge		Hutt at Birchville	
Return period (years)	[obs. flood]	[obs. & hist. floods]	[obs. flood]	[obs. & hist. floods]
2	858	777	688	677
5	1180	1089	970	973
10	1394	1296	1157	1169
20	1599	1494	1336	1356
50	1864	1751	1568	1598
100	2062	1944	1741	1780
200	2260	2135	1915	1960

To calculate changes in flood frequency from climate change Pearson and McKerchar (1999) used regional warming scenarios published in Whetton, Mullan et al. (1996). The scenarios are based on five Global Climatological Models (GCMs) with CO_2 levels in 1992 and doubled 1992 CO_2 levels. The results for Wellington indicate no change through to a possible halving of return periods of extreme rainfall by 2030 and 2070 (Table 3).

Table 5. Scenarios of precipitation change for New Zealand districts. Values for 2070 have been rounded to the nearest 5%. Ranges include seasonal variation in precipitation change. Adapted from Whetton, Mullan et al. (1996) and Pearson and McKerchar (1999).

Region	Regional precipitation response (%) per degree of global warming	Projected precipitation change in 2030 (%)	Projected precipitation change in 2070 (%)
Wellington and east coast North Island	-5 to +5 average 0%	-10 to +15 average 2.5% No change through to halving of return periods	-20 to +30 average 5% No change through to fourfold reduction in return periods

Figure 2, in Pearson and McKerchar (1999:15) shows Taita Gorge flood frequencies for no climate change, halving of return periods (by 2030), and a further halving again (by 2070).

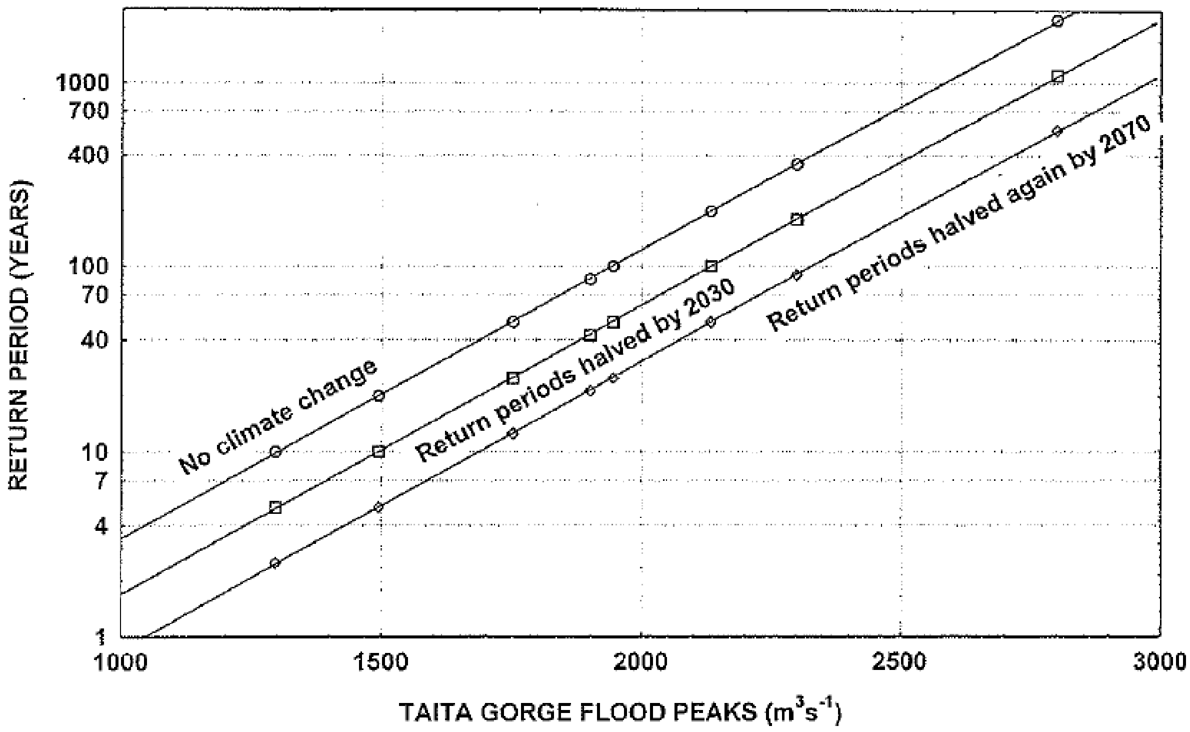


Figure 2. **Plot of return periods of Hutt River at Taita Gorge flood peaks under assumed climate change regimes. Source: (Pearson and McKerchar 1999)**

3.2.3 Tait et al., (2002)

Tait et al., (2002) predictions of climate change effects are based on work by Salinger and Griffiths (2001) which documented historical changes in New Zealand extreme rainfall, and Whetton, Mullan et al. (1996) Global Climatological Models cited earlier by Pearson and McKerchar (1999). Tait et al., (2002:129) concluded that by 2050, the intensity of heavy rainfall could increase by up to 10%, and the return period between severe flooding could decrease by up to a factor of 2. However, Tait et al., (2002) also acknowledged that the figures were quite uncertain and that it's possible that there will be no discernible reduction in return periods.

3.2.4 Ministry for the Environment (2008)

The Ministry for the Environment (MfE) published regional climate change projections based on the IPCC's fourth assessment report (2007) and NIWA's regional climate model. Results for the Wellington region (1990 to 2040) show a change in temperature range of 0.3 to 2.2°C with an average increase of 0.9 °C. This could cause a change in seasonal and annual precipitation with Paraparaumu (located on Wellingtons west coast) ranging between -3 and +10% (Ministry for the Environment 2008).

Table 6. Projected changes in seasonal and annual mean temperature (in °C) and precipitation (in %) from 1990 to *2040* for Wellington. Lower and upper limits are shown in brackets (Ministry for the Environment 2008).

Region/Location	Summer	Autumn	Winter	Spring	Annual
Temperature (°C) Wellington	2.2 [0.9, 5.7]	2.1 [0.6, 5.1]	2.1 [0.6, 5.0]	1.8 [0.3, 4.8]	2.1 [0.6, 5.2]
Precipitation (%)					
Wellington: Masterton	2 [−17, 25]	4 [−8, 32]	−6 [−20, 4]	−1 [−8, 10]	−1 [−7, 9]
Paraparaumu	0 [−21, 13]	4 [−3, 14]	4 [−1, 13]	2 [−5, 14]	2 [−3, 10]

In addition, the MfE guidelines also provide some information on the projected increase in heavy precipitation events as a result of a warmer atmosphere being able to hold more water (based on the Clausius-Clapeyron equation). Calculations of changes in flood risk will generally need to use information on both changes in monthly or seasonal average rainfall and changes in short-period (hours to several days) intense rainfall episodes. However, the MfE (2008) guidelines provide only limited instructions as to how this information should be used in practice for quantitative simulations of future changes in flood risk.

3.2.5 Ministry for the Environment (2010)

The Ministry for the Environment (MfE) subsequently published specific technical and quantitative guidance on how to use projected changes in average rainfall and heavy rainfall episodes for the simulation of future changes in flood risk (MfE 2010). Details of this guidance and its implementation for this case study are described in Section 4.2 of this report.

3.3 Sea level rise

In the IPCC's Fourth Assessment Report (2007a) a global rise in sea level of 18 to 59cm is projected out to 2090. A further 10 to 20cm increase could occur if Greenland and Antarctic melting rates increase were to increase linearly with future temperature increase, but even greater changes cannot be ruled out. Pearson and McKerchar (1999) after assessing similar sea level projections published in Whetton, Mullan et al. (1996) concluded that even if the maximum ranges (albeit less than 1m) eventuate it would have little effect on riverine flooding for the majority of the Hutt floodplain. However, if sea level rise were to be factored in for the lower valley, including Petone and Seaview areas, then sea level rise would result in inundation of parts of these low lying areas. Effects are not limited to surface inundation; sea level rise might also lead to significantly raised water tables, enhanced risk of soil liquefaction and additional flood risk from the Waiwhetu Stream.

4 Modelled and observed flood frequency

4.1 TopNet validation

This project aimed to develop and demonstrate a methodology for making climate change projections of potential changes in flood frequency on the Hutt River using meteorological data adjusted to represent inferred conditions under climate change to drive a hydrological model. The model used was NIWA's TopNet, a semi-distributed physically based model. The rationale for its use was:

a) TopNet's physical basis—where future climate conditions are expected to lie outside of the range of current data available for model validation, it is only through confidence of the model representation of physical processes that we can expect that our models will respond reasonably to changing patterns of precipitation and temperature under climate change.
b) The availability of a version of TopNet calibrated for the Hutt River. The time required to effectively calibrate a model such as TopNet is substantial, and was outside the scope of this project.

This section assesses the validity of TopNet's flow output when compared to observed flow over the period 1 Jan 1970 to 1 Jan Dec 2010.

The frequency analysis of annual maximum discharge was calculated using the EV1 distribution, flow records, and least squared fit at 7 Hutt River locations. Birchville and Kaitoke had flow records spanning 37 years, Dude Ranch 33 years, Te Marua 32 years, Truss Bridge 31 years, Cemetery 30 years, and Taita Gorge 27 years. The validity of the frequency analysis was checked by comparing it with existing studies (figure 3) by (Leong *et al.* 1992; Pearson and McKerchar 1999). The regression fit closely matched Pearson and McKerchar's (1999) observed fit indicating the analysis methodology was correctly implemented and consistent with previous studies. Overall differences between modelled flood frequency results and observed flood frequency results at each observation station are displayed in Table 8. Figures 3, 4 and 5 compare modelled flow versus observed flow via least squared fit, return periods, and flow duration curves respectively. Table 7 compares our return periods at Birchville station to the results listed in Leong *et al.* (1992) and Pearson & McKerchar (1999).

Differences between observed and modelled flood estimates are graphed as flood frequency curves, which show the relationship between flood magnitude and their recurrence interval at each flow station (figure 4). These results are also illustrated in flow duration curves (Figure 5). Flow duration curves characterise the ability of each basin to provide flows of various magnitudes. This information is useful when comparing flow extremes such as low flows and floods.

When comparing modelled flow against observed flow, TopNet's best fit overall was at Birchville station with slight over and underestimates throughout the record. At the 100 year return period (using the EV1 distribution to extrapolate both simulated and observed floods), simulated estimates at Birchville are 17% larger than estimates obtained using observed flow data. TopNet also performed well at Taita Gorge with small over and underestimates throughout the record and a slight overestimate of 19% at the 100 year return period flood. Like Taita Gorge, Te Marua fluctuated above and below observed flow but still had a reasonable fit. At the 100 year return period, Te Marua slightly overestimated flow by 14.4%.

The worst inconsistency between observed and simulated flood estimates was at Dude Ranch where simulated flow consistently underestimated flow, and there was a 52% discrepancy at the 100 year recurrence interval. Simulated Cemetery station similarly had a 34% discrepancy. At Truss Bridge and Kaitoke, TopNet both under and over estimated flow throughout the record, and the simulated 100 year return period flood exceeded the observed data estimate by 40% and 33% respectively. We note that issues with model performance at Kaitoke might be partially explained by the Kaitoke Weir, a freshwater source for the Hutt Valley and Wellington City, which could regulate flow thereby buffering flood peaks. It is also important to note that the discrepancies in the 100-year return period flood estimates may be in part to do with the use of the EV1 distribution and the least squares optimisation function—given the short record lengths for both simulated and observed data, the extrapolation can be highly influenced by minor discrepancies between the observed and simulated data records.

Although TopNet adequately predicted flow at Birchville, Te Marua and Taita Gorge, the differences between its output and observed flow at Dude Ranch, Truss Bridge, and Kaitoke means its overall performance was fair. The differences were particularly pronounced during the peak flood in 2000 with large overestimates in most cases. It is important to note that the parameterisation we were provided with was produced using data prior to 2000. As a consequence any forecasts based on this model would benefit from further calibration and validation to take account of the additional information provided by the last decade of data. For flood prediction, particular emphasis could be given in the calibration stages to “good” performance in high flow events—the current TopNet parameterisation can be assumed to have been achieved by calibration to all flows, rather than emphasising performance during floods. An updated, flood-focussed calibration would give more credibility to studies such as this.

Table 7. Comparison of calculated flood return periods at Birchville station against previous studies by Leong *et al.* (1992) and Pearson and McKerchar (1999).

Return period (years)	Peak flow (m^3/s^{-1}) at Birchville station			
	This study [obs. flood]	Leong, Jordan, & Ibbit (1992) [obs. flood]	Pearson & McKerchar (1999) [obs. flood]	Pearson & McKerchar (1999) [obs. flood & hist. floods]
2	681	-	688	677
5	970	930	970	973
10	1162	1100	1157	1169
20	1345	1280	1336	1356
50	1583	1500	1568	1598
100	1761	1660	1741	1780
200	1939	1830	1915	1960
500	2173	2040	-	-
1000	2350	2210	-	-

Table 8. Selected return periods for observed and modelled flow assuming EV1 distribution and least squares fit. Std is the standard deviation.

Station peak flow (m^3/s^{-1})		Return period (years)									
		2	5	10	20	50	100	200	440	500	1000
Birchville	Obs. flood	681	970	1162	1345	1583	1761	1939	2140	2173	2350
	Obs. std	55.9	56.4	57.5	59.2	62.0	64.6	67.6	71.3	72.0	75.6
	Mod. flood	669	1059	1317	1565	1886	2126	2365	2637	2681	2920
	Mod. std	94.5	95.3	97.2	100.0	104.8	109.2	114.2	120.5	121.6	127.7
Cemetery	Obs. flood	274	410	500	587	699	784	867	963	978	1062
	Obs. std	24.5	24.8	25.4	26.3	27.8	29.3	30.8	32.8	33.2	35.1
	Mod. flood	171	262	322	380	455	512	568	631	642	698
	Mod. std	23.4	23.6	24.2	25.1	26.6	27.9	29.4	31.3	31.7	33.5
Dude Ranch	Obs. flood	71	116	145	173	210	237	265	296	301	328
	Obs. std	12.0	12.1	12.3	12.7	13.4	14.1	14.8	15.7	15.8	16.7
	Mod. flood	43	62	74	85	100	112	123	136	138	149
	Mod. std	2.4	2.5	2.5	2.6	2.7	2.9	3.0	3.2	3.2	3.4
Kaitoke	Obs. flood	236	305	351	395	451	494	536	585	592	635
	Obs. std	17.6	17.8	18.1	18.6	19.5	20.3	21.3	22.5	22.7	23.8
	Mod. flood	240	375	464	549	659	742	825	918	933	1016
	Mod. std	32.6	32.9	33.6	34.6	36.2	37.7	39.5	41.7	42.0	44.1
Taita Gorge	Obs. flood	882	1208	1424	1631	1899	2100	2300	2527	2564	2764
	Obs. std	93.6	94.8	97.5	101.4	108.1	114.1	120.8	129.2	130.7	138.7
	Mod. flood	851	1324	1637	1937	2325	2616	2906	3235	3288	3577
	Obs. std	92.2	93.5	96.1	99.9	106.5	112.5	119.1	127.4	128.8	136.7
Te Marua	Obs. flood	120	188	233	275	331	373	414	461	469	510
	Obs. std	18.9	19.1	19.6	20.2	21.4	22.4	23.5	25.0	25.2	26.6
	Mod. flood	145	223	274	324	388	436	484	538	547	595
	Mod. std	11.9	12.0	12.3	12.7	13.4	14.0	14.8	15.7	15.8	16.7
Truss Bridge	Obs. flood	82	106	122	138	158	173	188	205	208	222
	Obs. std	9.9	10.0	10.3	10.6	11.2	11.8	12.4	13.2	13.3	14.1
	Mod. flood	81	136	173	209	254	289	323	362	368	402
	Mod. std	24.4	24.7	25.3	26.1	27.6	29.0	30.5	32.5	32.8	34.7

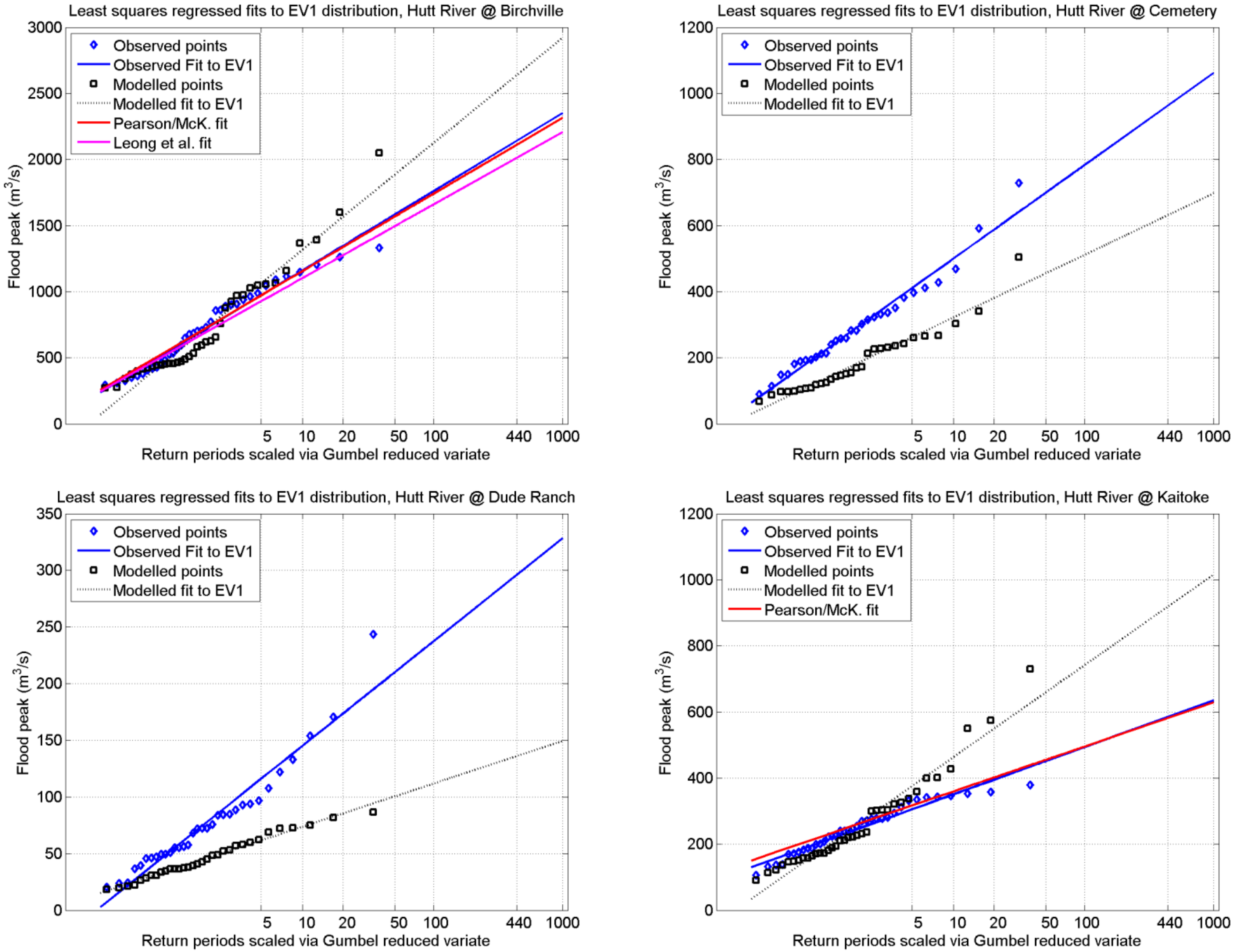
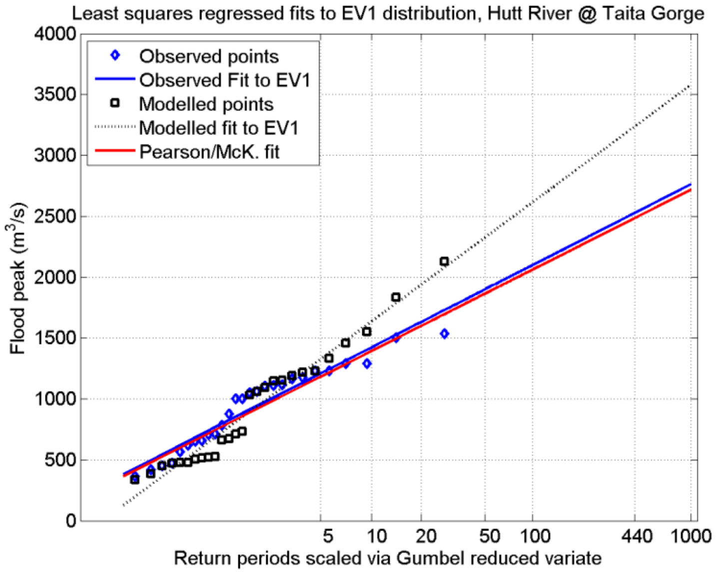
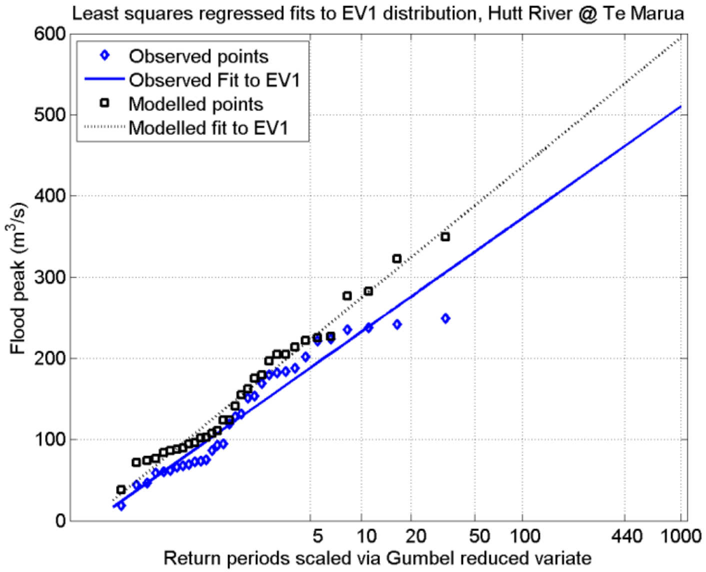
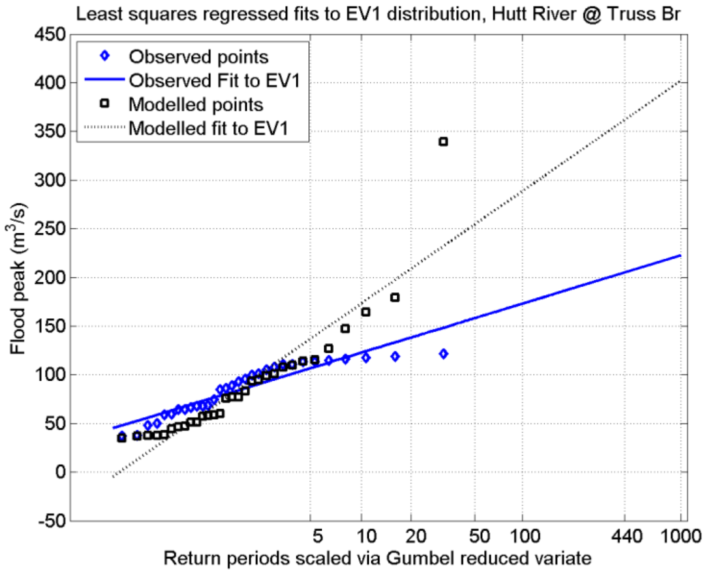


Figure 3. Least squares regression fits to EV1 distribution at various stations on the Hutt River


Least squares regressed fits to EV1 distribution, Hutt River @ Taita Gorge
Observed points
Observed Fit to EV1
Modelled points
Modelled fit to EV1
Pearson/McK. fit
Flood peak (m3/s)
Return periods scaled via Gumbel reduced variate
0
500
1000
1500
2000
2500
3000
3500
4000
5
10
20
50
100
440
1000


Least squares regressed fits to EV1 distribution, Hutt River @ Te Marua
Observed points
Observed Fit to EV1
Modelled points
Modelled fit to EV1
Flood peak (m3/s)
Return periods scaled via Gumbel reduced variate
0
100
200
300
400
500
600
5
10
20
50
100
440
1000


Least squares regressed fits to EV1 distribution, Hutt River @ Truss Br
Observed points
Observed Fit to EV1
Modelled points
Modelled fit to EV1
Flood peak (m3/s)
Return periods scaled via Gumbel reduced variate
-50
0
50
100
150
200
250
300
350
400
450
5
10
20
50
100
440
1000

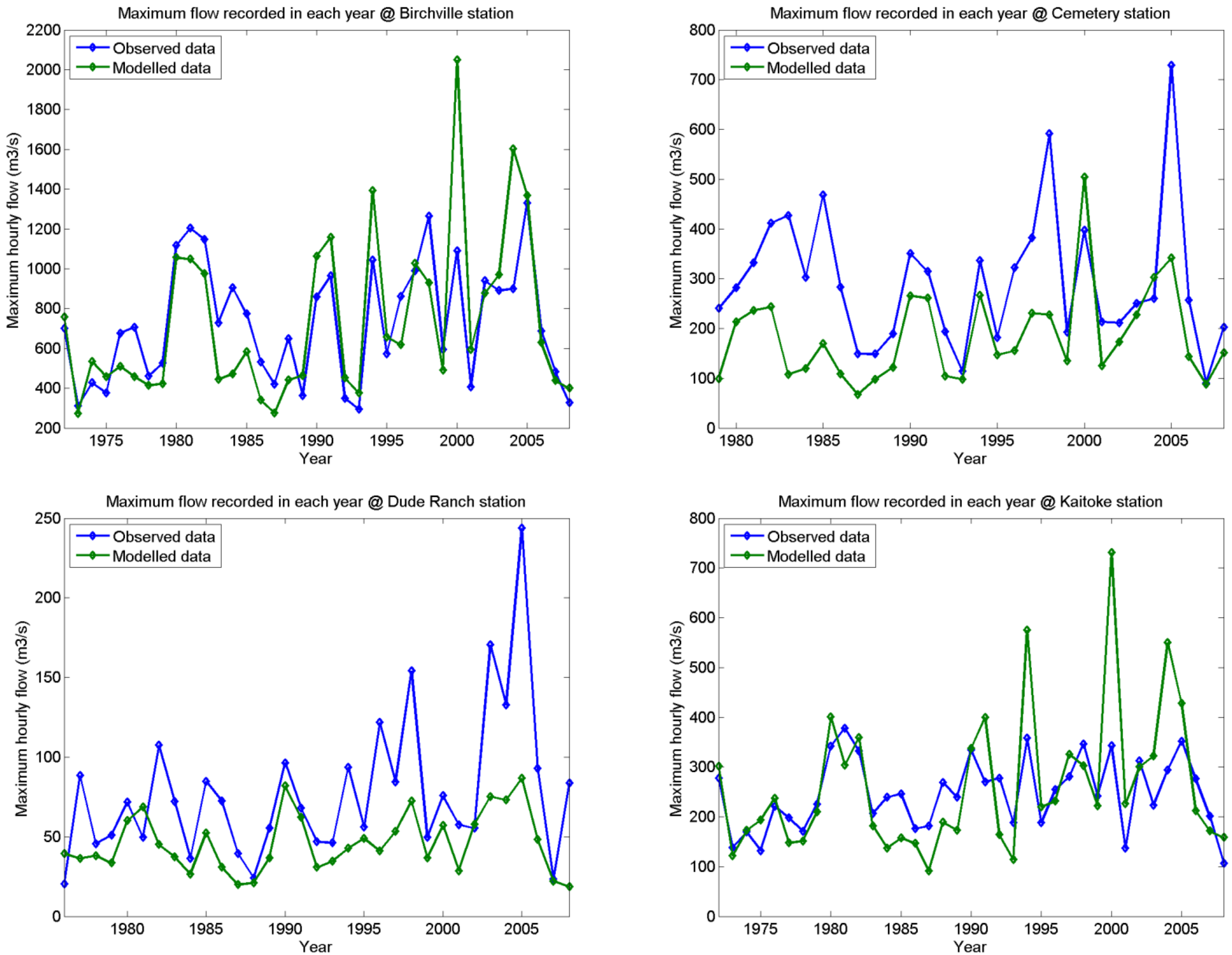
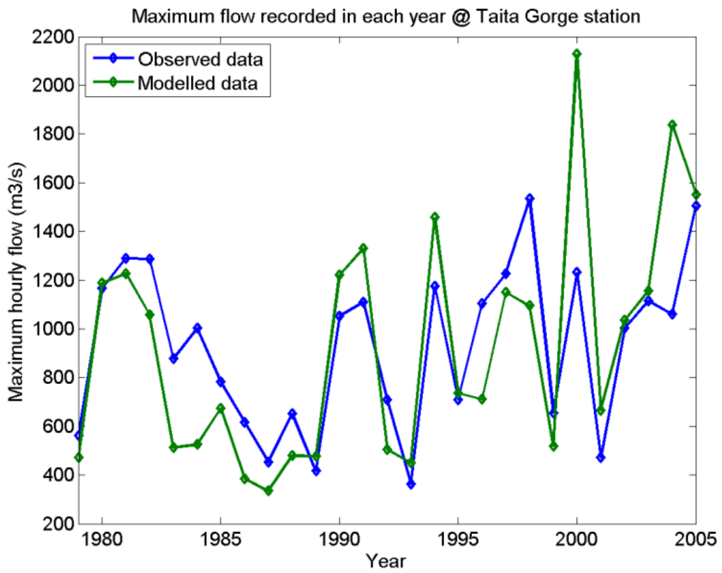
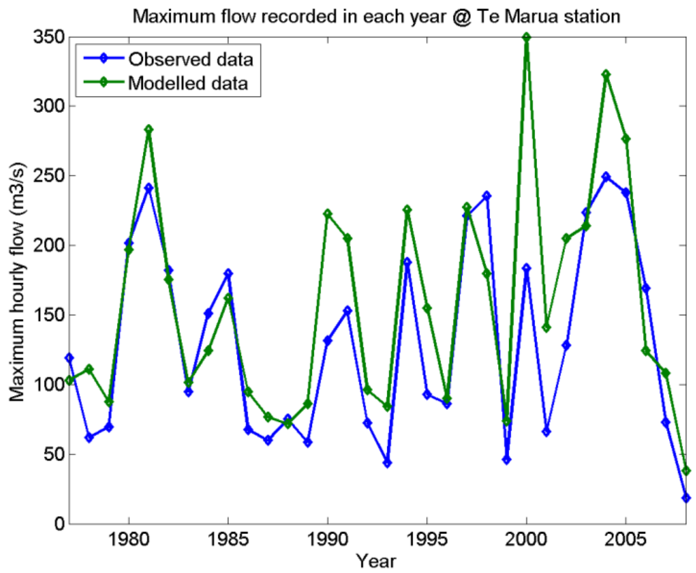
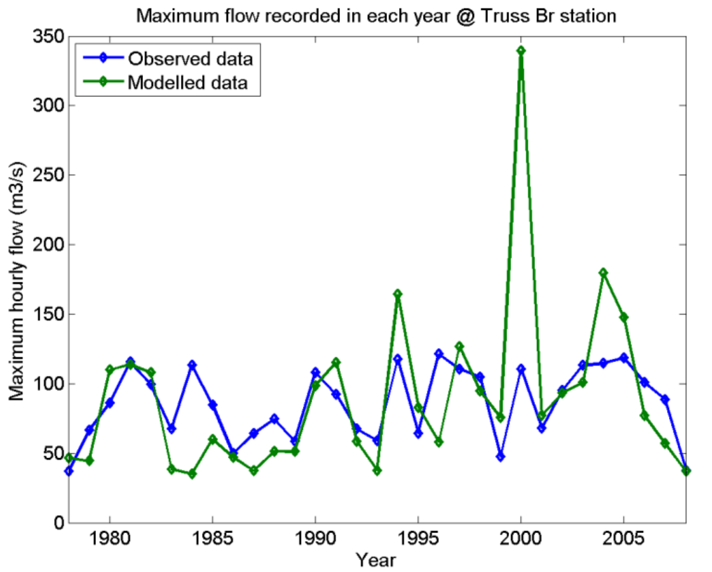


Figure 4. Annual maximum flow, observed versus TopNet at various stations on the Hutt River


Maximum flow recorded in each year @ Taita Gorge station
Observed data
Modelled data
Maximum hourly flow (m3/s)
Year


Maximum flow recorded in each year @ Te Marua station
Observed data
Modelled data
Maximum hourly flow (m3/s)
Year


Maximum flow recorded in each year @ Truss Br station
Observed data
Modelled data
Maximum hourly flow (m3/s)
Year

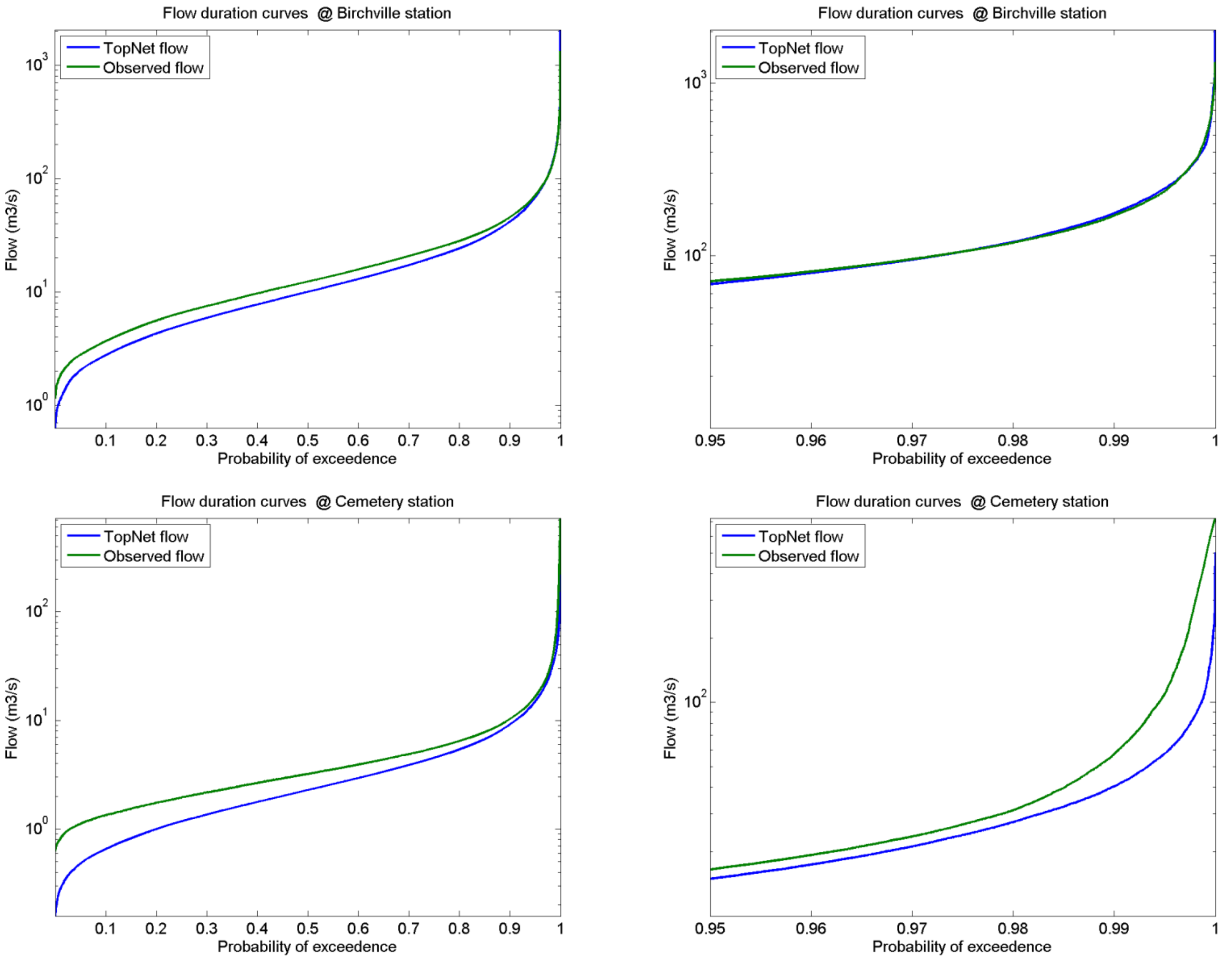
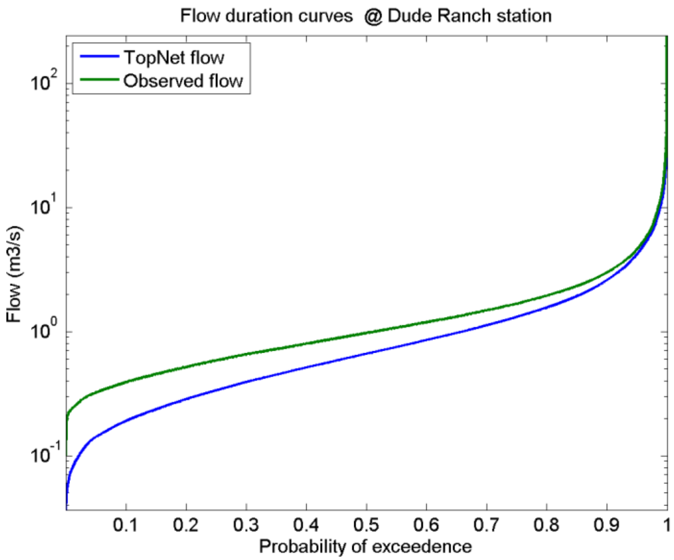
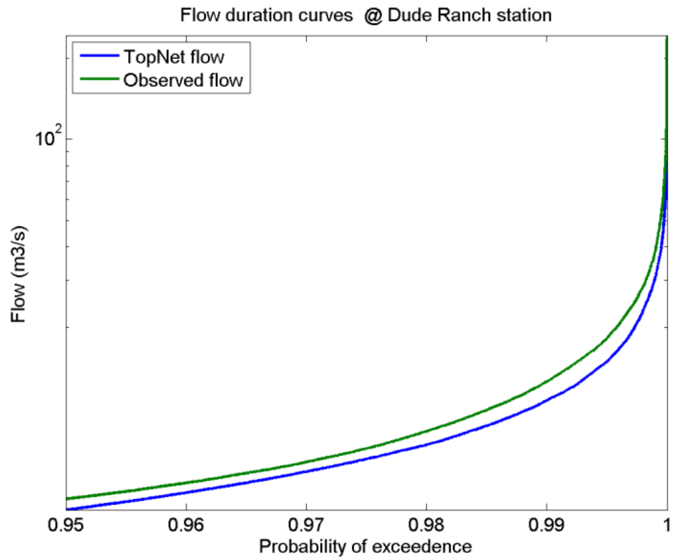
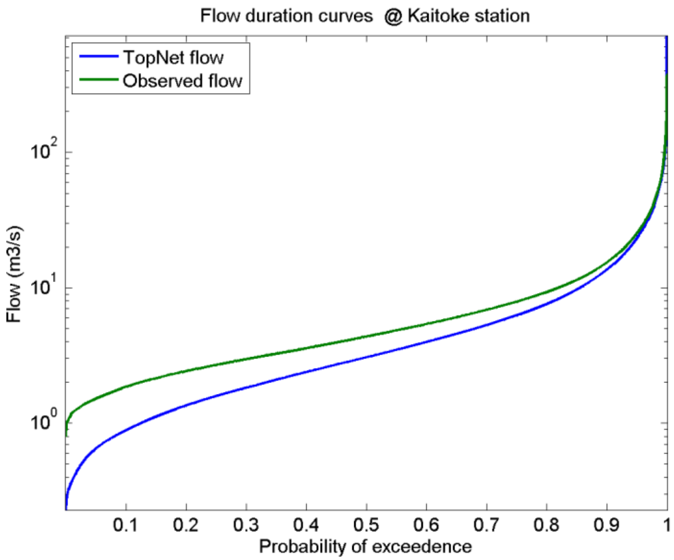
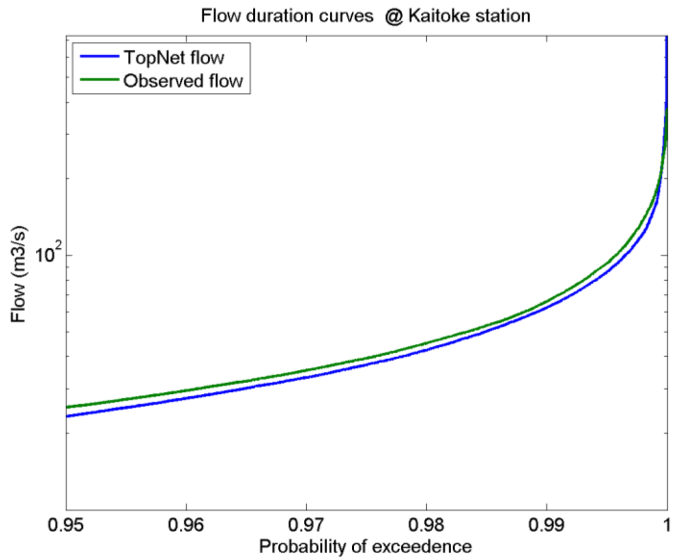


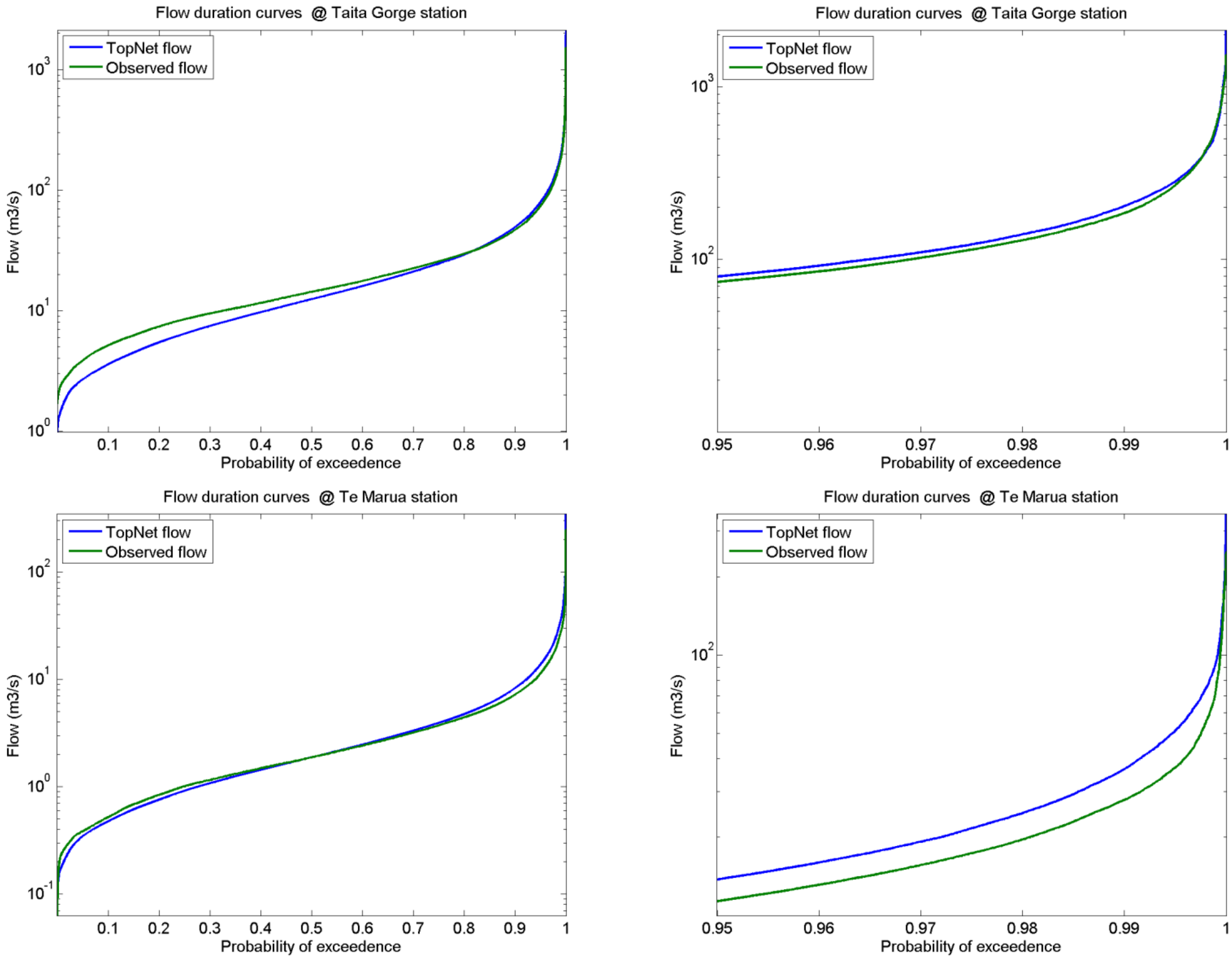
Figure 5. Flow duration curves at various stations on the Hutt River

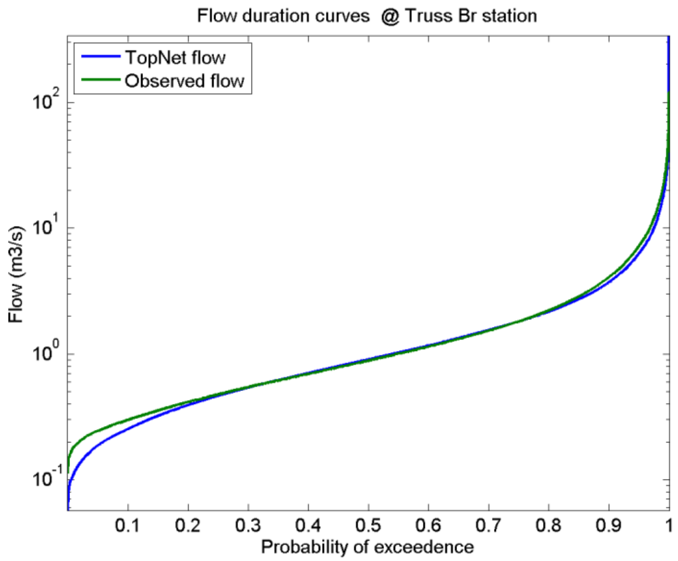

Flow duration curves @ Dude Ranch station
TopNet flow
Observed flow
Flow (m3/s)
Probability of exceedence

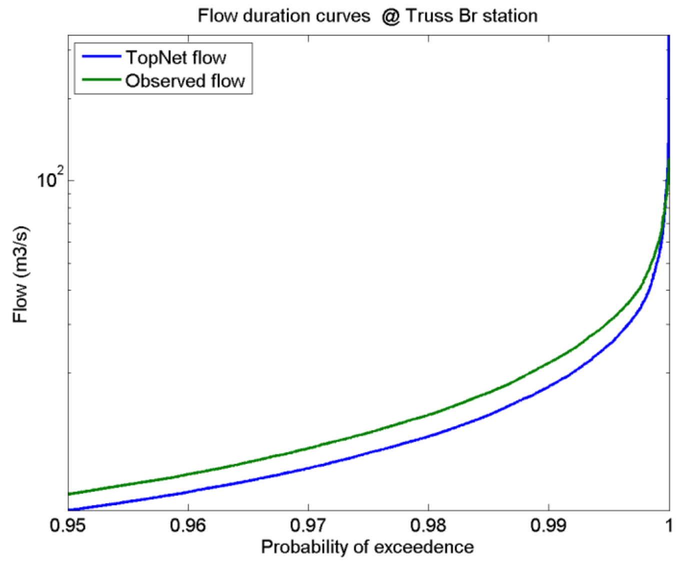

Flow duration curves @ Dude Ranch station
TopNet flow
Observed flow
Flow (m3/s)
Probability of exceedence


Flow duration curves @ Kaitoke station
TopNet flow
Observed flow
Flow (m3/s)
Probability of exceedence


Flow duration curves @ Kaitoke station
TopNet flow
Observed flow
Flow (m3/s)
Probability of exceedence


Flow duration curves @ Taita Gorge station
TopNet flow
Observed flow
Flow (m3/s)
Probability of exceedence
Flow duration curves @ Taita Gorge station
TopNet flow
Observed flow
Flow (m3/s)
Probability of exceedence
Flow duration curves @ Te Marua station
TopNet flow
Observed flow
Flow (m3/s)
Probability of exceedence
Flow duration curves @ Te Marua station
TopNet flow
Observed flow
Flow (m3/s)
Probability of exceedence


Flow duration curves @ Truss Br station
TopNet flow
Observed flow
Flow (m3/s)
10^2
10^1
10^0
10^{-1}
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Probability of exceedence


Flow duration curves @ Truss Br station
TopNet flow
Observed flow
Flow (m3/s)
10^2
0.95
0.96
0.97
0.98
0.99
1
Probability of exceedence

4.2 Adjustment of rain and temperature inputs for climate change scenarios

A total of 96 scenarios were used in this study: three SRES emissions scenarios (B1, A1B, A2) and one scenario where global temperature increase is limited to 2°C above pre-industrial levels, for two future time periods (2040=2030-2049 and 2090=2080-2099, relative to 1990=1980-1999), and for 12 downscaled global climate models. Climate changes from global models were downscaled to match the NIWA 5×5km virtual climate grid using the methodology described in (Mullan et al. 2001). The 12 climate models used in this study were selected for their ability to reproduce observed climate changes and climate variability in the Pacific region. The projected changes in rainfall and temperature for those models and different emissions scenarios are described in Reisinger et al. (2010).

For each of these models and emissions scenarios, NIWA provided monthly offsets for temperature (°C) and precipitation (%) relative to the average 1980-1999 climate conditions, for each grid-point over region 40.90-41.25°S, 174.80-175.35°E. Grid-points are from NIWA's Virtual Climate Station (VCS) network on a 0.05° x 0.05° grid.

Minimum and maximum daily temperatures were adjusted by these offsets for each scenario, and input into TopNet. Precipitation was adjusted using a methodology for empirical adjustment of a daily rainfall time series as per guidance provided by the Ministry for the Environment (MfE 2010). This methodology respects the monthly average changes in temperature and precipitation for each scenario, but also adjusts the distribution of rainfall percentiles to increase the most extreme daily amounts consistent with the basic physics as expressed in the Clausius-Clapeyron equation. This precipitation adjustment methodology is as follows:

Step 1: The monthly climate change scenario rainfall offsets as provided by NIWA scenario files for different global climate models and greenhouse gas emissions scenarios is applied to the daily precipitation data. The change in monthly climatological rainfall is calculated (e.g., 10% increase in a monthly climatology of 120mm means an extra 12mm), and this extra rainfall is apportioned across all rain days in that month. This step does not change the number of rain days in the record, or alter the interannual variance in monthly rainfalls.

Step 2: Rainfall percentiles are calculated from the daily data after the monthly mean adjusted has been applied (using all months and years combined). The percentiles are calculated over rain-days only; i.e., ignoring dry days. The percentile values are then changed according to the formula:

$$\text{Change in daily rainfall (in \% per °C)} = \max(8, [6.15 * (1. - \ln(100-P)/2.3)]).$$

This formula gives zero change at percentile P=90, +8% per °C change at P=99.5, and about -6% per °C change at P=0. For P>99.5, the change is capped at +8% per degree Celsius of local warming (taken as the change in annual-average temperature provided by the climate change scenarios and individual global climate models over each grid point). This maximum 8% per °C value is widely recognised as the rate at which the water vapour saturation level increases in the atmosphere (the so-called Clausius-Clapeyron relationship), and is also the upper limit recommended in the MfE (2008a) guidance manual for adjusting return periods of extreme rainfall. These % changes in rainfall are then applied to the results of step (i).

Step 3: The number of rain-days is reduced (where rain-days are defined as days with a daily total equal to or exceeding 0.1mm). The probability of a rain-day is lowered by 1.75% per 1°C increase in annual-average temperature. This reduction in low-rainfall days helps to balance the increased rainfall extremes in step (ii). Thus, if:

> NW = number of rain-days, NT = total number of days, and ΔT = warming, then the number of rain-days will change from NW to NW – 0.0175 * ΔT * NT .

This corresponds to about 6 fewer rain-days per year for a 1°C warming. This reduction is achieved by ranking all rain-days as in step (ii), and setting the calculated number (0.0175 * ΔT * NT) of lowest rainfall days to zero rainfall.

Step 4: Monthly mean rainfalls are recalculated for the adjusted record, and a check is carried out to ensure that the monthly mean values are still consistent with the prescribed scenario changes obtained at step (i). If not, all daily rainfalls are adjusted by the factor required for consistency with the monthly scenario changes. If this adjustment leads to some daily rainfalls dropping below 0.1mm (the threshold for a rain-day), rainfall on these days is set to zero, and this procedure is repeated (from the start of step iv) until convergence occurs.

The distributional adjustment in steps (ii)-(iv) has the effect of decreasing the number of days per year when rain falls, and pushing more precipitation into the upper tail of the rainfall distribution. The overall resulting modification in rainfall data is consistent with the results obtained from Regional Climate Model runs at a few grid-points in the Wellington region (Figure 8, from MfE (2010)).

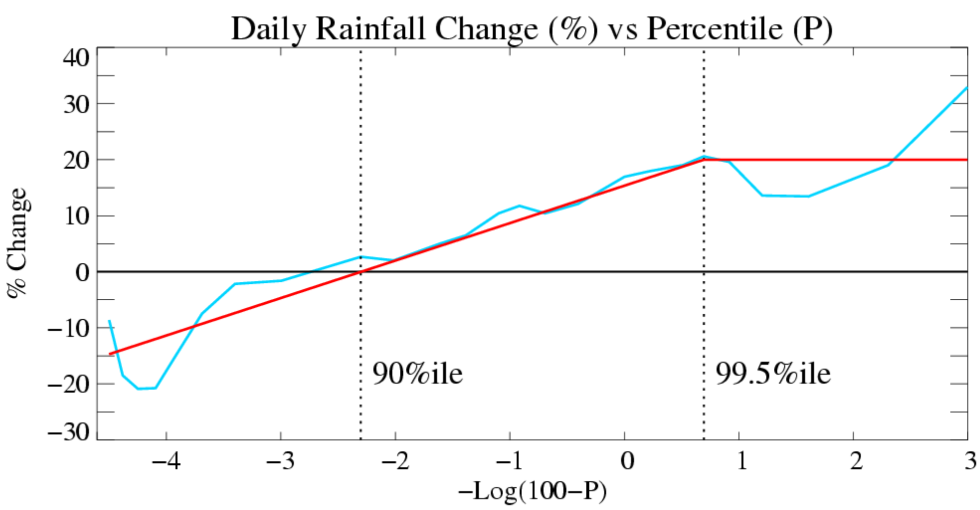


Figure 6. Percentage change in rainfall amount as a function of the percentile in the distribution of daily rainfall: NIWA Regional Climate Model data (averaged over several grid squares in the Wellington region) with local warming of 2.5°C (blue line) and idealised rainfall distributional-adjustment model (red line). The horizontal coordinate is minus the natural logarithm of (100-P), where P is the percentile in the distribution of daily rainfall amounts. This coordinate scale accentuates the high-end rainfalls. Figure reproduced from MfE (2010)

4.3 Calculation of changes in flood frequency of the Hutt River

The altered rainfall and temperature files were used as input to repeated runs of TopNet to calculate climate-induced changes in flood frequencies of the Hutt River, for the range of different emissions scenarios and climate models. A total of 48 runs were carried out based on 12 climate models and 4 different emissions scenarios.

Since there was a systematic difference between modelled and observed flood frequencies for historical rainfall files, a correction had to be applied to use these TopNet outputs to obtain projections of future changes in flood frequencies. The correction uses the difference between the modelled flood volumes with and without climate change, and adds those flood volumes to the observed flood volumes, before calculating flood frequencies using the EV1 distribution. This methodology ensures that the corrected modelled flood frequencies in the absence of climate change are identical to observed flood frequencies.

Figures 4 and 5 show an example of the resulting changes in flood frequencies for the B1 (medium-low) and A2 (high) emissions scenarios, with individual lines representing changes simulated by individual climate models. The modelling results suggest a significant increase in peak flood volumes and frequencies (or, conversely, a significant reduction in return periods for a given flood volume) under both emissions scenarios, but with a large variation between individual models. The inter-model variations are due to different projected changes in average rainfall in the Hutt River catchment area as well as different climate sensitivities, which result in different amounts of warming and hence the future change in heavy precipitation events as per Step 2 in the adjustment procedure.

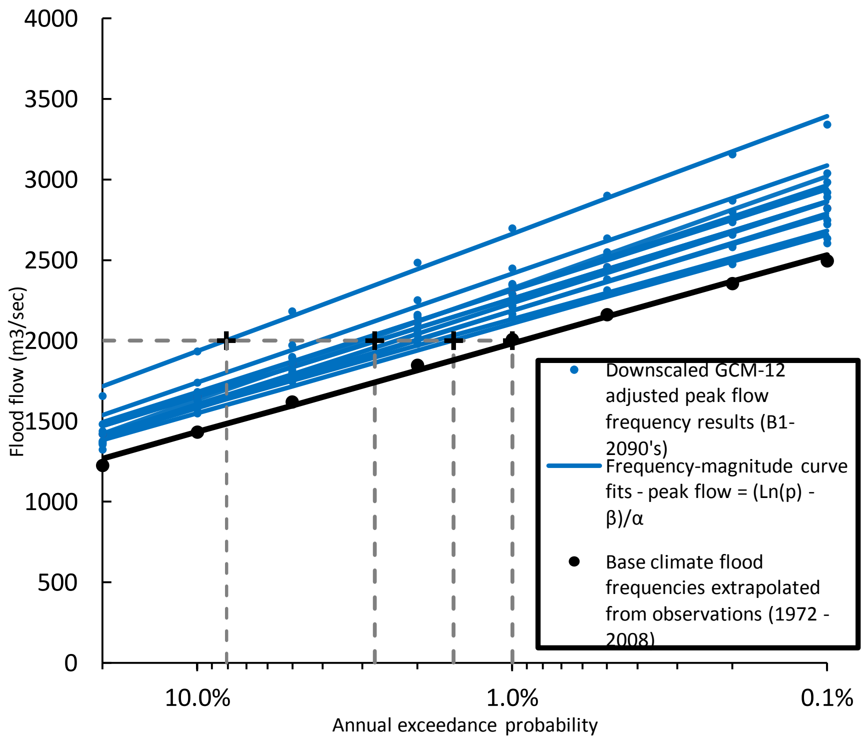


Figure 7. Flood frequencies for the Hutt River at Taita Gorge under current (1972-2008) and modelled future climate (B1 emissions scenario, 2090s), corrected for the difference between modelled and observed flood volumes under current climate conditions (for details, see text).

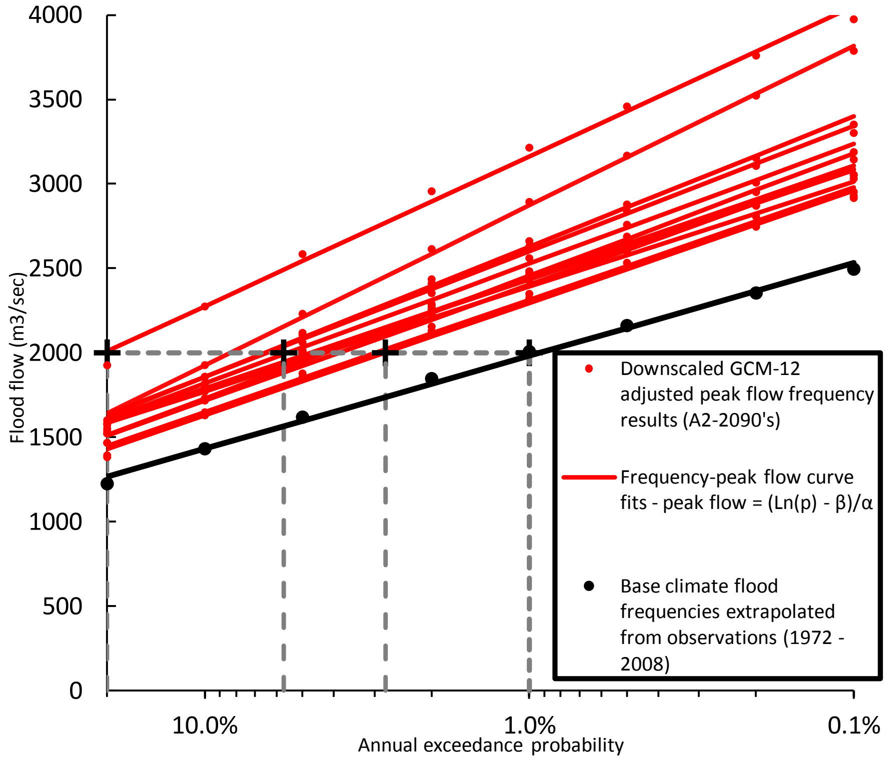


Figure 8. Flood frequencies for the Hutt River at Taita Gorge under current (1972-2008) and modelled future climate (A2 emissions scenario, 2090s), corrected for the difference between modelled and observed flood volumes under current climate conditions (for details, see text).

Under the B1 emissions scenario, the annual probability of occurrence for what is currently a 1% probability flood could reduce by the 2090s to between a 1.5 and 8% flood across the full range of models, with a mean of just under 3%. Expressed in return periods, this means that the return period of a 100-year flood would be reduced to between about 13 and 60 years, with a best estimate of about 35 years. For the A2 emissions scenario in the 2090s, the same flood would have a return period of between 35 years but could occur more often than once every 10 years. The most extreme changes are obtained under the Miroc32-Highres model, which has the most rapid warming rate of the climate models used in this study (see Reisinger et al (2010) and hence leads to the strongest enhancement of extreme precipitation under the methodology (Step 2) applied in this study.

The modelled changes in flood frequencies are comparable to but slightly stronger than those estimated by Pearson and McKerchar (1999), who estimated that the current 100-year flood could become a 25-year flood by the 2070s, but also that the change could be much smaller; potentially negligible. Our study is the first to apply a more detailed modelling approach using catchment-specific climate data and a hydrological model, and it provides an updated quantitative estimate of uncertainties based on different climate models and emissions scenarios.

Under the highest emissions scenario used in this study, the current 100 year flood could become about a 17 year flood by the 2090s as a mean across all climate models, roughly consistent with the estimate from Pearson and McKerchar taking the different time horizons into account. A lower global emissions scenario would result in a smaller change, but even for a scenario where gobal greenhouse gas emissions are reduced sufficiently rapidly to limit the global average temperature increase to 2°C relative to pre-industrial levels, our model simulations suggest that the current 100-year flood would still become about a 50-60 year flood by the 2090s owing to the unavoidable warming and its implications for the hydrological cycle.

Confidence in these estimates of changes in flood frequencies is limited by the simplified modelling approach taken, and by the imperfect ability of the current Hutt River calibration available for TopNet to reproduce observed flood frequencies and peak volumes under current climate conditions. The fact that the rainfall adjustment methodology is based on simulations with a complex regional climate model for the Wellington region suggests that for this particular catchment, the simplified methodology is adequate for the task. The following section briefly explores the options and effects of adjusting the calibration of TopNet to provide a better simulation of observed flood frequencies and volumes.

4.4 Alternative calibrations of TopNet and its effect on modelled changes in flood frequency

A brief exploration of alternative calibrations of TopNet was carried out, to see whether an improved simulation of observed high flow events and annual river maximums could be obtained. Given the limited resources available for this study and the time constraints imposed by the computational expense of running TopNet (a single simulation takes about 7 hours on a top-end PC), only a limited set of parameters was varied. The parameters that were selected were: the effective soil depth for subsurface flow, drainable water, plant available water, overland flow velocity and the in-river roughness coefficient Manning's n. Overland flow velocity and Manning's n affect the routing elements of the model, while the others change the storage components influencing subsurface flow. From this limited sensitivity analysis and calibration, peak flows appeared to be most sensitive to changes in the f-parameter and overland velocity. Peaks were also somewhat sensitive to drainable water, but showed very little sensitivity to the plant available water. Manning's n had an influence on peaks at the most downstream sites, due to the longer in-river travel distance for water to these sites, but little influence on results at gauges further upstream.

These parameters were varied, and performance of the resulting output was evaluated visually at all stations, looking to minimise differences between observed versus modelled annual maxima, and a range of small to large individual flood events. Where visual inspection suggested the new parameterisations outperformed the original according to these criteria, the models were further evaluated against observed annual maximum at Taita Gorge using the Nash Sutcliffe model efficiency, a normalised form of least squared errors. 1 is a perfect fit, while 0 implies equivalent predictive power would be gained via a linear regression. The original calibration had a very poor Nash Sutcliffe model efficiency of 0.088. The calibration performing best according to this criterion had a Nash Sutcliffe Model Efficiency of 0.35. Whilst this is an improvement, the efficiency is still very poor. Further investigation using the parameters identified in this and automated methods might well provide a more robust model calibration for use in future impact studies.

The result of this adjustment was a slight improvement in the simulation of observed flows, particularly at Cemetery and Dude Ranch nodes. The revised calibration gives a better though still not perfect simulation of observed flows (see Figure 6), and also reduces the over-prediction of observed low-probability flood volumes (see Figure 7).

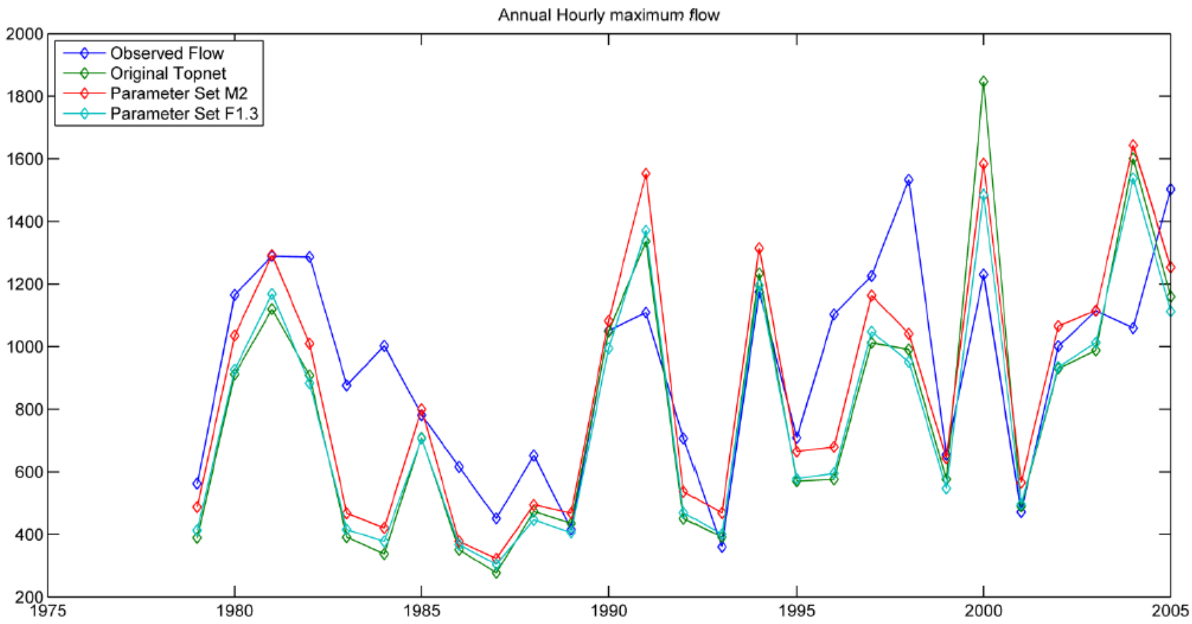


Figure 9. **Observed flow at Taita gorge versus the original TopNet calibration and two of the better performing re-calibrations (the M2 parameter set was the final one used). Flow is given in cumecs.**

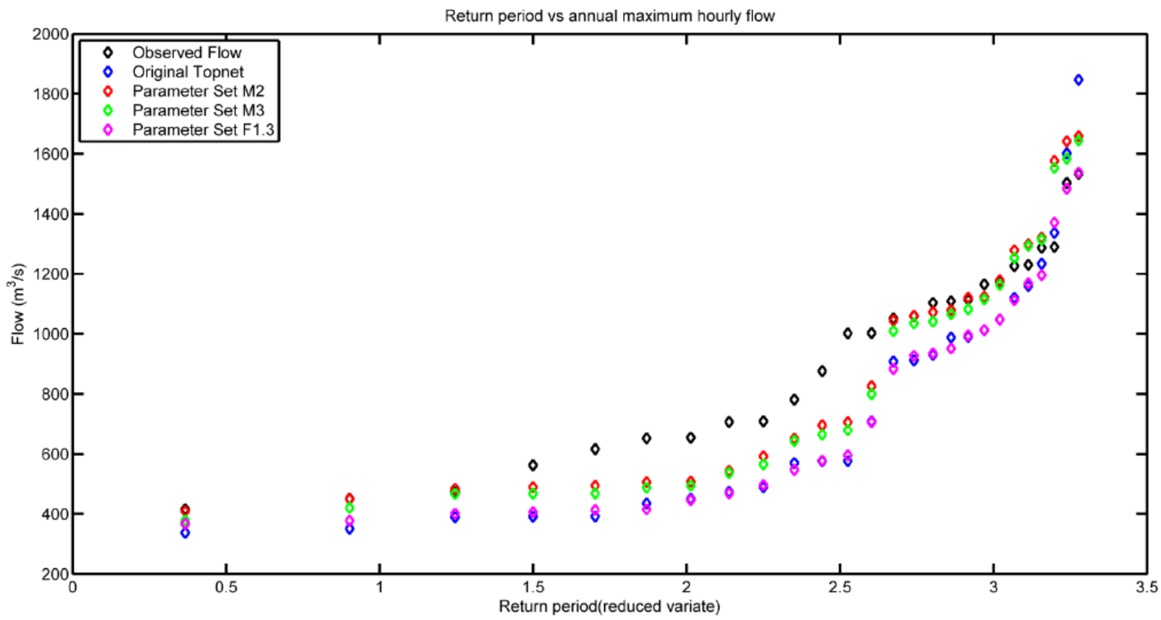


Figure 10. **Observed versus modelled flood frequency data at Taita gorge versus the original TopNet calibration and three of the better performing re-calibrations (the M2 parameter set was the final one used).**

TopNet simulations across all climate scenarios were re-run with this revised calibration. It was found that the projected changes in flood frequencies for different climate change scenarios using the revised TopNet calibration differed on average by less than 1% from the flood frequencies obtained using the original calibration. This high degree of consistency in results shows that the climate-induced changes in flood frequencies of the Hutt River do not depend strongly on this set of TopNet calibration parameters. While the high level of agreement does not guarantee that the results are correct, they do lend some confidence that the robustness of the results are not strongly influenced by the performance of TopNet. However, we stress that only a small set of TopNet parameters was varied in this exercise. Adjustment of other parameters relating to soil moisture storage could have bigger effects on the response of the catchment to increased heavy rainfall events, but we have been unable to explore these effects as part of this study.

5 Summary and conclusions

The Hutt Valley and its residents face a significant flood hazard. Estimates of impact from 2000 suggest approximately 106,000 residents and up to $6 billion of property is at risk. Greater Wellington Regional Council and the Hutt city councils have put significant effort into understanding and managing this hazard. The Hutt River Floodplain Management Plan (HRFMP) is the main document for managing flood risk on the Hutt River. Substantial engineering projects to enhance protection are underway, with the full programme of work scheduled to be completed by 2040. Concurrently there is also ongoing work on implementing non-structural measures as part of the Hutt River Environmental Strategy (Wellington Regional Council 2001b). Section 2 of this report overviewed the history of flooding in the Hutt Valley, the management strategies in place, and both existing and planned protection measures in the valley.

The onset of climate change and its predicted impacts on river flow and flooding is expected to further increase the risk to those communities. Section 3 reviewed work to date examining the potential impacts of climate change on the Hutt River. Impacts of sea level rise are not thought to pose a significant risk to much of the valley. Estimates of changes in flood return periods vary from very significant (halving of return periods) to insignificant (no change) and are acknowledged to be very uncertain.

In Section 4, we adjusted historical precipitation and temperature data with statistically downscaled global general circulation model projections for climate change in the 21st century. A simplified technique to perturb historical rainfall data was used that takes account of changes in monthly mean precipitation as well as the enhancement of heavy rainfall events, based on guidance by the Ministry for the Environment and a technical report by NIWA. The perturbed rainfall scenarios provided driving data to NIWA's hydrological model TopNet. The output from TopNet was used to explore projected changes in flood frequency.

To explore the extent of confidence we could have in using TopNet for such projections, Section 4 also examined how well the calibrated model performed on historical data from the Hutt catchment. Due to constraints in budget, time, and data, we were not able to produce a calibration of the TopNet model specifically tailored to the project.

The model results indicate the potential for a significant increase in flood frequencies over the 21st century under climate change scenarios, but also a significant spread of results depending on the emissions scenario and climate model. Under a high emissions scenario, flood return periods could reduce to a fifth of current-day values on average. Under a scenario where the global temperature increase is limited to 2°C relative to pre-industrial conditions, return periods would still about half by the end of the 21st century. These are average values across all twelve climate models considered in this study; the spread across different models is large and suggests that rather than using a single number for future changes in flood risk, a risk-management approach that considers uncertainties and evaluates impacts and response options across a range of alternative futures is warranted.

Our results are not intended to be used for specific planning purposes. There are significant uncertainties surrounding both the atmospheric driving data provided to the hydrological model and the physical "realism" of the Hutt-calibrated hydrological model TopNet. The global climate projections are highly uncertain in themselves. Further uncertainties are associated with the downscaling methodology used to adjust daily driving data from the monthly estimates of change provided by the GCM projections. The precipitation adjustment technique used appears promising and allows the effect of intensity of rainfall to be considered in the flood projections. However, it is new and requires further investigation and verification before it could be used for planning purposes.

Further uncertainties are associated with the use of the TopNet model. Like any hydrological model, the TopNet model is a simplified representation of the system and does not represent all of the mechanisms that translate rainfall into river flow. As mentioned previously, it is only through confidence of the model representation of physical processes that we can expect that our models will respond reasonably to changing patterns of precipitation and temperature under climate change.

The opinion of the authors is that the structure of TopNet; its fundamental assumptions, simplifications and consequent equations, appears to be suitable for the Hutt catchment. However, examination of internal flows in the model (overland flow, throughflow and groundwater, stream routing parameters etc) suggested the calibrated parameters were not all consistent with those expected given the catchment properties (topography, soil type, land use, etc). The internal behaviour of the model could probably be improved, which would allow more confidence in its output when driven by climate change projections.

The fit to river flow provided by the TopNet model were reasonable, but our modelled flood frequencies were larger than observed flood frequencies under current climate conditions. Additional effort in calibration might also reduce this discrepancy (although some discrepancy is unavoidable given errors in data and model simplifications).

We also did not take into account potential changes in land use or river channels. If substantial change occurs over the 21st century, this could significantly affect the characteristics of the catchment and hence the magnitude and timing of flood events.

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