Environment Waikato Technical Report 2009/21

Summary of the effects of land use change between Taupo and Karapiro on the flood hydrology of the Waikato River catchment

www.ew.govt.nz
ISSN 1172-4005 (Print)
ISSN 1177-9284 (Online)

Prepared by:

Technical Expert Panel:

Ross Woods	NIWA	Independent
Ian Jowett		Mighty River Power
Rory Nathan	SKM	Wairaki Pastoral Ltd.
Jon Williamson	SKM	Wairaki Pastoral Ltd.
Alan Pattle	PDP	Carter Holt Harvey
Murray Mulholland		Environment Waikato
Ghassan Basheer		Environment Waikato

Contributing authors:

Daniel Collins and Jochen Schmidt	(IWA)
John Hansford and Blair Thornborrow	(SKM)
Dr. Steven Joynes	(Golovin)

For:
Environment Waikato
PO Box 4010
HAMILTON EAST

January 2010

Document #: 1560954 version 4

Approved for release by:
Scott Fowlds Date May 2010

Disclaimer

Summary of the Effects of Land Use Change Between Taupo and Karapiro on the Flood Hydrology of the Waikato River Catchment

Authors: **Technical Expert Panel:** Ghassan Basheer, Ian Jowett, Murray Mulholland, Rory Nathan, Alan Pattle, Jon Williamson, and Ross Woods.

Contributing authors: Daniel Collins, John Hansford, Steve Joynes, Jochen Schmidt, and Blair Thornburrow.

Revision History	
4 June 2009	Incomplete draft by Ross Woods for Ghassan Basheer
8 June 2009	Incomplete draft by Ross Woods for Ghassan Basheer
30 August 2009	Draft for TEP teleconference 31 August 2009, incorporating SKM material from JW 18 June
08 September 2009	Draft for review incorporating revisions discussed at TEP teleconference 31 August 2009
28 September 2009	Final draft circulated to TEP members.
30 September 2009	Track changes from Ross and Ian incorporated. Final version to Murray Mulholland.
23 October 2009	Revisions by Daniel Collins in response to comments from PCG
10 November 2009	Revisions by Daniel Collins and Ross Woods in response to comments from TEP
15 December 2009	Revisions by Daniel Collins, Ross Woods and Malcolm Lumsden, in response to comments from PCG and additional model runs (HEC-HMS 1958, MIKE11 500-y flood results)
21 December 2009	Revised Figures 68 & 69 in response to TEP comments
15-26 March 2010	Revisions in response to Stakeholder feedback, final edits proposed by Pattle, Jowett

Executive Summary

The Waikato River at Rangiriri drains a catchment of approximately 12420km^2. This study looks at changes to the upper catchment between Karapiro and Taupo which comprises an area of 4400km^2. Within this upper catchment, 52% of land cover is exotic forest, indigenous vegetation, scrub, or unmanaged areas, while 45.7% is being used for agricultural purposes. The potential conversion of 567 km^2 of forest (24% of the existing forested land) to pastoral agriculture over the next 15 years represents an area of land use change of 12% of the total land area of the Taupo to Karapiro catchment; this is equivalent to 4% of the catchment that drains to Rangiriri.

Any significant change in land use has potential to impact on flood hydrology of the Waikato River and its tributaries. This includes subsequent effects downstream of Karapiro dam and impacts on the flood protection works of the Lower Waikato Waipa Control Scheme.

Previous scientific studies within the Waikato catchment on the effects on flood size of conversion from forest to pastoral agriculture indicate that both the rate and total volume of flood runoff increase. The studies were in very small catchments and cannot be extrapolated to large catchments. The magnitude of these observed increases in flood peaks ranged from a factor of two to ten. The explanation given for this change is the reduction in the infiltration capacities of the soil following conversion to pastoral agriculture as a result of soil compaction due, for example, to grazing animals and vehicle use. Thus, while scientific consensus exists for an increase in flood flows from pasture, the increases are highly variable and based on limited and small-scale studies. This necessitated a concerted modelling study at the regional scale as presented herein.

Environment Waikato established a project in 2007 to assess the effect that the anticipated potential changes in land use may have on the flood hydrology of the Waikato River and its tributaries. The scope of the project was defined by a Project Brief, and overseen by both a Project Control Group and a Technical Expert Panel.

This report assesses the change in Waikato flood hydrology for different magnitude floods at three different scales: (i) local flooding within the upper Waikato; (ii) Karapiro outflows, and (iii) the lower Waikato River system. The floods investigated here range in size from small to extreme, and correspond to rainfall events of specified return intervals. This range of event sizes enables the study to produce assessments that are relevant to a wide range of possible impacts, ranging from small relatively frequent floods to design and over-design events. These will assist stakeholders in their respective responsibilities for long-term planning. However, it must be stressed that the specific return intervals for the rainfall events do not translate to the floods.

The major steps in the study were to summarise data and research on floods and land use in the region, and to use simulation models to predict the impacts of land use change in the Upper Waikato on flood hydrology.

The simulation modelling comprised three steps:

1. Modelling of the flood response of the seven hydrolake sub-catchments, using two separate models;
2. The propagation of the resulting flood responses through the hydrolake system; and
3. Assessment of how these flood pulses affect inundation in the Lower Waikato.

The first step provided the basis for the study. It comprised the use of two distinct catchment hydrology models to predict the flood response to storms of different magnitude. These predictions were made twice, for each model: once for the current land cover, and once for potential future cover following forest-to-pasture conversion. The differences between the pre- and post-conversion scenarios thus provided an estimate of how the forest conversion might affect flooding.

The modelling approach was employed because observational data alone were insufficient to identify the effects of land cover differences. The majority of the historical forest-pasture conversion pre-dates even the longest of flow records, and the flow observations are mostly from catchments with relatively similar land cover composition.

Data used to underpin the modelling study comprised:

- catchment land use, derived from the Land Cover Database (LCDB2),
- geology,
- soil characteristics, derived from the New Zealand Land Recourse Inventory (NZLRI),
- hydrological data, including streamflow and rainfall records as well as in situ observational studies,
- hydraulic data for the Lower Waikato, and
- dam operational information.

The authors consider that this report presents a defensible approach to the estimation of land-use change impacts on floods at the catchment scale of interest. Factors contributing to our level of confidence include:

(i) a reasonable match between modelled and measured flood response under current land use

(ii) results are consistent with physically-based reasoning (e.g., larger impacts on small catchments with large fraction of the land cover changing)

(iii) results for changes in local flooding are consistent with measurements in small catchments

(iv) limitations in the data available to validate change predictions for large catchments

The modelling study found that:

1. Simulation models provide a useful means to investigate how land use affects the transformation of rainfall into flood runoff; and

2. The projected changes in land use would lead to the following changes in flood peaks:

	Small flood (5-year rainstorm)	**Medium flood (20-year rainstorm)**	**Large flood (100-year rainstorm)**	**Extreme flood (500-year rainstorm)**
Local flooding within Upper Waikato 10-100 km^2 catchment area, 0-80% upstream land use conversion	Significant increase (5-50%) for streams where most of catchment has land use change	Significant increase (5-50%) for streams where most of catchment has land use change	Very significant increase (more than 50%) for streams where most of catchment has land use change	Very significant increase (more than doubled) for streams where most of catchment has land use change
Upper Waikato Taupo-Karapiro inflow 4405 km^2 area, 542 km^2 land use conversion (12%)	Little or no change	Little or no change	From 2-9% increase in peak flow rate (average 4%) 0-5% increase in 72-h flood volume (average 2%)	From 2-16% increase in peak flow rate (average 6%) 2-10% increase in 72-h flood volume (average 4%)
Upper Waikato Karapiro outflow 7852 km^2 area	Little or no change	Little or no change	From 0.5-3% increase in peak flow rate (mean of 2%)	From 1-12% increase in peak flow rate (mean of 7%)
Waikato River at Hamilton 8230 km^2 area	Little or no change	Little or no change	0-110 mm water level increase 0-21 m^3s^{-1} peak flow increase	0-530 mm water level increase 0-140 m^3s^{-1} peak flow increase
Waikato River at Ngaruawahia 11395 km^2 area	Little or no change	Little or no change	0-40 mm water level increase 0-18 m^3s^{-1} peak flow increase	0-270 mm water level increase 0-150 m^3s^{-1} peak flow increase
Waikato River at Huntly 12066 km^2 area	Little or no change	Little or no change	0-40 mm water level increase 0-17 m^3s^{-1} peak flow increase	0-220 mm water level increase 0-150 m^3s^{-1} peak flow increase
Waikato River at Rangiriri 12420 km^2 area	Little or no change	Little or no change	0-30 mm water level increase 0-17 m^3s^{-1} peak flow increase	Flood exceeds design standards even under current land use; stopbanks overtopped

The study found that the projected change in land use is expected to cause an increase in flood risk during large and extreme rainstorms (that is, 100-year and 500-year rainstorms) that contain intense rain bursts.

The study also found that, consistent with previous small-catchment studies, local flooding may increase significantly for streams where most of the catchment's land use is converted, but the exact magnitude of change will depend on site-specific details that were beyond the scope of this report. Increases in hydrolake inflows are likely to be greater where fed by sub-catchments with greater portions of forest under conversion, and with smaller coverage of pumice soils beneath the converted forest.

The uncertainty ranges presented in the summary table above reflect the range of model results and rainfall inputs chosen. The uncertainty ranges presented in the report thus reflect a combination of uncertainty in our knowledge of hydrological behaviour and of assumed natural variability. The methods we have adopted provide the best available bounds for what could happen.

The overall conclusions from the study as agreed by the Technical Expert panel are that the effect on flood flows and water levels from land use change in approximately 12% of the Upper Waikato catchment are likely to have:

- Significant to very significant increases in peak flow rate for local flooding in small catchments where full conversion is expected.

- While the 72 hour storm simulated is appropriate for defining the effects of land use change over the whole catchment, the effects on the local tributary sub-catchments are larger for storms with shorter durations. To make assessments of impacts on local flooding in specific cases, a range of design storms with different durations need to be considered, to assist in identifying the magnitude of the local effects and appropriate mitigation measures

- At Hamilton, insignificant impacts during small to medium floods, increases of up to 40-110 mm in peak water level for large floods, and increases of 280-530 mm for extreme floods

- From Ngaruawahia to Rangiriri, insignificant impacts during small to medium floods, increases in the peak flood water level of 20-40 mm during large floods, and increases of 170-270 mm in extreme floods;

The assumption that land use change will take place on 567 km^2 is a realistic scenario, rather than a precise prediction of what future land use changes will occur. When further information becomes available on actual or planned forest conversion in the catchment, the methods developed here can readily be applied with the new land use information. Other potential changes in land use were outside the scope of this report.

Mitigation measures such as flood detention dams can reduce increases in flood size associated with conversion from forest to intensive agriculture, and are being used in the Waikato catchment. The methods used in this study could be extended to include effects of mitigation, if required, but this was outside the scope of the study.

Assessing the significance of these level and flow changes in terms of design and policy considerations was not within the scope of this report.

Table of Contents

1 Introduction ... 9
2 Study Framework ... 10
3 Literature Review ... 10
4 Data ... 11
4.1 Catchment Overview ... 11
4.2 Land Use and Land Cover Data ... 13
4.3 Hydrological Data ... 16
4.3.1 Streamflow Data ... 16
4.3.2 Rainfall Data ... 16
4.3.3 Soil Infiltration Data ... 17
5 Statistical Relationship between Land Cover and Flood Magnitude ... 18
6 Model Selection ... 19
6.1 Model Overview ... 19
6.2 Model Descriptions ... 20
6.2.1 TopNet (Woods et al, 2009) ... 20
6.2.2 HEC-HMS (SKM and EW, 2009) ... 23
6.2.3 WaikatoFlood (Jowett, 2009b) ... 26
6.2.4 MIKE11-NAM (Joynes, 2009) ... 27
6.3 Comparison of TopNet and HEC-HMS ... 29
7 Model Calibration and Validation ... 29
7.1 TopNet: Calibration and Validation ... 31
7.2 HEC-HMS: Calibration ... 40
7.3 HEC-HMS: Validation ... 49
7.4 Rainfall-runoff response of TopNet and HEC-HMS Models ... 53
7.5 WaikatoFlood ... 58
7.6 MIKE11-NAM ... 58
8 Scenario Modelling ... 60
8.1 Test Events Simulations ... 60
8.2 Land Use Change Predictive Analysis ... 62
8.2.1 TopNet ... 62
8.2.2 HEC-HMS ... 63
9 Results ... 63
9.1 Local flooding within the Upper Waikato Catchment ... 63
9.1.1 TopNet ... 64
9.1.2 HEC-HMS ... 65
9.1.3 Discussion ... 66
9.2 Inflows to Dams ... 67
9.2.1 TopNet ... 67
9.2.2 HEC-HMS ... 71
9.2.3 Summarising TopNet and HEC-HMS ... 73
9.3 Effects of Dam Operations ... 77
9.4 Karapiro Daily Discharges ... 79
9.5 Lower Waikato flooding ... 82
9.6 Summary of Key Modelling Results ... 84
10 Discussion and Interpretation ... 86
10.1 Sub-Catchment Variation of Effects ... 86
10.2 Effects of Land Use Change on Flood Volume and Annual Runoff ... 88
10.3 The Role of Catchment Size and Storm Duration ... 89
10.4 Uncertainties and Confidence Limits ... 89

10.5 Assessment 91
10.6 Future Data Collection 91
11 Conclusions 92
12 References 94
13 Appendix 1: TEC Member Profiles 96
14 Appendix 2: Project Brief 99
15 Appendix 3: Study Specification 105

1 Introduction

Environment Waikato established a project in 2007 to assess the flood hydrology effect of potential changes in land use within the Waikato River catchment between Karapiro and Taupo. In addition, the project was intended to identify the subsequent effects downstream of Karapiro dam and impacts on the flood protection works of the Lower Waikato Waipa Control Scheme. The scope of the project was defined by a Project Brief (see **Appendix 1**), and overseen by both a Project Control Group and a Technical Expert Panel.

The project was motivated by the potential for a significant proportion of the forested land area to be converted to pastoral agriculture within the Upper Waikato catchment in the coming 15 years. Some removal of forest in the catchment had already commenced at the beginning of the project. As summarised later in this report, conversion of forest to pasture in other locations has caused increases in flood magnitude, though the sizes of the reported increases vary considerably. Environment Waikato established this project to assess potential changes specifically in the context of the unique combination of climate, soils, geology, land use and flood-sensitive infrastructure in the Waikato catchment.

To address the technical information needs of the project, a Technical Expert Panel was formed to develop and oversee a study programme (see **Appendix 2**). A study specification (Technical Expert Panel, 2007) was drafted by the Technical Expert Panel, and approved by the Project Control Group. The overall goal of the study programme was, as indicated above, to predict and evaluate changes in flood magnitude for the Waikato River and its tributaries, as a result of forest-to-pasture land use conversion in the Waikato River catchment between Taupo and Karapiro. **Due to limited observational data, a modelling approach was adopted.**

Specifically, the study programme was to estimate the change in flood hydrology for small, medium, large and extreme rainfall events (peak flood magnitudes generated from rainfall with average recurrence intervals of approximately 5, 20, 100 and 500 years) at three spatial scales, given a distribution of potential forest-to-pasture land use conversion:

1. Local flooding within Upper Waikato
2. Upper Waikato hydropower lakes
3. Lower Waikato flood protection works

This technical report summarises the overall findings of the study programme. It contains the Technical Expert Panel's estimates of the expected changes in flood magnitude due to the land use changes.

The technical work was carried out in subsidiary studies which are referred to in this report. Members of the Technical Expert Panel provided review comments on draft reports from those subsidiary studies, and the authors of those reports made revisions in response. The reports produced by those subsidiary studies are considered by the Technical Expert Panel to have the status of working papers.

The purpose of this report is only to assess the potential effect of a particular land use change scenario on floods. There are numerous design considerations, such as selection of design rainfall events, and potential impacts of climate change, that were not considered in this study. The report does not provide revised design flood estimates, though some of the subsidiary studies (e.g. Woods et al, 2009; SKM and EW, 2009; Jowett, 2009b; Joynes, 2009) could serve as precursors to future design flood studies. Furthermore, the number of significant figures displayed in the results is for illustrative purposes only and not meant as an indication of precision.

Mitigation measures such as flood detention dams can reduce increases in flood size associated with conversion from forest to intensive agriculture, and are being used in the Waikato catchment. The methods used in this study could be extended to include effects of mitigation, if required, but this was outside the scope of the study. The standard process for designing any mitigation measures is to understand the full range of effects first. The current models and information derived from them can be used to assess the need for mitigation measures.

2 Study Framework

The study was structured in three main steps as follows:

1. Summarise data and international research on floods and land use.
2. Build models that can predict how floods on upper Waikato tributaries will change with land use change
3. Apply the models to predict impacts on flood hydrology

The study programme makes extensive use of time-stepping simulation models of flood hydrology, to extrapolate from the current land use to the projected future land use. As will be seen in **Section 5**, the catchment hydrology data were not appropriate for a purely data-driven analysis of how land use affects flood hydrology.

The primary methodology used in this report was the development of computer simulation models that adequately simulated flood response throughout the study area. The models were first used to produce a control simulation, i.e., characterising present-day catchment response. This included the current spatial variations in rainfall, soils and vegetation. The models were then altered to represent the projected future land use changes in specified areas, and the models were run again, with all other factors (including climate) unchanged. The differences between the floods generated by the two model runs were interpreted as representing the effects of the projected vegetation change.

3 Literature Review

The literature on effects on flood size of conversion from forest to pastoral agriculture indicates that both the rate and total volume of flood runoff increase (see Sections 2 and 3.1 of Mulholland, 2006). Documented examples of such changes in very small Waikato pumice catchments are provided by Selby (1972), Jackson

(1973), and Rowe (2003). The magnitude of these observed increases in flood peaks ranged from a factor of two to ten.

The studies of Selby and Jackson concluded that the main hydrological process that causes changes in flood magnitude in these small catchments was the change in infiltration properties at the soil surface. When forest is converted to pastoral agriculture, the structure of the soil surface is changed and the soil surface may subsequently become compacted by stock trampling and vehicle use (Selby, 1972). One or several factors reduces the maximum rate at which rain can infiltrate, and if rainfall is intense enough, more surface runoff is produced on pasture than on forest.

The catchments in the above studies are very small (from a few square metres up to tens of hectares). No standard method exists for transferring those results to the scales of interest of this study, which are tens to thousands of square kilometres. However, if land use conversion were sufficiently extensive and only limited mitigating factors (e.g. channel storage) were active, then it is rational to conclude that forest-to-pasture conversion *could* cause an increase in peak flows and levels in rivers downstream.

We conclude that there is a scientific basis for investigating the *possibility* that conversion from forest to pastoral agriculture on Waikato pumice soils could change flood magnitude significantly. However, since there is no information in the published literature that provides a direct assessment of the magnitude of those impacts, a detailed investigation was required. The remainder of this report summarises the investigation that followed.

4 Data

4.1 Catchment Overview

The Waikato River begins upstream of Lake Taupo, flows through the Upper Waikato catchment between Taupo and Karapiro, meets with the Waipa River at Ngaruawahia downstream of Hamilton, and then flows past Huntly to the sea at Port Waikato (**Figure 1**). The land area draining to the Waikato River between Taupo and Karapiro Dam (approximately 4400 km^2) is referred to here as the Upper Waikato catchment. Most of the projected changes in land use are in the Upper Waikato catchment. Tokoroa is the largest town in this part of the catchment; there are numerous culverts and bridges on small waterways that are potentially affected by changes in local flooding. The major assets that could be sensitive to changes in flood magnitude are the eight hydropower dams and the areas adjacent to the Waikato River downstream of Karapiro dam which are protected by the Lower Waikato Waipa Control Scheme (LWWCS). The levels of protection provided by the LWWCS range from 5-year to 100-year, plus freeboard of 300-600 mm, depending on location.

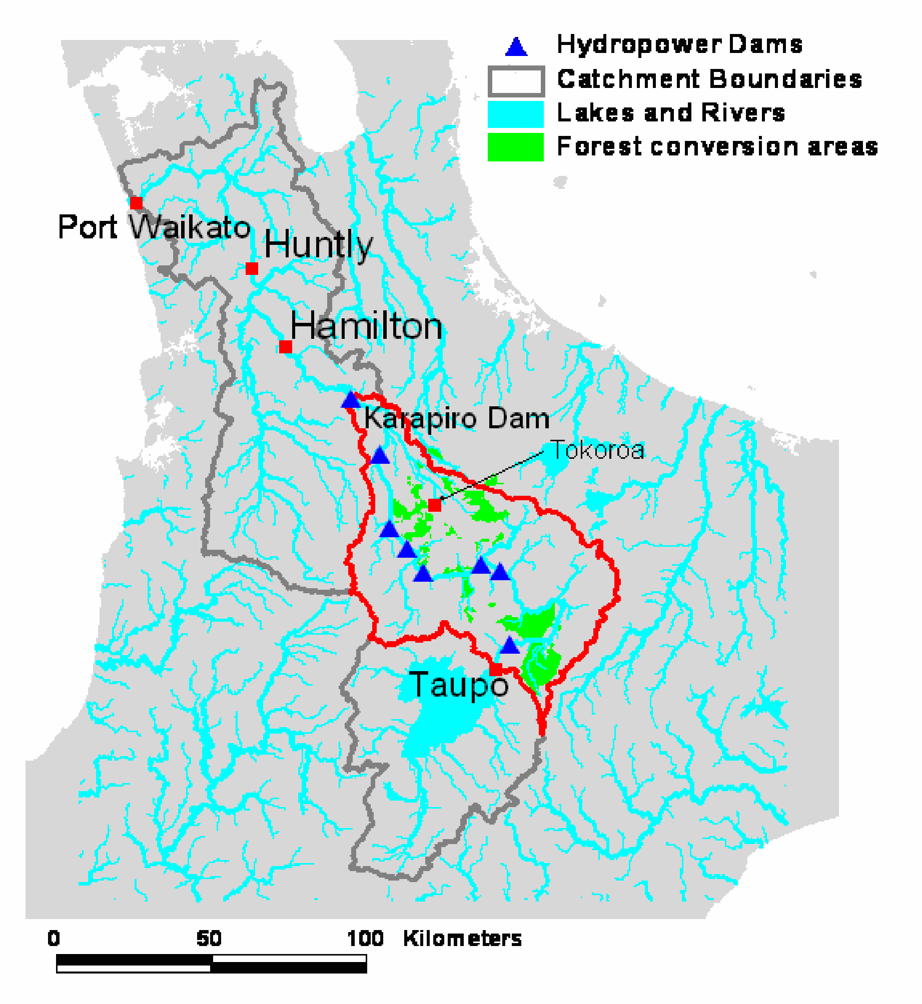


Figure 1: Overview of Waikato catchment, with the Upper Waikato outlined in red, and the land use change areas shown in green.

Figure 2: Separation of the Upper Waikato catchment into the seven dam sub-catchments considered in the hydrological analysis.

4.2 Land Use and Land Cover Data

The land use in the Upper Waikato catchment was analysed in an Environment Waikato study (Environment Waikato, 2007) using a simple land cover classification that groups land cover types together with similar hydrological characteristics. The base data for the information reported here is the second edition of the Land Cover Data Base, which is based on satellite imagery from 2001-2002. The mapped land cover classification is shown in **Figure 3**.

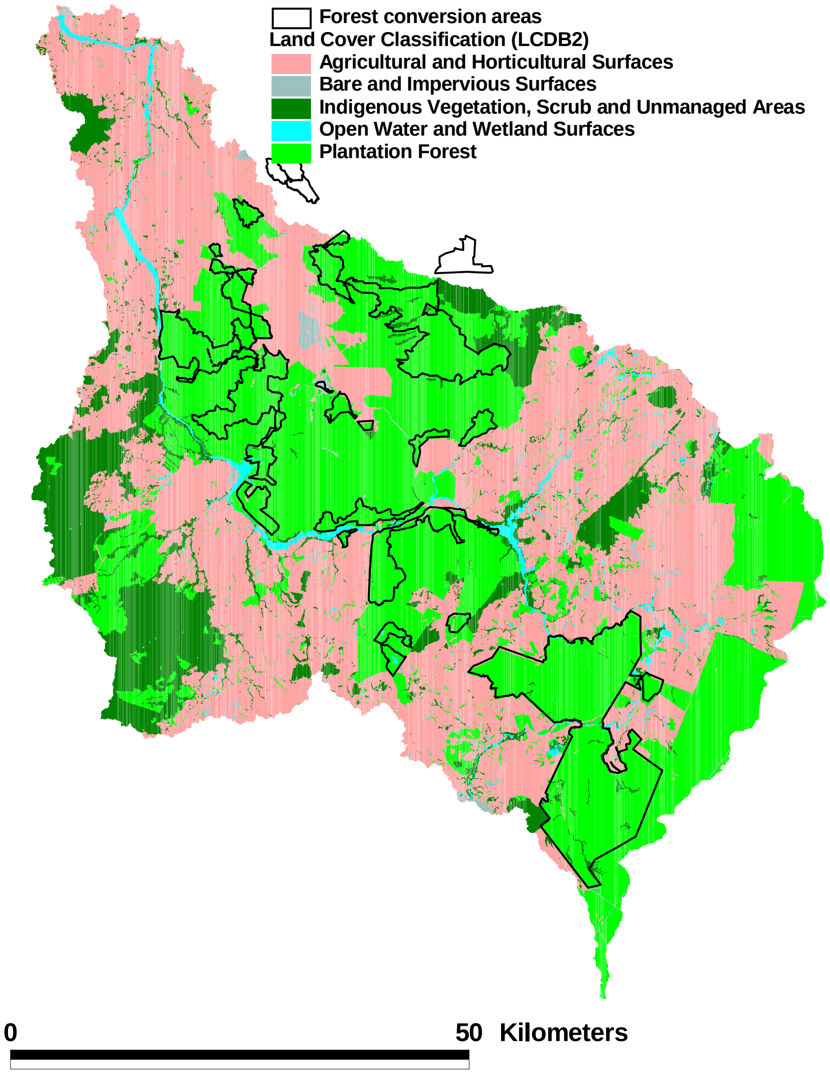


Figure 3: Upper Waikato catchment land cover classification and forest conversion areas

Analysis of the land cover data showed that approximately 52% of the study area is classified as exotic forest, indigenous vegetation, scrub or unmanaged areas. The other 48% is predominantly covered by agricultural and horticultural surfaces, i.e., mainly pasture. The area statistics are given in **Table 1**.

An area totalling 567 km^2 has been identified by Environment Waikato as either recently converted or likely to be converted from forestry to intensive agriculture in the next 15 to 20 years. This area was defined on the basis of information presented to Environment Waikato in November 2006 by Wairakei Pastoral Ltd and Carter Holt Harvey. The areas were defined on hard copy maps, digitised, and subsequently confirmed by members of the Technical Expert Panel who work closely with these two land owners. This area is approximately 12% of the Upper Waikato catchment, and is shown in **Figure 3** using black outlines. Approximately 200 km^2 of this land use conversion has already commenced. The total conversion area could be smaller or bigger than the test area of 567 km^2, depending on future land use economics and other factors such as the Carbon Emission Trading Scheme (ETS).

Table 1: Land cover classification statistics for Upper Waikato

Hydrologic Land Cover Class	Area (km^2)	Area (%)
Indigenous Vegetation, Scrub and Unmanaged Areas	553	12.6%
Plantation Forest	1743	39.6%
Bare and Impervious Surfaces	25	0.6%
Agricultural and Horticultural Surfaces	2009	45.7%
Open Water and Wetland Surfaces	66	1.5%
TOTAL	4397	100.0%

Complementing the land cover data are the soils data. These are obtained from the New Zealand Land Recourse Inventory (NZLRI, Newsome et al., 2000). Within areas of land identified for potential deforestation, the vast majority (94%) overlies pumice soils (**Figure 4**). This has implications for the results of land use change flood simulations because of the different hydrological characteristics of the different soil types, particularly infiltration. While observational evidence is not conclusive, sub-catchments with substantial pumice-based soil tend to be less hydrologically responsive, producing smaller floods compared with non-pumice-based soils.

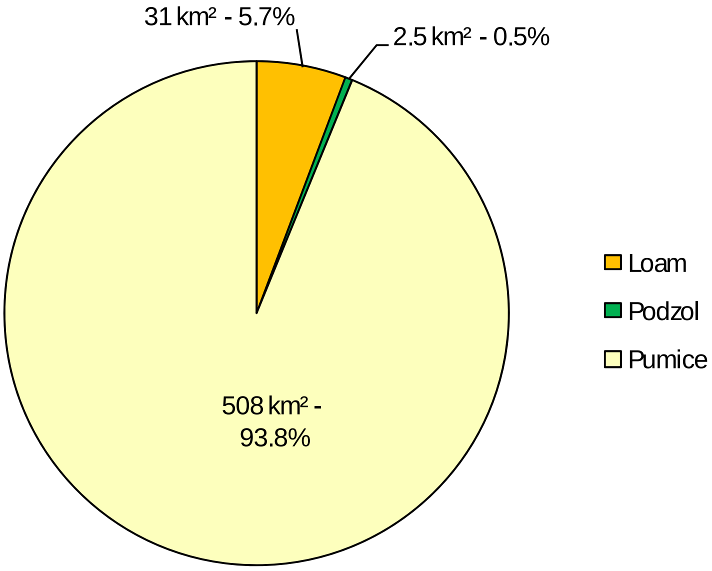


Figure 4: Soil type distribution of land identified for potential deforestation.

The third category of landscape information is geological, which governs the longer-term hydrological behaviour of the catchments. The western gauged catchments (Waipapa at Ngaroma Rd and Mangakino at

Dillon Rd) overlie densely welded Pakaumanu ignimbrites, whereas younger and more pumicious ignimbrites and other formations are predominant in other areas (e.g. the Whakamaru, Mamaku and Mokai ignimbrites).

4.3 Hydrological Data

This section documents the preparation of stream flow and rainfall data used for the study.

4.3.1 Streamflow Data

Continuous flow records were obtained for 18 sites from Environment Waikato (**Figure 5**). A summary of these records and their duration is provided in **Table 2**. Flow records with a resolution of less than 1 hour were aggregated to hourly.

Table 2: Summary of available stream flow records.

Site ID	River	Site	Area (km^2)	Start Date	End Date
1043434	Mangakara	Hirsts	22	Jun-69	Apr-93
1443462	Mangahanene	Sh1	8.75	Sep-72	Jan-07
1043427	Mangakino	Dillon Rd	337	Apr-64	Jan-07
2143404	Mangatete	Te Weta Rd	30.6	Dec-86	Dec-94
2043446	Mokauteure	Forest Rd	38	Jul-86	Aug-91
2043497	Orakonui	Ngatamariki	73.5	Sep-87	Mar-92
2143401	Otamakokore	Hossock Rd	40.1	Dec-86	Jan-07
2143412	Otumaheke	Spa Hotel	9.1	Dec-86	Jan-03
43411	Pokaiwhenua	Forest Products Weir	62.1	Jan-60	Nov-99
1043419	Pokaiwhenua	Puketurua	448	Oct-63	Jan-07
1143409	Purukohukohu	Puruki	0.344	Dec-68	Jan-07
1143407	Purukohukohu	Weir	1.69	Mar-70	May-84
1143442	Purukohukohu Stream	Purutaka	0.225	Dec-68	May-06
1043428	Tahunaatara	Ohakuri Rd	210	Apr-64	Jan-07
2043493	Waiotapu	Campbell Rd	47.6	Dec-86	Jul-01
43472	Waiotapu	Reporoa	228	Feb-60	Jan-07
2043441	Waipapa Stream	Mulberry Rd	85.4	May-86	Sep-95
43435	Waipapa River	Ngaroma Rd	137	Apr-64	Jan-07

4.3.2 Rainfall Data

Hourly rainfall data from 1960 to 2006 on a 5-km grid were obtained over the catchment in a two step procedure. First, the daily rainfall totals from all available gauges (recording and manually-read) on each day from 1960 to 2006 were interpolated onto a 5-km grid using an interpolation technique (Tait et al., 2006). The number of gauges with daily totals available varied from day to day (black dots in **Figure 5**).

Hourly time series of rainfall were obtained at each grid point by taking the daily total at that grid point and subdividing it into 24 hourly values, on the basis of the hourly rainfall patterns at nearby recording rain gauges (open squares in **Figure 5**).

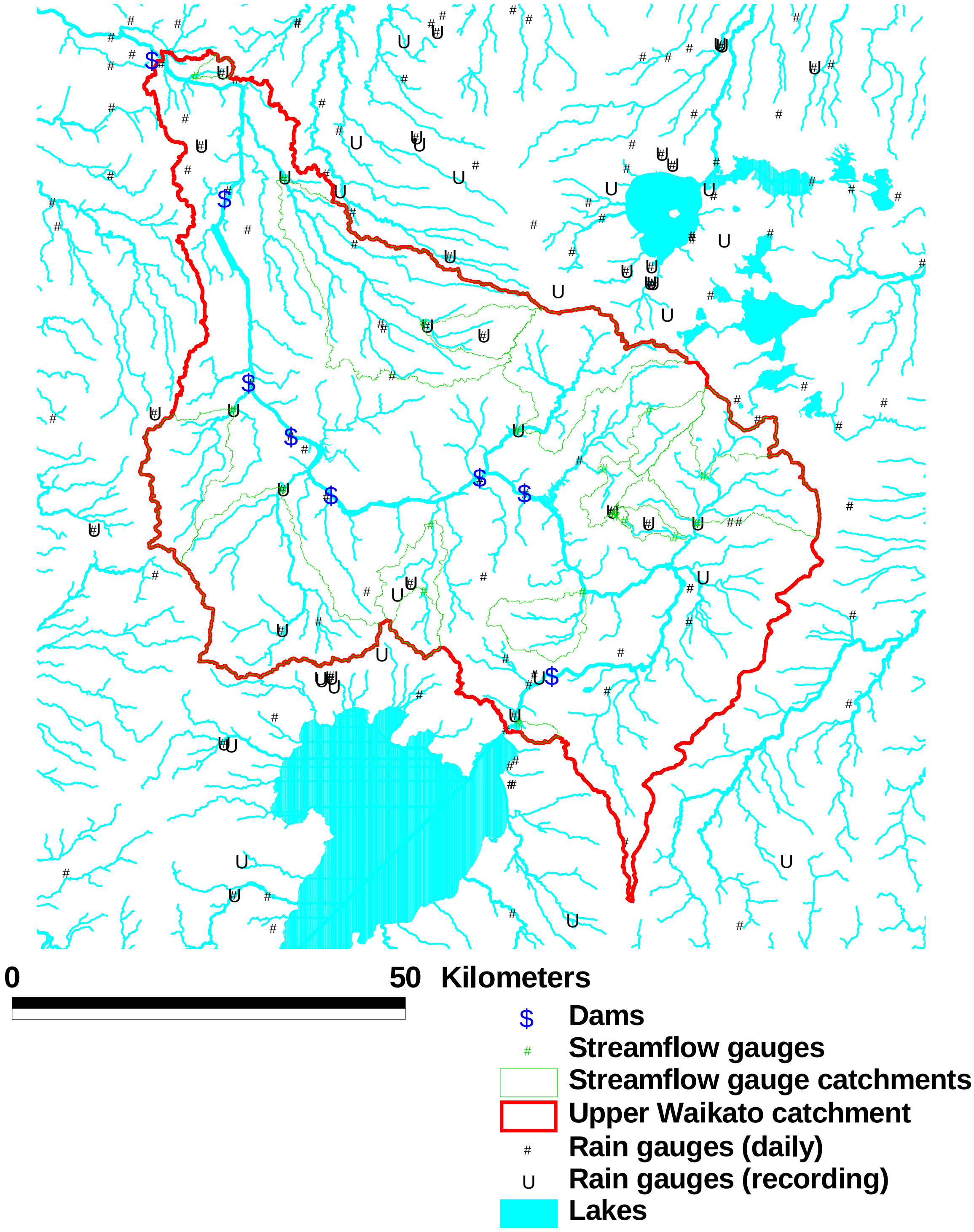


Figure 5: Streamflow and rainfall gauge locations

4.3.3 Soil Infiltration Data

Given the importance of infiltration to land use hydrology in the upper Waikato region, Taylor et al. (2009) investigated the differences in infiltration rates among soils under both pastoral agriculture and forest. They measured infiltration rates at paired forest and pasture (dairy and beef) sites on five different soil classes in the upper Waikato. They found that infiltration rates, while very high in most soil types, were an order of magnitude less under pasture than under forest. Taylor et al. (2009) also measured the porosity of soil cores from the top 10cm of the soil profile. The results are summarised in Table 3.

Table 3: Measured infiltration rates under pastoral agriculture and forestry land uses.

Soil class	Infiltration rate (mm/h) +/- 1 standard deviation		Macroporosity (%)		Total Porosity (%)	
	Agriculture	Forestry	Agriculture	Forestry	Agriculture	Forestry
Tirau	31 ± 23	489 ± 165	4.9	25.7	65.3	67.9
Tihoi	3 ± 2	121 ± 89	4.9	41.0	78.1	79.4
Taupo	17 ± 5	409 ± 75	4.5	20.7	71.8	77.5
Ngakuru	86 ± 65	1130 ± 209	6.4	37.5	65.3	74.9
Waipahihi	99 ± 54	1207 ± 691	8.4	33.3	67.3	72.7
Average	47 ± 39	671 ± 335	5.8	31.6	69.6	74.5

Table 3 shows that the % macroporosity decreased very significantly when moving from forest to a paired pastoral agricultural site, but the total porosity decreased only slightly. The soil has the same volume of voids, but under pastoral agriculture the larger voids are much less common. The change in the size of voids is significant because the larger voids are very effective at allowing water to infiltrate under the saturated conditions that develop during intense rainfall. The data in the table show that infiltration rate at the sampling sites is an order of magnitude lower on the pastoral agricultural sites, compared to forest.

The data collected by Taylor et al. (2009) also indicated that soil texture does not have a major influence on infiltration rates. As noted in Section 3, several factors can lead to the noted differences in infiltration properties at the soil surface between forest and pastoral agriculture including change of surface soil structure and compaction caused by stock trampling and vehicle use.

5 Statistical Relationship between Land Cover and Flood Magnitude

The historical land cover and streamflow data outlined in the previous section provided two potential methods for quantifying the relationship between land cover and flood magnitude.

The first approach was to check whether any monitored Upper Waikato catchments had experienced significant land cover changes during the time when recorded flood data was available. An analysis of the land cover data indicated that for catchments with river flow monitoring stations, there had only been small changes in forested area since 1960. As a consequence, the analysis of historical trends in measured flow rate at individual flow monitoring stations is not useful for assessing potential impacts of future land cover changes. Measured changes in flood response after forest removal can be inferred from the experimental catchment data at Purukohukohu and Otutira, but the very small areas studied in these experiments makes it impossible to reliably transfer the results to the entire study area.

The second approach was to check whether the monitored Upper Waikato catchments show a statistical correlation between the fraction of forested catchment and the size of floods. This analysis requires catchments of greater than 10 km^2 and at least 20 years of continuous data. However, most of the catchments with long flow records are at least 50% forested. There is only one predominantly pasture catchment larger than 10 km^2 with more than 20 years of flood record (Mangakara at Hirsts, 66% pasture, operated by Ministry of Works from 1969-1994). These are not sufficient data to support a statistical argument regarding the effect of changes in land cover on flood magnitude for catchments larger than 10 km^2.

Having eliminated these two approaches, the study took a simulation modelling approach to the problem, as described in **Sections 6 and 9** of this report.

6 Model Selection

6.1 Model Overview

The analysis of floods in the Waikato catchment has been undertaken in several stages:

(i) The generation and routing of flood runoff within the Upper Waikato catchment (Woods et al, 2009; SKM and EW, 2009);

(ii) The routing of floods through the eight hydropower dams (Jowett, 2009b); and

(iii) The routing of floodwaters downstream of Karapiro (Joynes, 2009).

This project used computer models to represent each of these stages in sequence, as shown schematically in **Figure 6**.

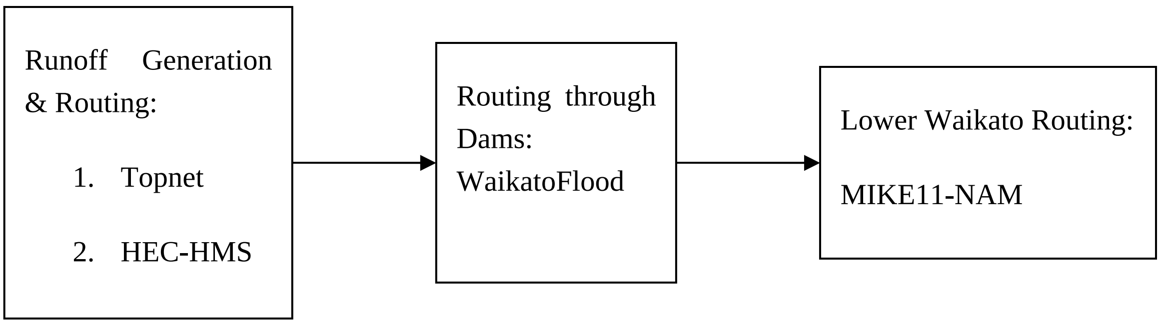


Figure 6: Schematic of the models used in this study

Two different models (TopNet and HEC-HMS) are used for the Runoff Generation & Routing, as a means of providing two separate assessments of the effect of land use change on flood magnitude. Two models were used only for this part of the modelling, because this is where the land use change issue is addressed. It should be noted that previous models of runoff generation and routing for the Upper Waikato have not explicitly addressed the effect of land cover. The routing models for the hydropower dams and the Lower Waikato are used to transform any changes in Upper Waikato inflows into peak flows and levels further down the catchment.

6.2 Model Descriptions

6.2.1 TopNet (Woods et al, 2009)

TopNet is a catchment model designed for continuous simulation of water balance and river flow across a landscape. A summary of TopNet is provided below, while comprehensive details of the model are provided in Woods et al. (2009).

Inputs to TopNet are rainfall and temperature time series, and maps of elevation, vegetation type, soil type and rainfall patterns). These map data are used with tables of model parameters for each soil and vegetation type, to produce initial estimates of the model parameters (more details are given below).

TopNet models a catchment as a collection of sub-basins, linked by a branched river network (**Figure 7**). These sub-basins are the computational elements of the landscape. Flow is routed through the river network using kinematic waves using the shock-fitting technique of Goring (1994).

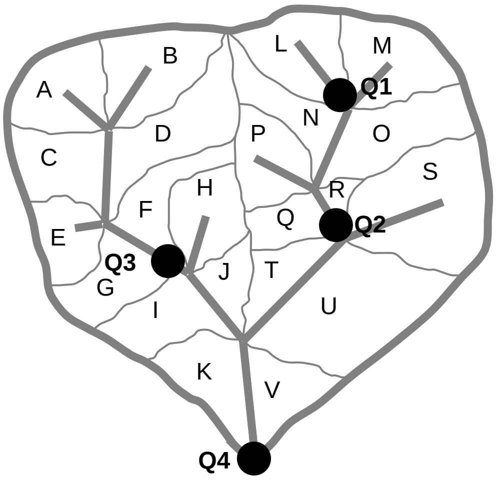


Figure 7: Schematic of TopNet model: Each letter indicates a sub-basin, and the symbols Q1 – Q4 indicate the location of flow recording sites.

Each sub-basin is modelled (**Figure 8**) using an adaptation of Topmodel (after Beven and Kirkby, 1979). Precipitation on each sub-basin- is modelled as either rain or snow, depending on the air temperature.

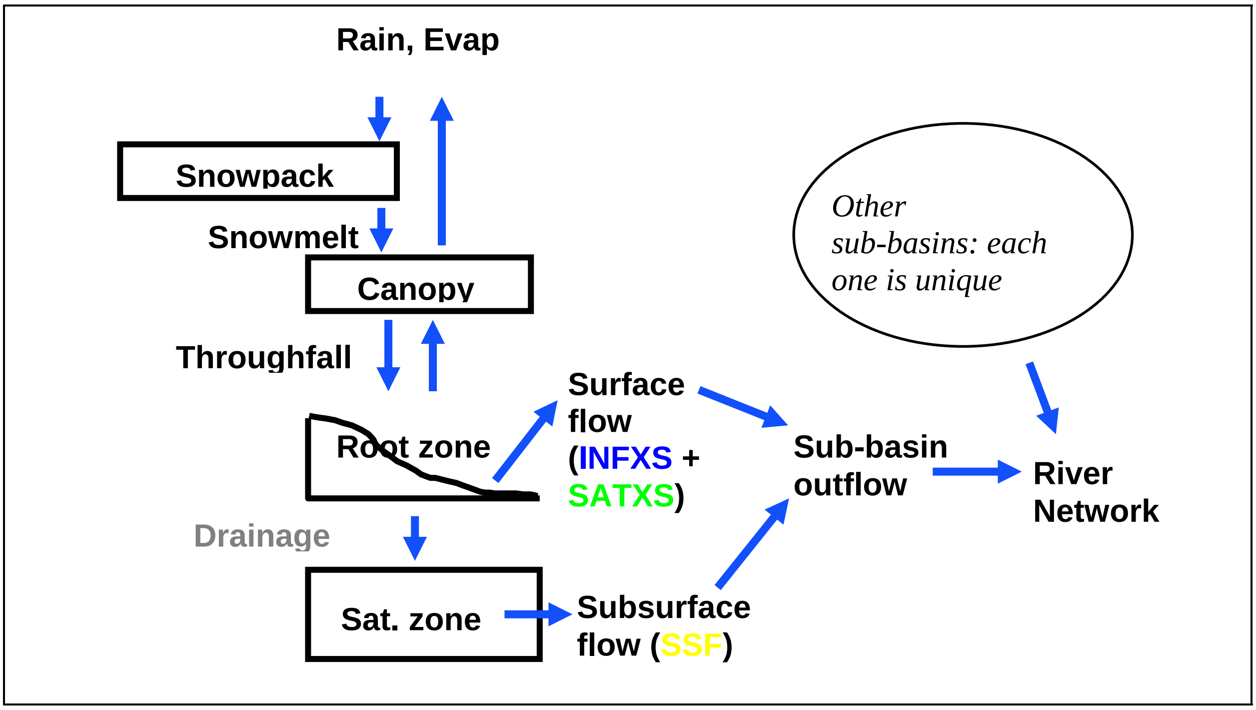


Figure 8: Overview of TopNet model structure, showing the snowpack, canopy, root zone, saturated zone and river network components of the model. Arrows indicate flows of water from one model component to another.

The snow component of the model was not used in this study.

Modelled streamflow is generated in 3 ways:

- rain falls on a location where soil is already saturated (saturation excess or 'Dunne runoff, indicated by SATXS)
- rain rate exceeds the soil's maximum infiltration rate (infiltration excess or 'Hortonian' runoff, indicated by INFXS)
- saturated zone discharge into stream (both subsurface storm runoff and baseflow, indicated by SSF)

TopNet assumes that available soil water storage can vary within a sub-basin- because of topographic effects - valley bottoms and flat areas tend to be wetter than ridges. TopNet uses a topographic index to measure the propensity for soil wetness at each location in a sub-basin. This index is derived for each point from an analysis of a digital elevation model of the catchment. The actual amount of soil water storage depends on the level of storage in the (lumped) saturated zone (which varies with time) as well as the topographic index.

The model does not explicitly route water from pixel to pixel within a sub-basin. The sub-basin model assumes that vegetation and soil characteristics are uniform within a sub-basin. The TopNet sub-basin model for the Waikato study region was derived as a 3rd order stream network, resulting in 483 sub-basins with an average area of about 9 km^2. Parameters for the canopy, soil and geometric characteristics of sub-basins are set using GIS data for elevation, vegetation and soil type, along with lookup tables which associate parameter values with soil, vegetation etc.

6.2.1.1 TopNet's Land Cover Representation

Given the project's emphasis on land cover change, it is valuable to delve deeper into the models' representations of forest and pasture hydrology. The three most important TopNet parameters controlled by land cover are the saturated hydraulic conductivity at the soil surface, the canopy capacity and the canopy enhancement factor, with the first being the most important in this case.

Values of saturated hydraulic conductivity at the soil surface were assigned on the basis of land cover, soil group and soil series, as specified for infiltration rate in an Environment Waikato study (Taylor et al., 2009) with higher values assigned to forest land covers, and lower values to pasture and bare land.

The scale of a TopNet model element is of the order 10 km^2, which is much larger than the sub-metre scale of the experiments. It is not necessary for the experimental values of infiltration rate to apply directly at the model element scale – real soils are variable within the model element, and processes such as infiltration are not spatially uniform in the real world, even though they are modelled in this way. The purpose of the model is not to represent every local variation in hydrology (an impossible task in almost every case), but to represent the main processes generating floods.

The infiltration rate values mapped by Taylor et al. (2009) were subject to further potential calibration by a single multiplicative constant, and they attempt to represent the infiltration process which is expected to change when land use changes from forest to pasture stocked with grazing animals. An adequate calibration was obtained by multiplying all infiltration values by 0.05. Since the Taylor et al. (2009) mapping links conductivity values to land cover classes, it is straightforward to apply the same rules to a future land cover scenario, and derive a new map of hydraulic conductivity.

The two canopy parameter values were assigned on the basis of the land cover classification mapped by Environment Waikato (see **Figure 3**), and are listed in **Table 4**.

Table 4: Parameter values assigned in TopNet model on the basis of Land Cover

Land Cover	Canopy Storage Capacity (mm)	Canopy Evaporation Enhancement Factor (-)
Plantation Forest	3	2
Indigenous Vegetation	3	2
Scrub and Unmanaged Areas	1	1
Agricultural and Horticultural Surfaces	1	1
Bare and Impervious Surfaces	0	1

The most obvious hydrological difference between land covers is the infiltration characteristics of the soils. This is represented within TopNet by the saturated hydraulic conductivity at the ground surface. Each modelled sub-basin has a different value of hydraulic conductivity, obtained by overlaying the sub-basin boundaries on a map of hydraulic conductivity (see Woods et al, 2009), and assigning the average value. The hydraulic conductivity value for a model sub-basin is found by taking the average of all conductivity values in the sub-basin.

Hydrological differences in land cover will also manifest themselves via interception and evaporation of the few millimetres of water that can be stored in the plant canopy. This amount is trivial compared to major storms, but a potentially significant longer-term effect on small to moderate rain events is that pasture soils are somewhat wetter than forest soils, all else being equal. If soils are wetter at the start of a storm, then the soils can store less storm rainfall, and will produce more runoff for the same depth of rainfall. This process is modelled in TopNet with two parameters of the plant canopy, which are given in **Table 4**.

6.2.2 HEC-HMS (SKM and EW, 2009)

The Hydrologic Modelling System (HEC-HMS) is designed to simulate rainfall-runoff processes of dendritic catchment systems. This model was selected as the second model to provide complementary analysis to TopNet (SKM, 2008). A summary of HEC-HMS is provided below, while comprehensive details of the model are provided in SKM and EW (2009).

HEC-HMS incorporates a variety of algorithms that are used to simulate catchment processes to various degrees of complexity. The algorithms selected for this study are listed in **Table 5**.

Table 5: Selected components of the HEC-HMS model.

Model operation	Selected algorithm
Loss model	Soil Moisture Accounting (SMA) method
Runoff routing	Clark Unit Hydrograph method
Baseflow routing	Linear Reservoir

The flow of information among the model components is illustrated in **Figure 9**. All catchment losses such as evaporation from the canopy, soil zone and surface storage are calculated in the Soil Moisture Accounting (SMA) routine. The primary input to this routine is precipitation, as well as the suite of parameters defining its operation. Outputs from the SMA are catchment losses, direct surface runoff, and baseflow. The SMA has two baseflow components, representing rapid groundwater response (interflow) and slower groundwater response (true baseflow).

Surface runoff output from the SMA routine is routed through a runoff routing model. The Clark Unit Hydrograph method was chosen for this study, which attenuates runoff based on a time of concentration (T_c) and a storage lag coefficient.

Similarly, baseflow is routed through a post-processor to simulate baseflow attenuation. For this application the linear reservoir option was selected. Separate linear reservoirs were used to route each of the two baseflow components produced by the SMA model.

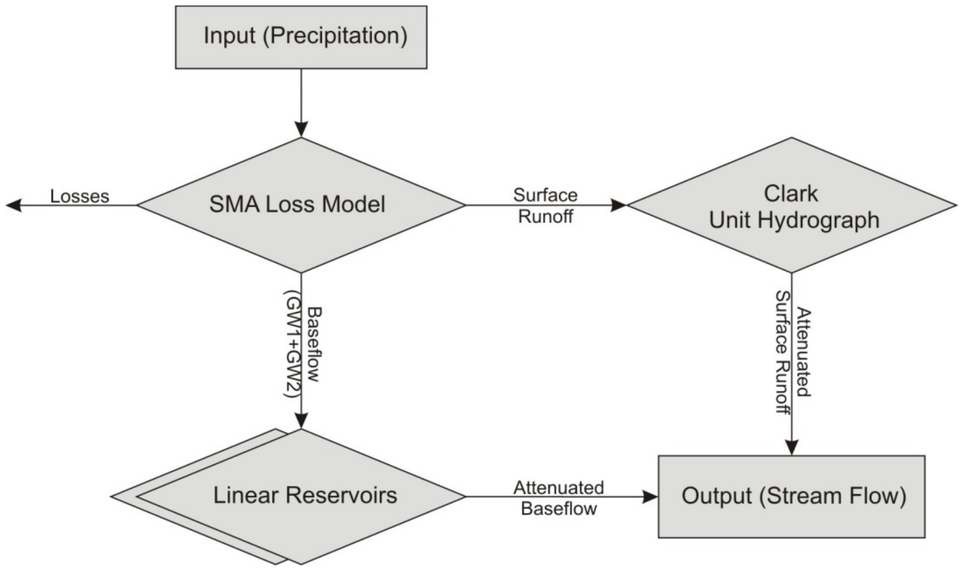


Figure 9: Interaction of HEC-HMS model components.

SMA Loss Model Operation

The SMA method uses five storage components:

1) Canopy storage;
2) Surface (ponding) storage;
3) Soil moisture storage;
4) Groundwater layer 1 storage, and;
5) Groundwater layer 2 storage.

Basic operation of the SMA model is illustrated in **Figure 10**.

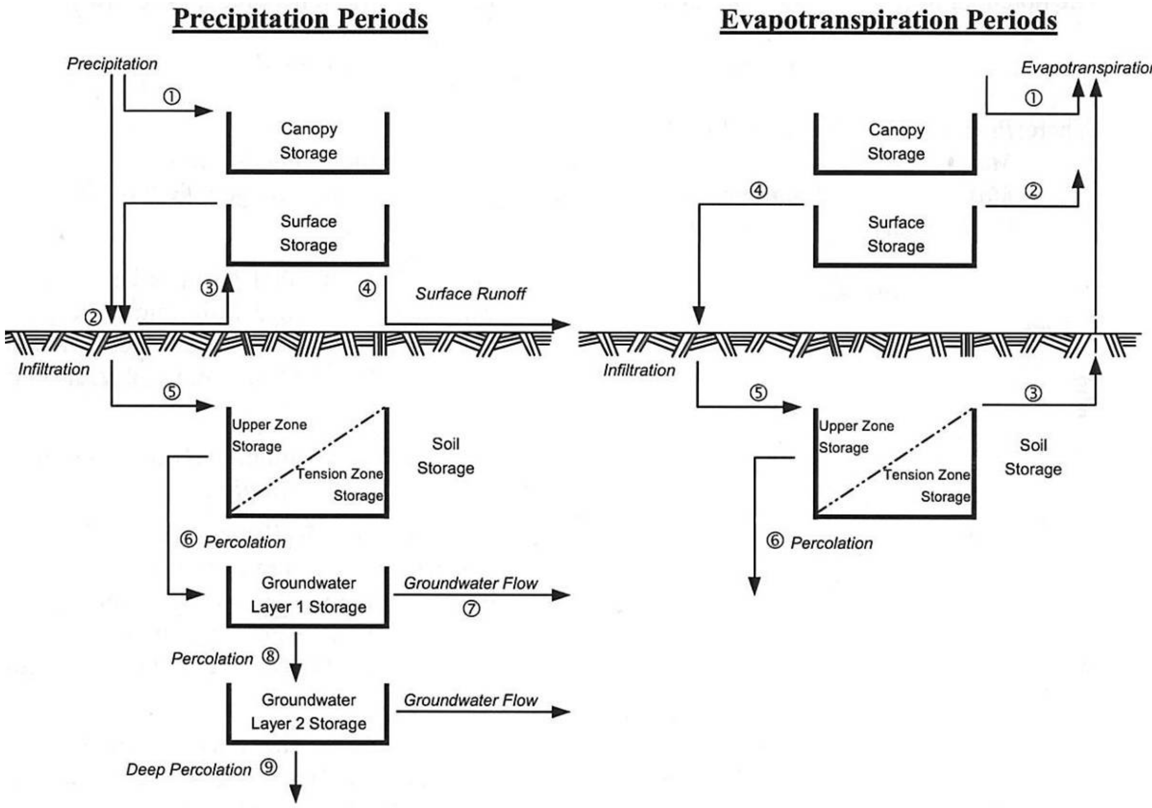


Figure 10: Operation of the SMA model (sourced from Bennett and Peters, 2000).

The SMA model operates in two modes depending on the occurrence or absence of precipitation in any particular time step (as illustrated in **Figure 10**).

While precipitation occurs, canopy storage must initially be satisfied (1) and once the canopy is full, additional precipitation will be available for infiltration (5) and surface storage (3). Water available for infiltration is the combination of any surface storage and precipitation reaching the surface (2). When this exceeds infiltration capacity, surface storage must then be filled before surface runoff (4) occurs. No evapotranspiration occurs in the SMA model while precipitation is occurring.

Infiltrated water (5) fills the soil moisture storage component, which is made up of two compartments (upper zone storage and tension zone storage). Soil evaporation can occur from the whole soil zone while there is no precipitation, but percolation (6) can only occur from the upper zone storage.

Water that percolates from the soil zone (6) enters the upper groundwater layer (GW1) where it is divided into two components, groundwater flow and percolation to the second or lower groundwater layer (GW2). Water stored in GW2 may leave as baseflow and as deep percolation out of the catchment system (9 – optional).

In the three subsurface storage components, flow between each layer is controlled by model parameters and the storage level within the donating and receiving storage zones. As such, parameter selection is complex due to these interdependences among storages.

Model Hierarchy within HEC-HMS

Like TopNet, HEC-HMS models catchment hydrology by breaking the catchment up into discrete sub-basins. A catchment can comprise a number of sub-basins or variable size connected by channel routing elements, storage reservoirs, sources and sinks etc.

For this investigation, each significant sub-catchment (either a gauged catchment or tributary to the hydro reservoirs) was modelled as a separate element, with each sub-catchment divided into a set of homogeneous sub-basins on the basis of soil and land use type (refer SKM and EW, 2009).

The rainfall-runoff process was modelled at the sub-basin level within HEC-HMS. The sub-basins are modelled discretely and the outputs are lumped together at a sub-catchment scale. Accordingly, routing parameters applied to each of the sub-basins were based on routing characteristics for the whole sub-catchment.

6.2.3 WaikatoFlood (Jowett, 2009b)

WaikatoFlood is a model developed by Jowett (2009b) to route flows from the catchment models, TopNet and HEC-HMS. The intent of the flood routing model was to assess the effects of different land use scenarios on discharges from the Waikato dams. One set of flood rules was used for this comparison. These rules were based on the phase II flood rules (see Jowett, 2009b) and are a simplification of the full flood rules. They were chosen so that both pre- and post-conversion flood flows were handled in the same manner, thus allowing comparisons between the various scenarios. In practice, flood management is more complex and sophisticated. For example, in large floods drawdown of lakes in advance of the flood and a reduction in Taupo discharge are actions that can be taken to reduce the magnitude of peak floods.

The model is a simple level pool routing described in Henderson (p. 356, 1966). This is the application of the continuity equation where the inflow, outflow and change in volume of water in each lake are balanced.

$$I - O = \frac{dV}{dt}$$

Where I = inflow from tributaries and outflow from upstream dam, O = outflow, dV = the change in lake volume (lake area times change in level) and dt the time increment.

Because the outflow from the lakes is controlled, the outflow is determined from lookup tables and when certain levels are reached the outflow is either increased or decreased. This corresponds to the physical operations that would be made by the system operators.

Operating experience and detailed field measurements have shown that it takes a little time before the release of water from an upstream dam is sensed by the water level recorders at the downstream dam. These times are known as the lag times and are applied in the model. The only significant lag time is the 12 hours it takes for water discharged at Taupo to reach Ohakuri. Any variation in this lag time has little effect on the flood routing results if Taupo discharges are kept constant throughout large floods.

As the flood proceeds, each power station discharge increases up to maximum turbine discharge, thus holding the lake levels constant. When inflows exceed maximum turbine discharge, the lakes rise to maximum control level and higher.

When the lake level exceeds maximum control level, the total discharge (spill plus turbine discharge) is set by the table discharges (see Jowett, 2009b). If levels exceed design flood levels, inflows are set to match outflows (by using all discharge facilities available at the dams). In practice, this should only occur in a probable maximum flood.

Taupo Gates discharge is set at nominal median release.

The flood routing model requires a similar set of inputs at each dam. These are:

1. Initial starting discharge and level (the median historical level was used)
2. Discharge rules (table discharges and rules when outside of table)
3. Lake area
4. Lag time to downstream dam
5. Tributary inflows

Numerical values for all the required parameters are given in Jowett (2009b).

6.2.4 MIKE11-NAM (Joynes, 2009)

MIKE11-NAM is a hydrological and hydraulic model that has been set-up and used to calculate the water levels and flows in the Waikato River downstream of Karapiro Dam (**Figure 11**). It includes the flood runoff from the Waipa River. MIKE11-NAM has been used extensively by Environment Waikato in the past 15 years for many projects. It includes all major structures, canals, tributaries, storage areas of the Lower Waikato Waipa Control Scheme (LWWCS). In the present programme, the model was used to assess how the modelled changes in Karapiro Dam discharges, evaluated by the WaikatoFlood model, translate into flood levels throughout the Lower Waikato Waipa Control Scheme. Joynes (2009) provides details of the calibration of the model.

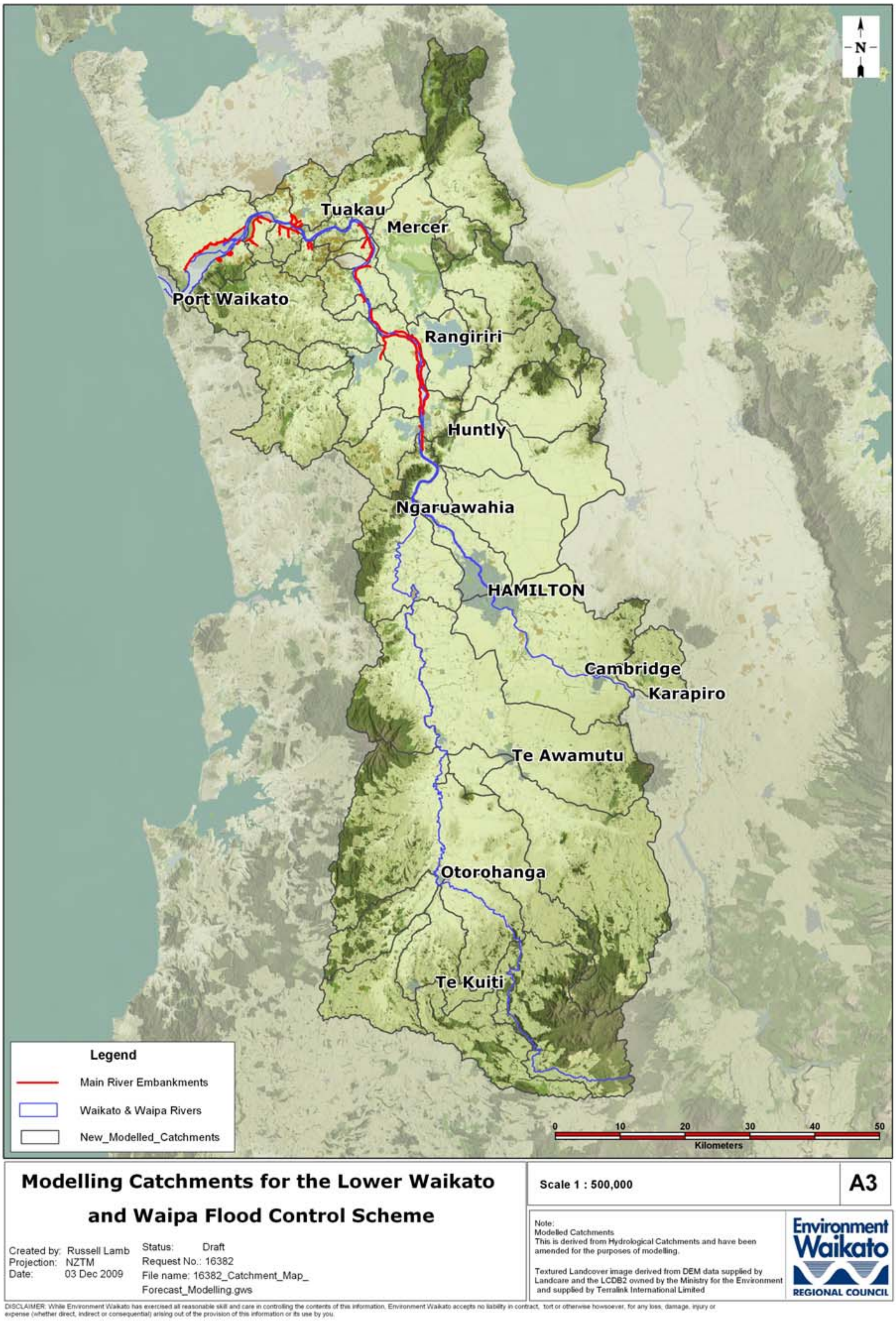


Figure 11: Location of the Lower Waikato flooding simulations.

The stopbanks on the Lower Waikato and Waipa Control Scheme provide flood protection to assets adjacent both to the Waikato River, and some of its tributaries (to aid clarity the protection works on tributaries are not shown in **Figure 11**). The design floods of the stopbanks vary within the LWWCS; some parts of the scheme protect against 5-year floods, while others are designed for as much as 100-year floods.

6.3 Comparison of TopNet and HEC-HMS

The TopNet and HEC-HMS models use broadly similar computational and hydrological concepts, including hourly timesteps, the sub-division of large catchments into smaller sub-basins with distinct attributes, the modelling of canopy interception, infiltration, sub-surface runoff, and channel flow. They also share common data requirements.

Their differences lie largely in the detail with which they represent both the hydrological processes and the spatial landscape data. TopNet is more physically based and resolves the landscape in much finer detail. TopNet resolves 483 sub-basins in contrast to HEC-HMS's 14. This translates into parametric differences, whereby parameters assigned to TopNet sub-basins are more representative of actual spatial variability. To compensate, HEC-HMS's final model parameters are more closely informed by calibration than are TopNet's. In the context of this study, these differences serve a valuable purpose. They allow robust conclusions to be drawn, as independent as possible from uncertainties in hydrological knowledge.

7 Model Calibration and Validation

Before the models can be used in a predictive capacity they must first be tailored to the specific study region. This includes:

- Representing the prevailing hydrology (e.g., runoff generation processes);
- Representing the landscape characteristics (e.g., soil types);
- Calibration; and
- Evaluation of the resulting model.

How the models represent the prevailing hydrology and landscape characteristics is described above. The present section considers how model calibration and evaluation was carried out to determine whether both models give realistic simulation results for the study area.

Model calibration is an iterative trial-and-error process of manipulating model parameters within plausible ranges, either automatically or manually, until the simulation resembles observational flow records, subject to pre-determined performance criteria. Calibration is used to compensate for models' inabilities to fully represent reality, be they in terms of the embodied hydrology or the detailed description of the landscape.

A calibrated model's predictions must be considered in the light of the observations used for the calibration, which are inevitably limited in both duration and spatial extent. In the present study, seven gauged sub-catchments were selected as the focus of both models' calibration (**Table 6**). None of these locations represent either complete forest or pasture. So while calibrations can be performed to reproduce flows corresponding to different storm magnitudes, they cannot be performed to reproduce flows from distinctly different land use types. These limitations mean that both models will be making predictions outside the range of conditions for which they were calibrated.

Table 6: Gauged catchments used in the model calibration procedure.

Site ID	River	Site	Comment
1043419	Pokaiwhenua	Puketurua	Five largest gauged catchments with a variety of hydrological responses
1043428	Tahunaatara	Ohakuri Rd	
43472	Waiotapu	Reporoa	
43435	Waipapa	Ngaroma Rd	
1043427	Mangakino	Dillon Rd	
1443462	Mangahanene	SH1	Only gauged catchment in the hydrologically responsive northern extent of the study area
2043497	Orakonui	Ngatamariki	Only gauged catchment displaying the extremely subdued hydrology typical of the southern area

The performance criteria, applied to the seven sub-catchments list above, were as follows:

- ***Hydrograph comparison*** – Simulated and observed hydrographs for key flood events (July 1998 and February/March 2004) were compared visually; and
- ***3-day flow annual maxima*** – Distribution graphs of three-day flow volume annual maxima for observed and simulated flow.

The performance criteria for defining an adequate calibration were as follows:

- Within the 90% confidence band on the observed GEV distribution for annual 3-day flow maxima; and
- Within 20% of flow volume for 3-day moving mean flow for the discharge at Karapiro minus the Taupo discharge (i.e. flow generated within the Upper Waikato catchments) during the July 1998 flood;
- Representative match to hydrographs.

Calibration of HEC-HMS used a sequential process where relatively homogeneous catchments were used to estimate a set of parameter values for particular combinations of geological, soil and vegetation attributes. These sets of parameter values were then assigned to other sub-catchments with similar attributes. Referring to the hydrological processes in Figure 10, the main parameters were the soil infiltration capacity and the storages, recession coefficients and percolation rates for GW1 and GW2.

The calibration approach used by Woods et al (2009) limited the ability of TopNet to meet the performance criteria defined above. The intent of these self-imposed limitations was to maintain a strong correspondence between mapped catchment characteristics (soils, land cover, etc), and to reduce the need for parameter estimation. The objectives used to calibrate TopNet were, primarily, similarity in the 3-day total runoff difference between Taupo outflow and Karapiro, and secondarily the performance of the model at reproducing flows in the Pokaiwhenua sub-catchment at Puketerua. On the one hand, it is the catchment as a whole that is of greatest importance, and on the other the Pokaiwhenua sub-catchment is subject to the most substantial land cover change. An implication of this focus is that there may be significant discrepancies at the smaller scales or in sub-catchments other than Pokaiwhenua.

Parameters used to calibrate TopNet were the saturated hydraulic conductivity of the soil, soil depth, and the factor that controls the baseflow and spatial extent of saturation during rainfall. These are functionally equivalent to the parameters used to calibrate HEC-HMS. TopNet calibration was performed manually at the sub-catchment scale, rather than sub-basin scale, and employed expert hydrologically based assessment in the interest of preserving hydrological realism and fidelity to measured environmental characteristics.

7.1 TopNet: Calibration and Validation

The typical performance of the model on tributary flood flow volumes can be assessed by analysing the annual series of largest 3-day flood volumes from each year. In **Figure 12** and **Figure 13** the bar chart allows an assessment of whether observed tributary flood volumes in individual years are well-matched by the model, and the flood frequency distribution plot allows an assessment of whether the observed distribution of flood magnitudes is well-matched by the model. The figures show the best and worst model performances from the five catchments with long flow records. The results in the bar chart for Mangakino at Dillon Road (**Figure 14**) indicate good performance after 1971. The early overestimates are caused by inadequate temperature data leading to underestimates of evaporation, and thus excessive modelled runoff. In contrast, the model estimates for Waiotapu at Reporoa are consistently higher than the observed floods.

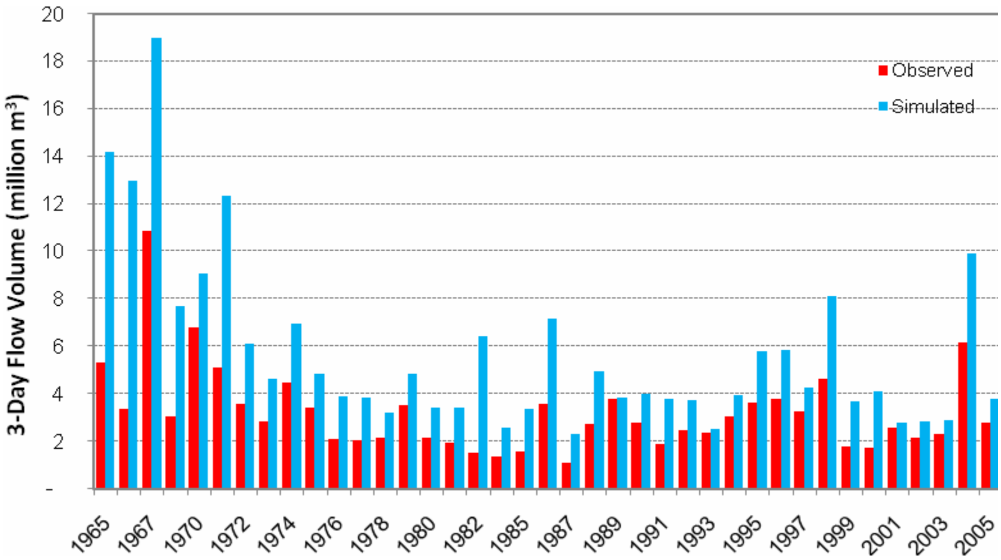


Figure 12: Observed and simulated 3-day flow volume annual maxima for Waiotapu at Reporoa calibration.

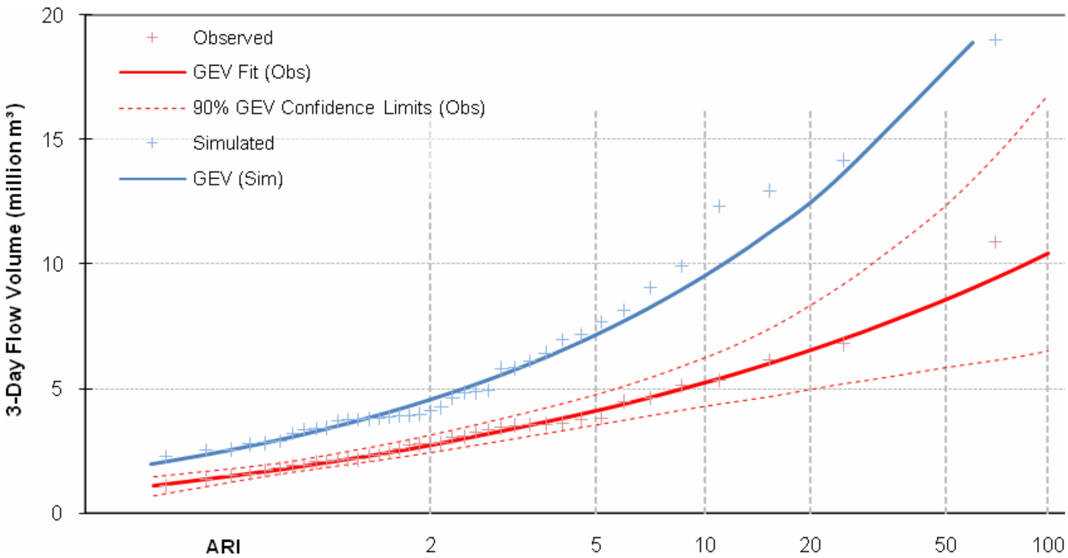


Figure 13: Distribution of observed and simulated 3-day flow volume annual maxima for Waiotapu at Reporoa calibration (using Gringorton plotting positions).

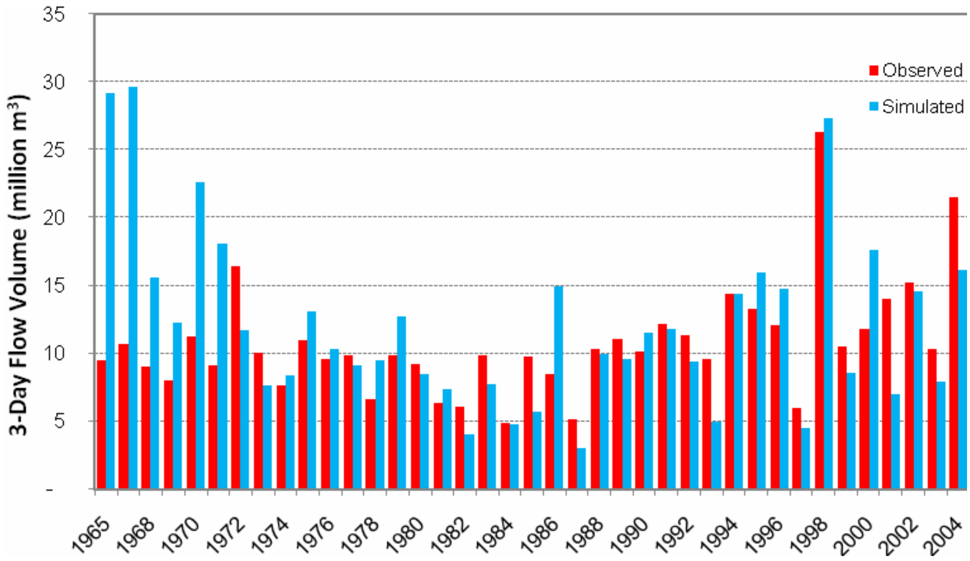


Figure 14: Observed and simulated 3-day flow volume annual maxima for Mangakino at Dillon Road calibration.

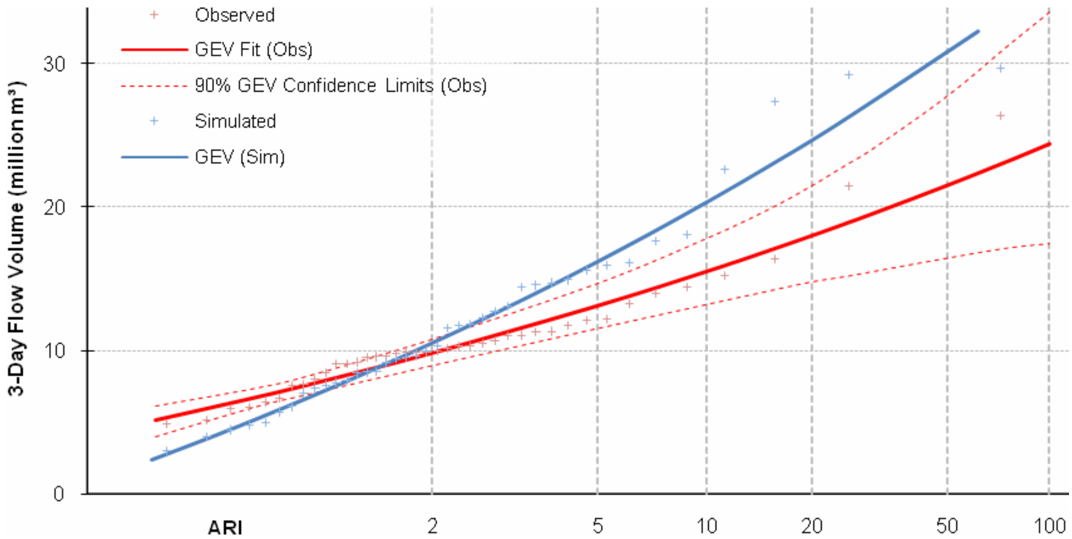


Figure 15: Distribution of observed and simulated 3-day flow volume annual maxima for Mangakino at Dillon Road calibration (using Gringorton plotting positions).

The following figures show the model calibration hydrographs for the July 1998 flood. **Figure 16** illustrates the model calibration at the whole catchment scale with an emphasis on event volume, by comparing time series of 72-hour moving means of Karapiro minus Taupo outflows.

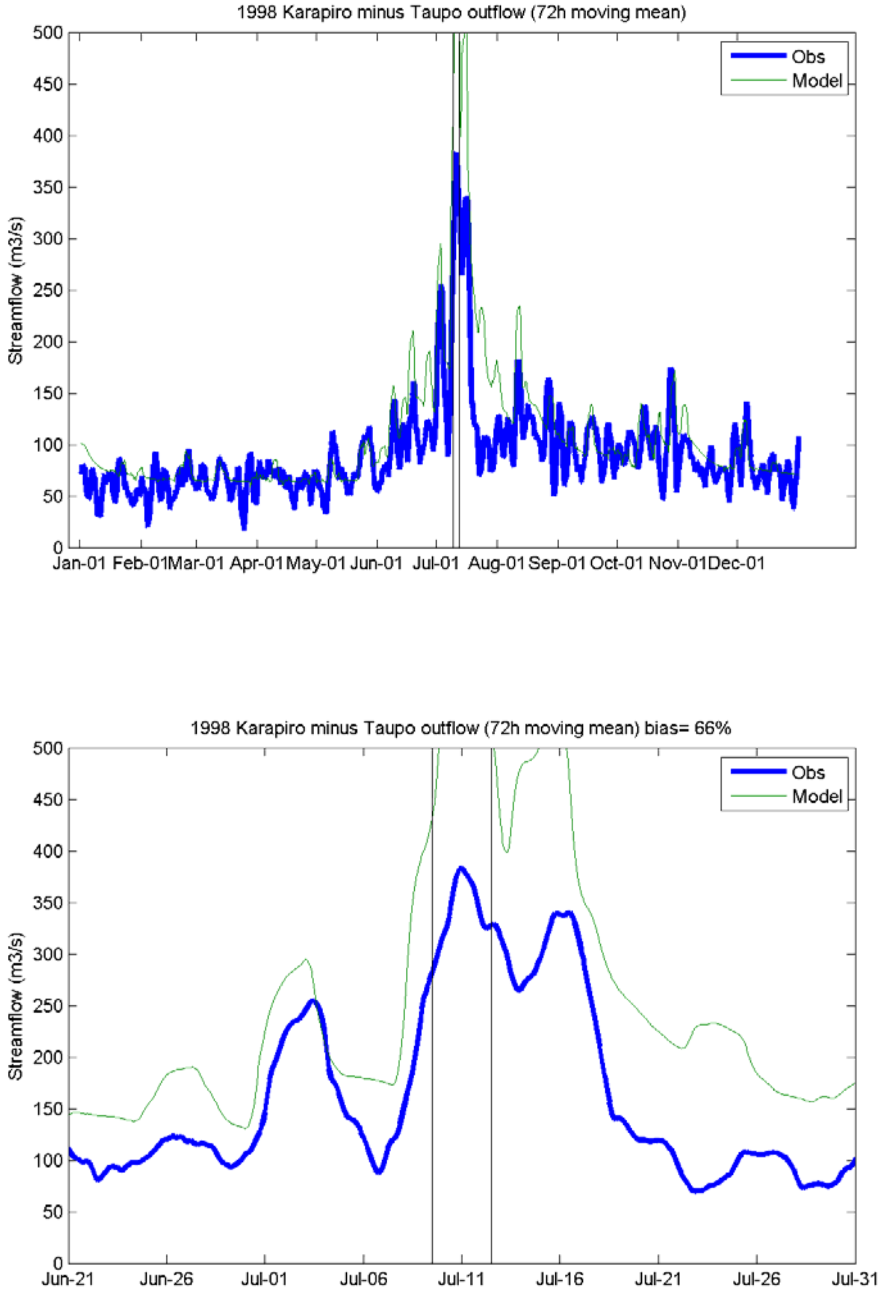


Figure 16: TopNet validation plot for 1998 flood, for the difference between Karapiro and Taupo outflows. Top panel shows observed and modelled 72-h moving mean flows for entire year; Bottom panel shows detail at time of flood.

The following figures (**Figure 17** to **Figure 21**) show additional model calibration hydrographs for the July 1998 flood. There is one page per flow recorder. Each flood is shown twice on the same page: once showing a 1-year simulation window using 72-hour moving mean flows, and once showing a close-up of the 3-day flood event using the hourly data. The sites are arranged from slowly responding to more rapidly responding.

In each plot, the upper panel shows streamflow (observed and modelled), with a bias statistic reported at the top (computed over the entire period shown), and an event runoff (observed and modelled), computed over the storm period (indicated by vertical dashed lines).

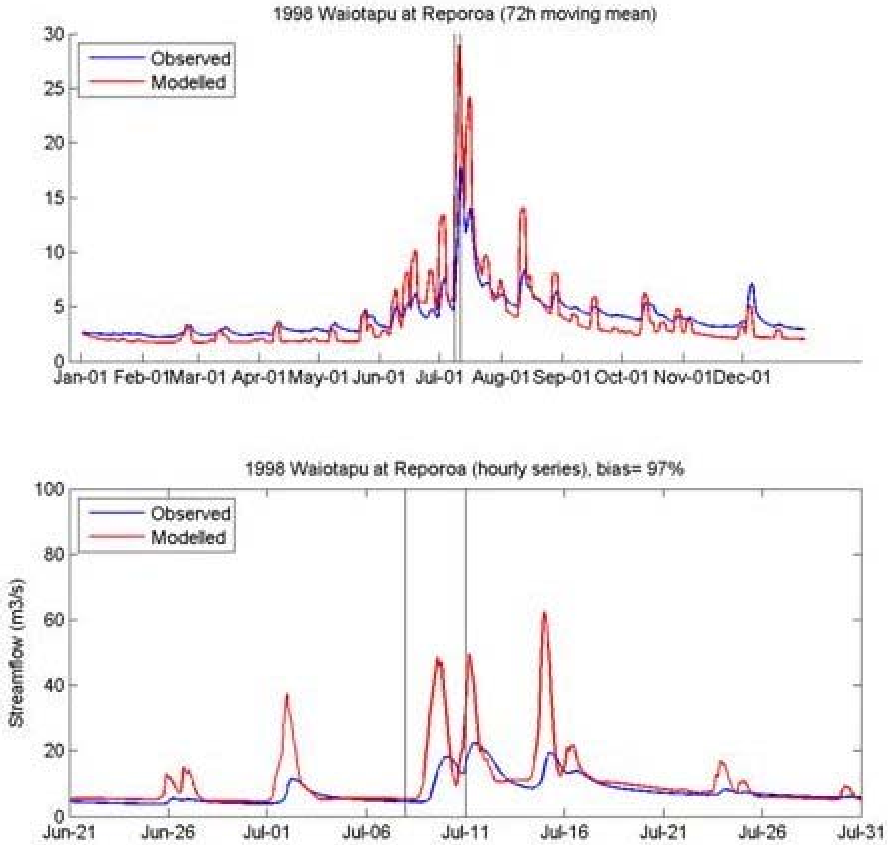


Figure 17: TopNet validation plot for 1998 flood, Waiotapu at Reporoa. Top panel shows observed and modelled 72-h moving mean flows in m^3s^{-1}; Bottom panel shows observed and modelled hourly flows in m^3s^{-1}.

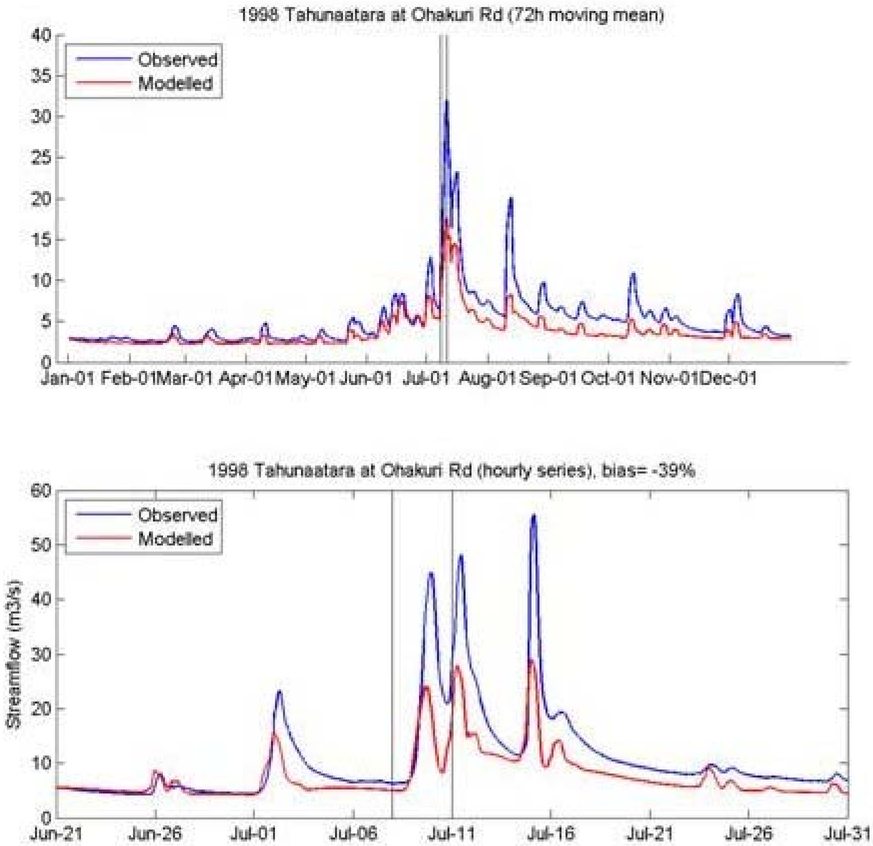


Figure 18: TopNet validation plot for 1998 flood, Tahunaatara at Ohakuri Road. Top panel shows observed and modelled 72-h moving mean flows in m^3s^{-1}; Bottom panel shows observed and modelled hourly flows in m^3s^{-1}.

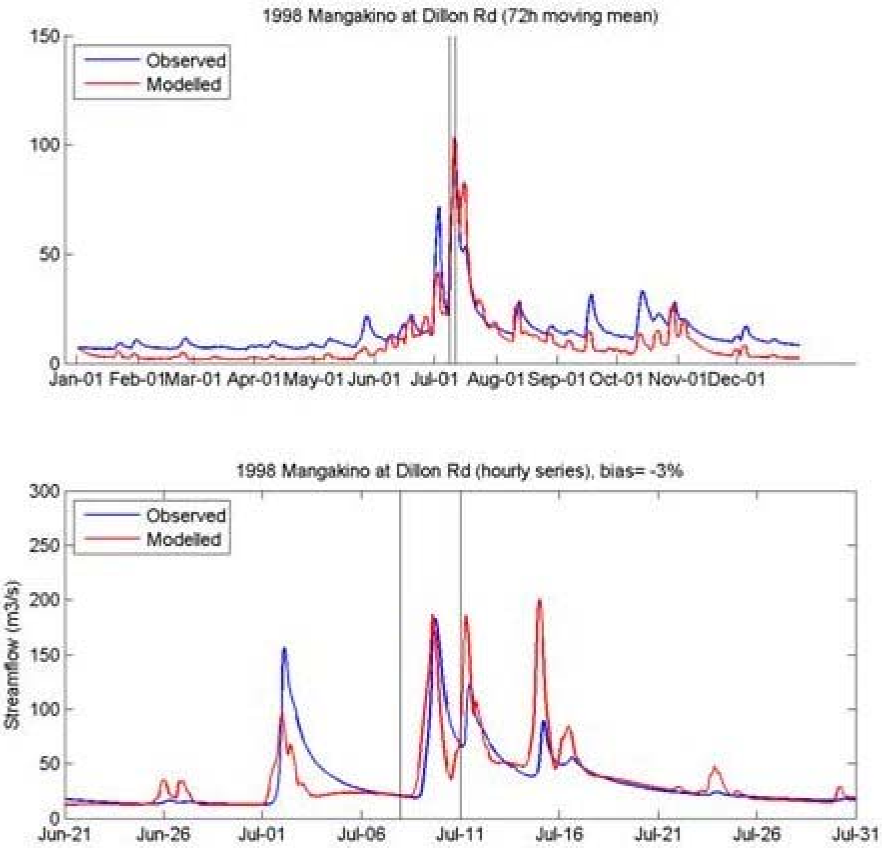


Figure 19: TopNet validation plot for 1998 flood, Mangakino at Dillon Road. Top panel shows observed and modelled 72-h moving mean flows in m^3s^{-1}; Bottom panel shows observed and modelled hourly flows in m^3s^{-1}.

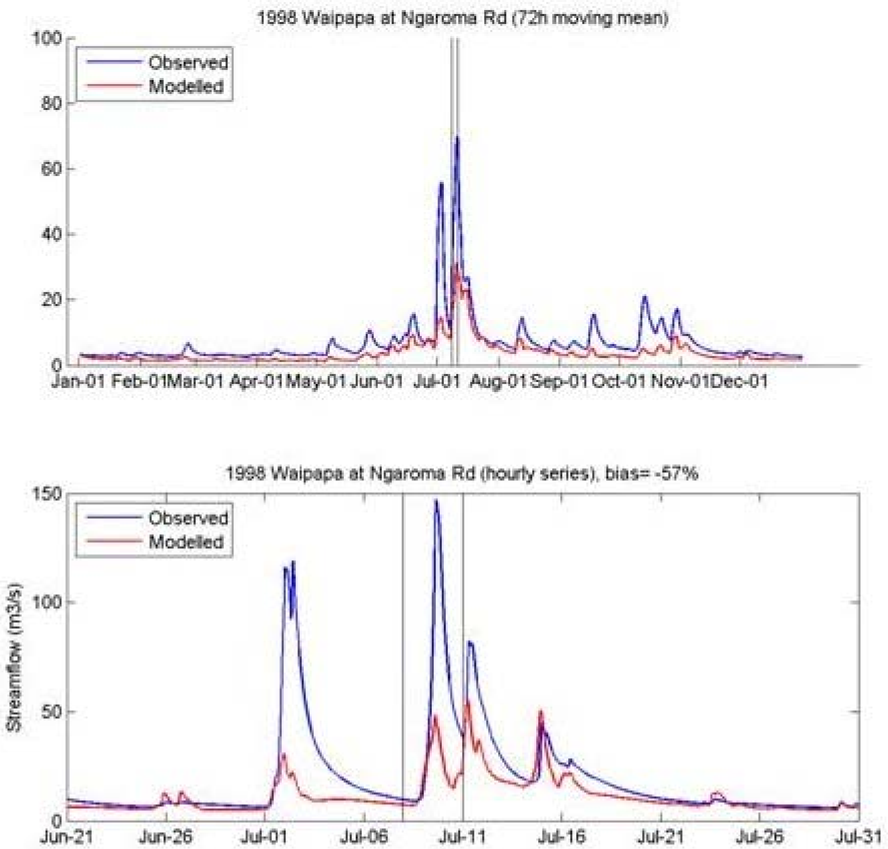


Figure 20: TopNet validation plot for 1998 flood, Waipapa at Ngaroma Road. Top panel shows observed and modelled 72-h moving mean flows in m^3s^{-1}; Bottom panel shows observed and modelled hourly flows in m^3s^{-1}.

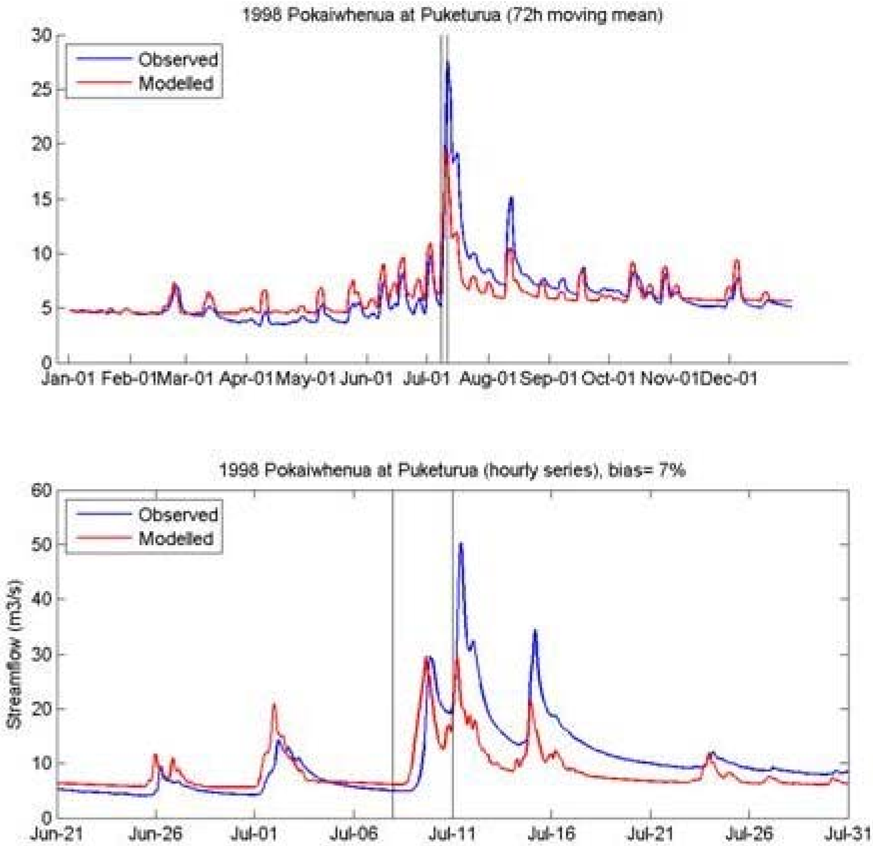


Figure 21: TopNet validation plot for 1998 flood, Pokaiwhenua at Puketurua. Top panel shows observed and modelled 72-h moving mean flows in m^3s^{-1}; Bottom panel shows observed and modelled hourly flows in m^3s^{-1}.

7.2 HEC-HMS: Calibration

The following figures in this section show the HEC-HMS calibrations. For comparison to total catchment flows, the difference in observed flow between the outlets of lakes Taupo and Karapiro were used as a calibration target.

The 1998 flood event was chosen as the primary focus for the validation exercise due to its significance as a large flood that affected the lower Waikato. Both observed and simulated records were smoothed (using a 72-hour moving mean) to remove noise.

No correction has been made to these data for storage fluctuations within the hydro lakes. It is expected that the observed difference between Taupo and Karapiro inflows under-reports peak catchment inflow due to the effect of storage fluctuations.

The comparison of simulated and observed total catchment flow is shown in **Figure 22**.

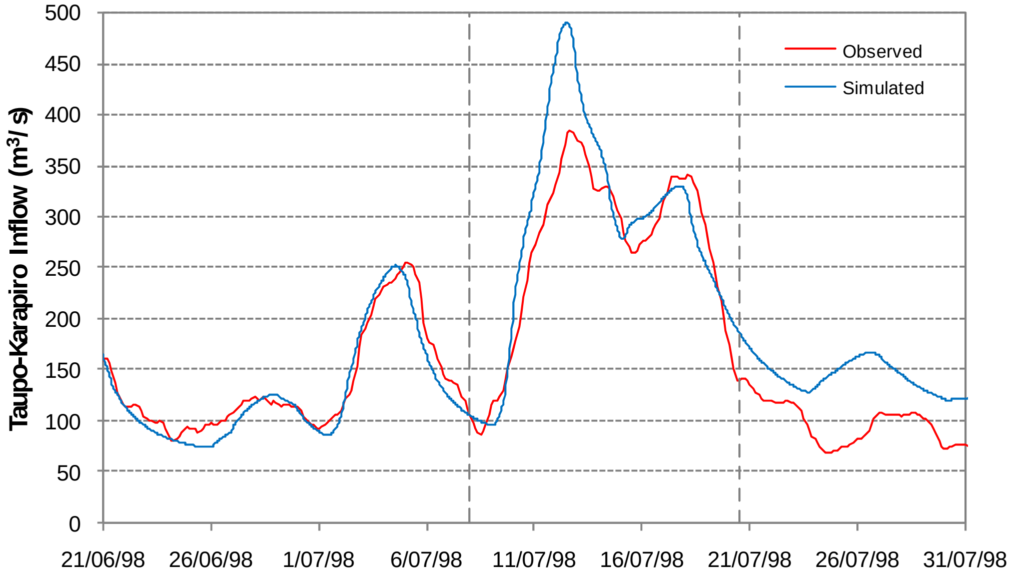


Figure 22: Observed difference between Taupo and Karapiro outflows and simulated catchment flow for the 1998 flood event (72-hour moving means).

Calibration graphs at each of the five selected gauged catchments are shown below. The first graph for each gauged catchment shows the distributions of simulated and observed 3-day flow volume annual maxima. The second shows the data as an annual time-series. The third and fourth graphs for each site show the 1998 and 2004 simulated and observed hydrographs.

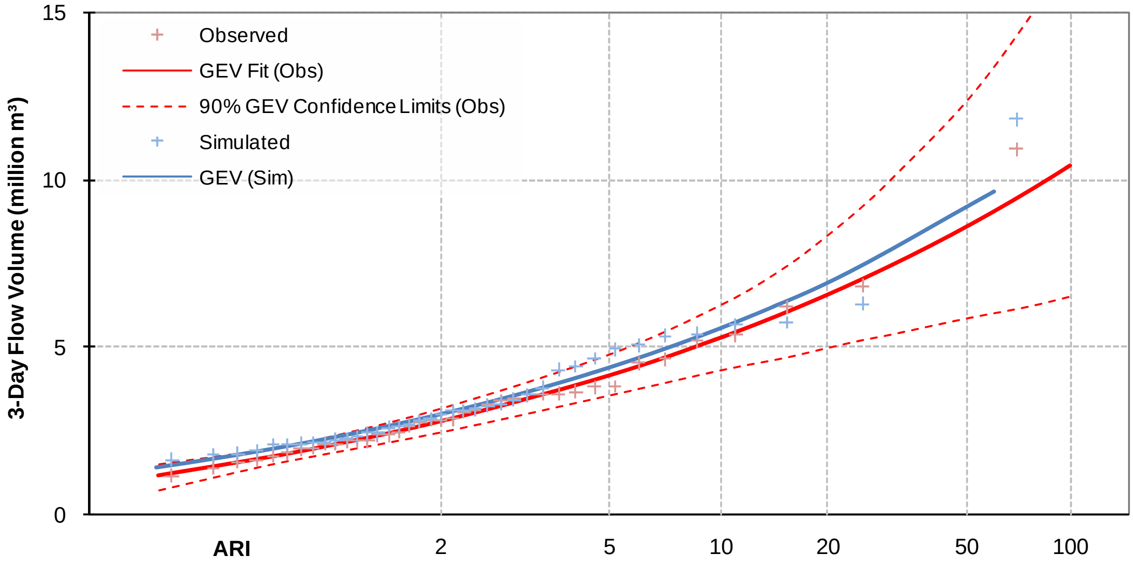


Figure 23: Distribution of observed and simulated 3-day flow volume annual maxima for Waiotapu at Reporoa calibration (using Gringorton plotting positions).

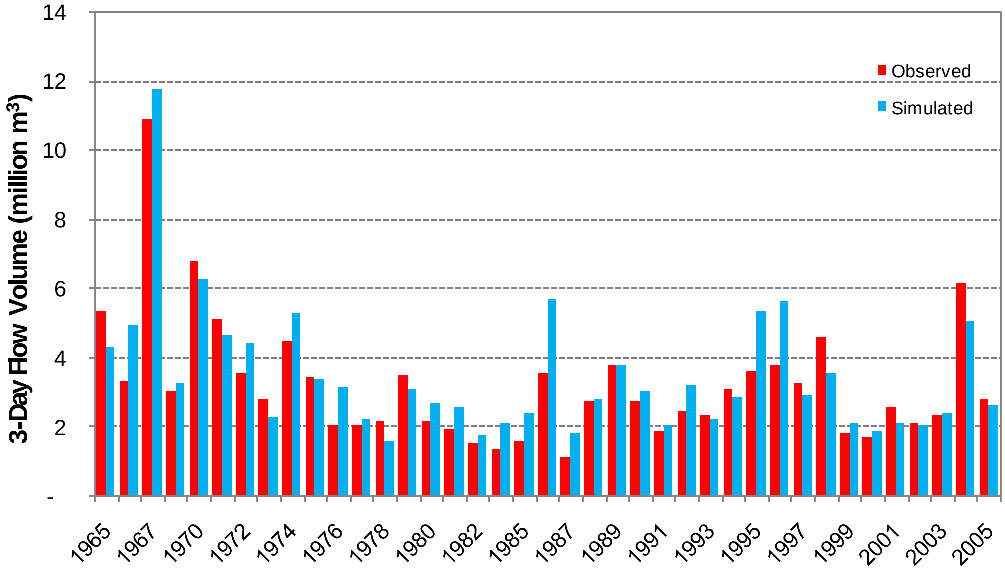


Figure 24: Observed and simulated 3-day flow volume annual maxima for Waiotapu at Reporoa calibration.

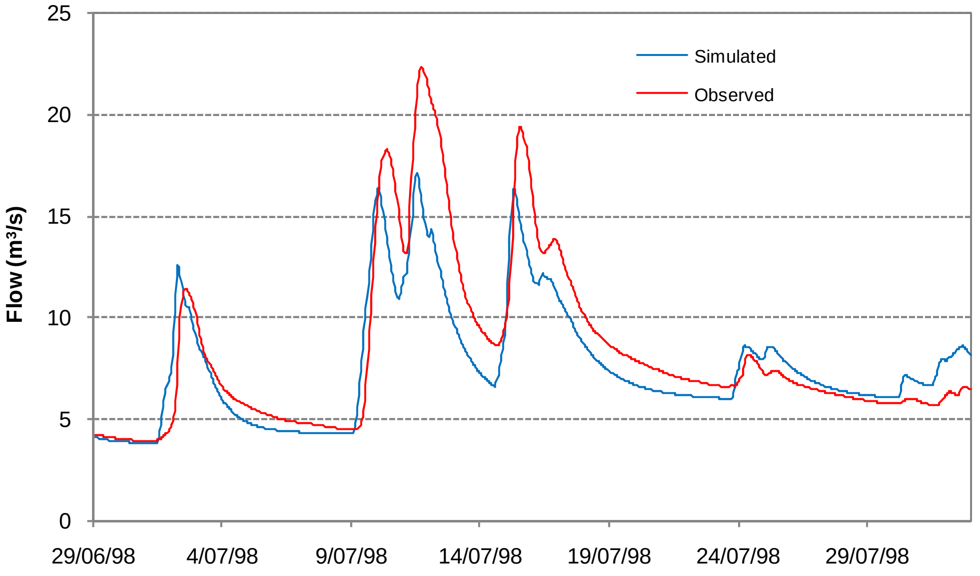


Figure 25: Observed and simulated flows for Waiotapu at Reporoa calibration (July 1998 flood).

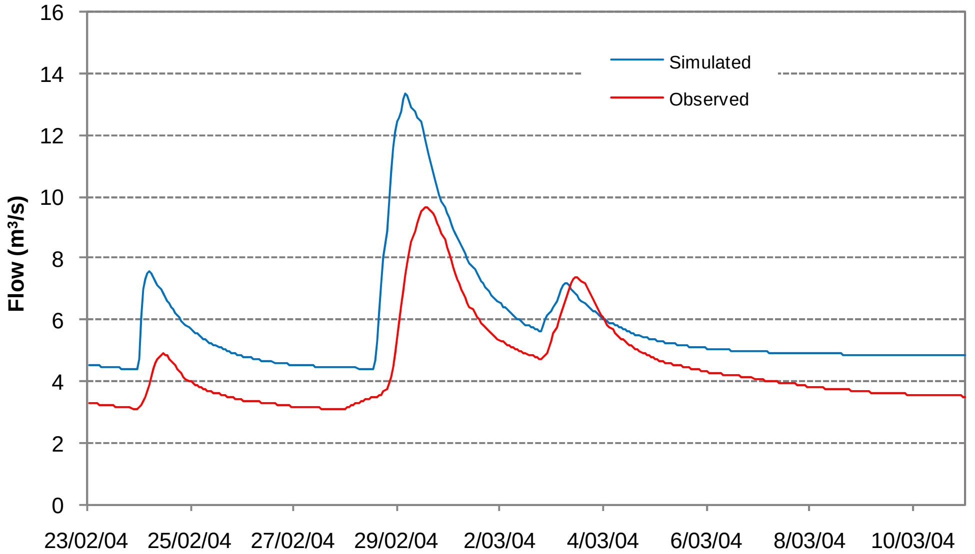


Figure 26: Observed and simulated flows for Waiotapu at Reporoa calibration (February 2004 flood).

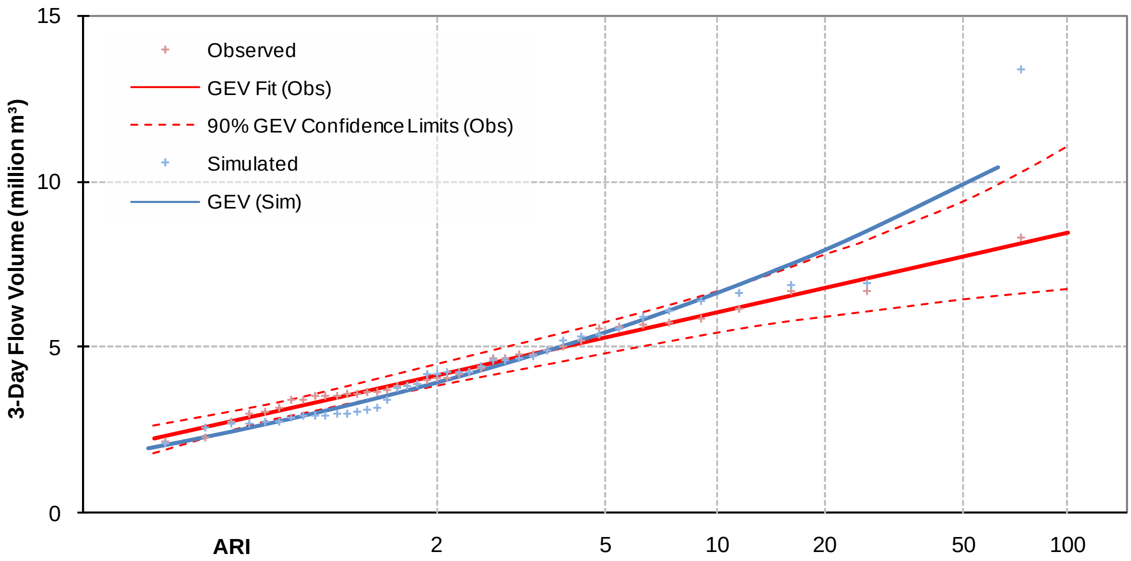


Figure 27: Distribution of observed and simulated 3-day flow volume annual maxima for Tahunaatara at Ohakuri calibration (using Gringorton plotting positions).

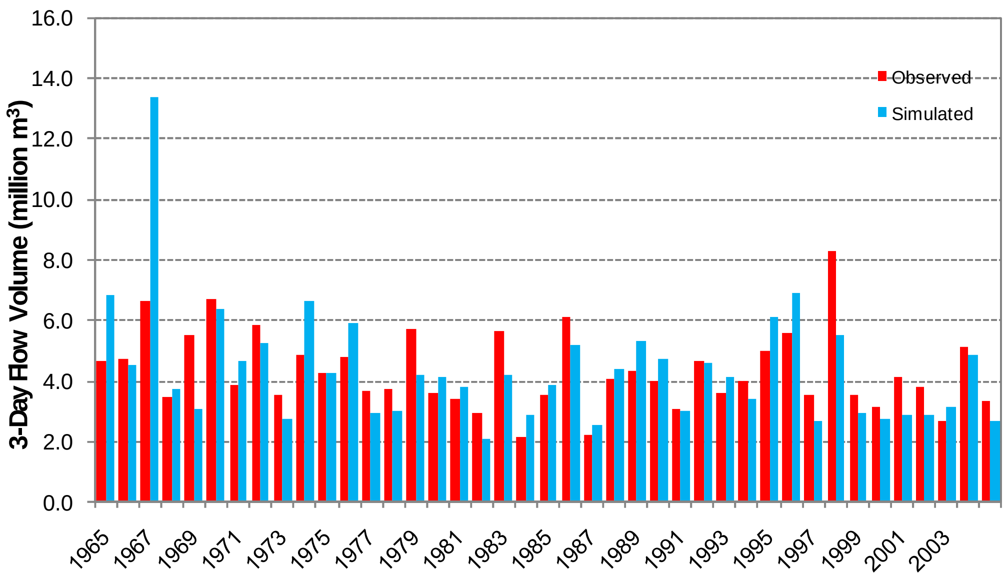


Figure 28: Observed and simulated 3-day flow volume annual maxima for Tahunaatara at Ohakuri calibration.

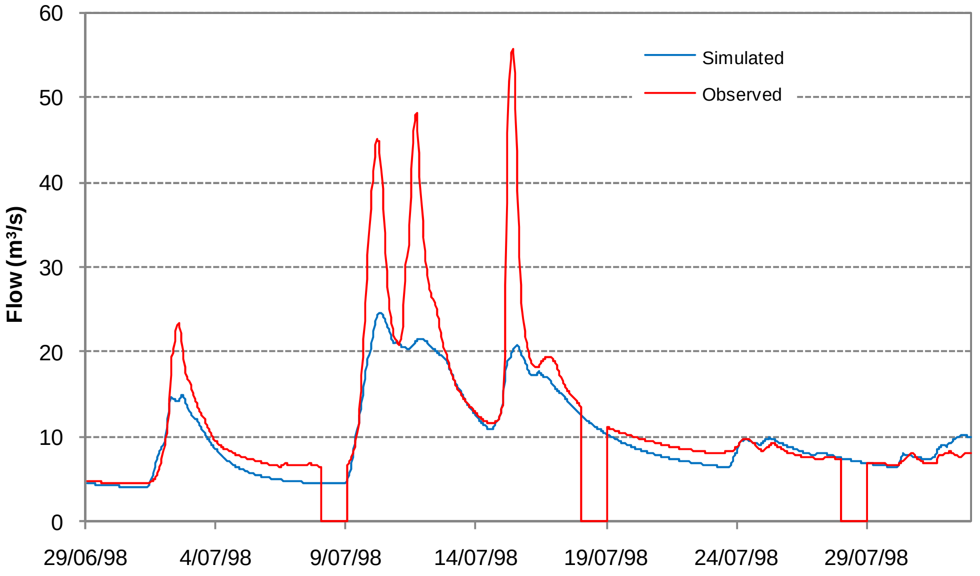


Figure 29: Observed and simulated flow at Tahunaatara at Ohakuri calibration for the July 1998 flood.

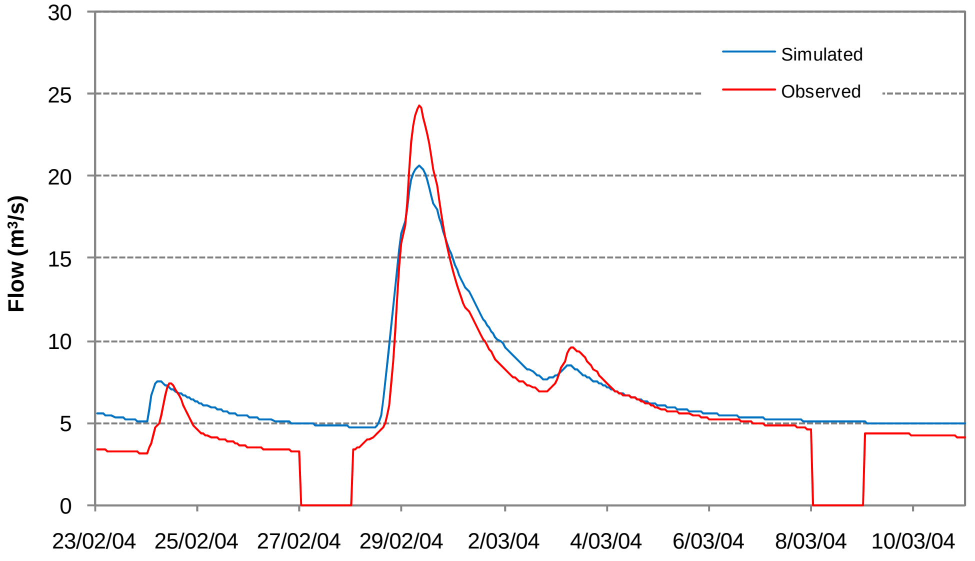


Figure 30: Observed and simulated flow at Tahunaatara at Ohakuri calibration for the February 2004 flood.

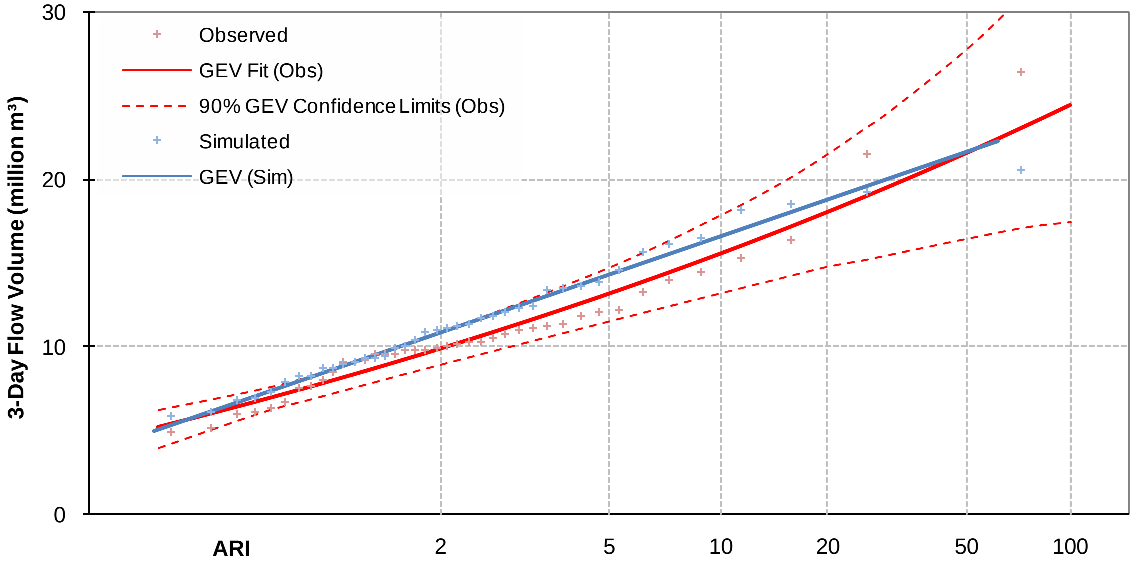


Figure 31: Distribution of observed and simulated 3-day flow volume annual maxima for Mangakino at Dillon Rd calibration (using Gringorton plotting positions).

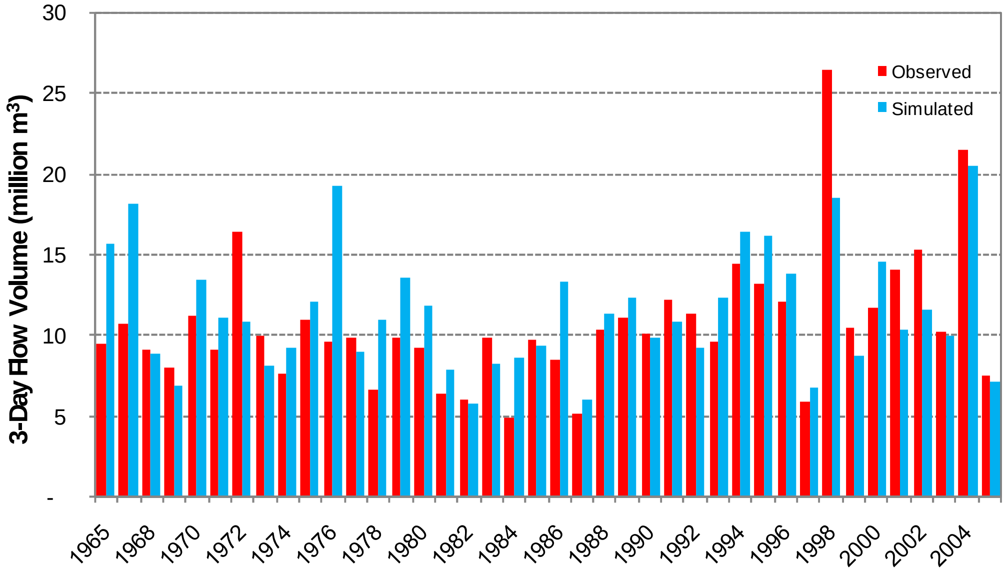


Figure 32: Observed and simulated 3-day flow volume annual maxima for Mangakino at Dillon Rd calibration.

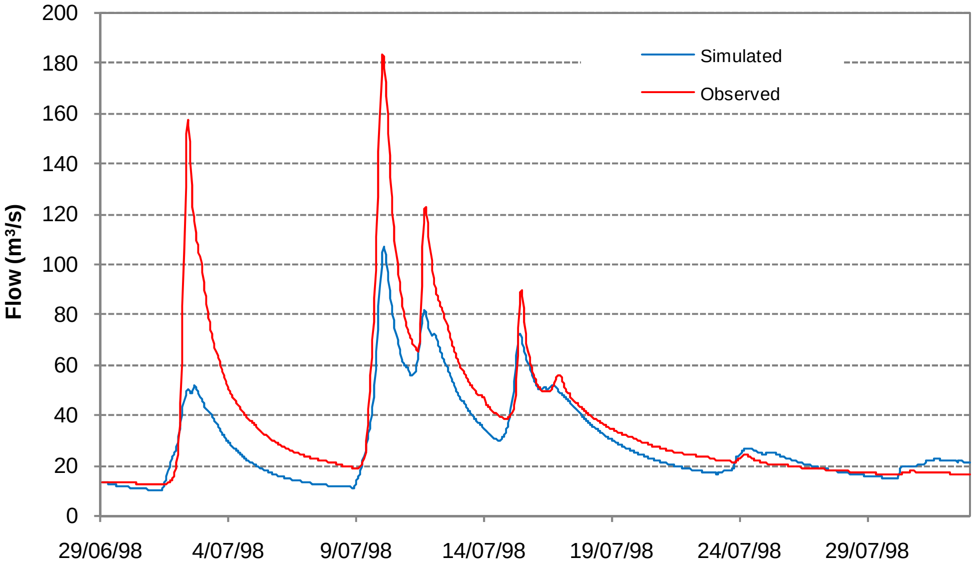


Figure 33: Simulated and observed flows for Mangakino at Dillon Rd calibration (July 1998 flood).

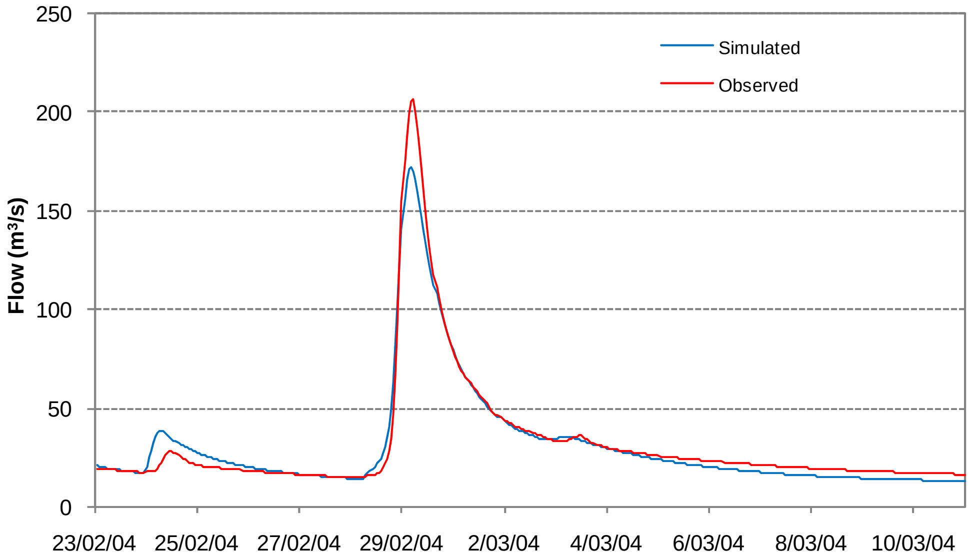


Figure 34: Simulated and observed flows for Mangakino at Dillon Rd calibration (February 2004 flood).

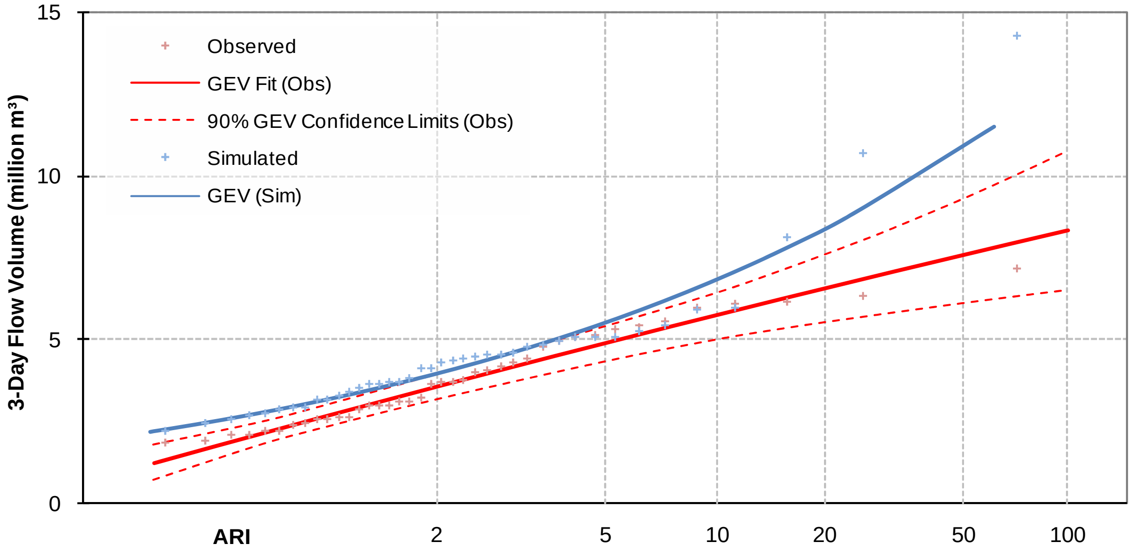


Figure 35: Distribution of observed and simulated 3-day flow volume annual maxima for Pokaiwhenua at Puketurua calibration (using Gringorton plotting positions).

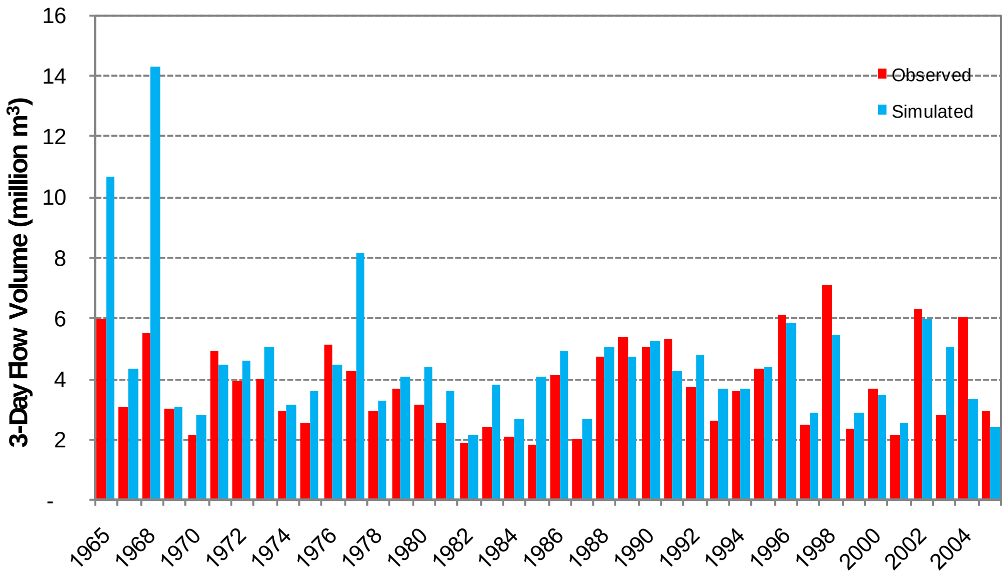


Figure 36: Observed and simulated 3-day flow volume annual maxima for Pokaiwhenua at Puketurua calibration.

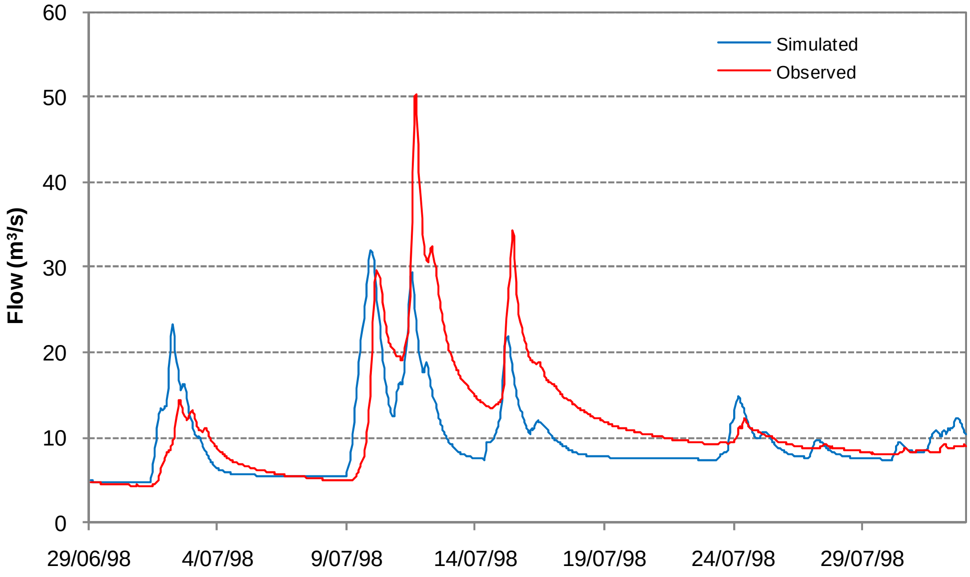


Figure 37: Observed and simulated flow at Pokaiwhenua at Puketurua calibration for the July 1998 flood.

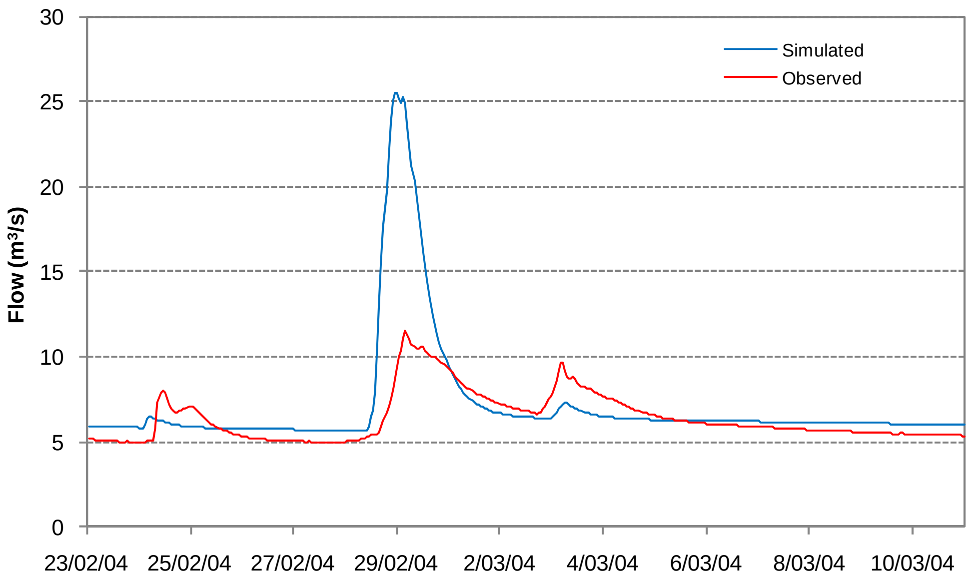


Figure 38: Observed and simulated flow at Pokaiwhenua at Puketurua calibration for the February 2004 flood.

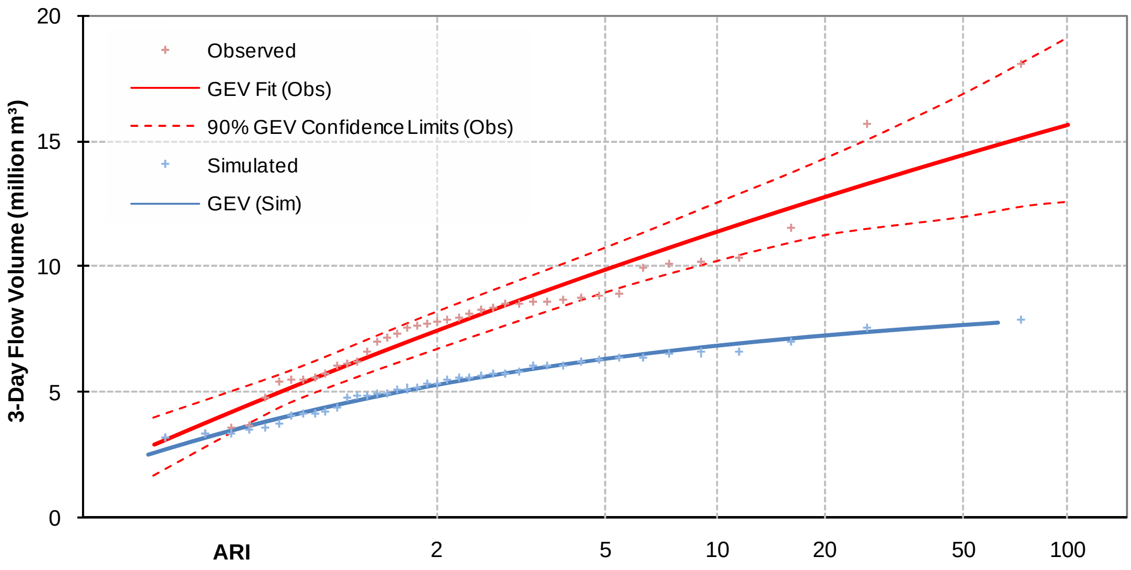


Figure 39: Distribution of observed and simulated 3-day flow volume annual maxima for Waipapa at Ngaroma Rd calibration (using Gringorton plotting positions).

Note that for this calibrated catchment depicted in **Figure 39**, a discrepancy has been identified in the gridded rainfall at this location. A water balance check showed more observed runoff than catchment rainfall meaning that at this location, the gridded rainfall is significantly underestimated. It is assumed that this discrepancy is localised and does not have a significant impact to the whole of catchment model results.

7.3 HEC-HMS: Validation

To validate the HEC-HMS results, simulations of discharge from the entire catchment were compared with observations. Data from three flow monitoring sites on the Waikato River at the outlets of lakes Taupo and Karapiro were available. The difference in flow between these sites over an extended period equates to the flow generated from the catchment simulated in this model and changes in storage within the eight hydrolakes. The 1998 flood event was chosen as the primary focus for the validation exercise due to its significance as a large flood that affected the lower Waikato. Both observed and simulated records were smoothed (using a 72-hour moving mean) to remove noise. No corrections were made for the effects of the hydrolakes. The comparison of simulated and observed total catchment flow is shown in **Figure 40**.

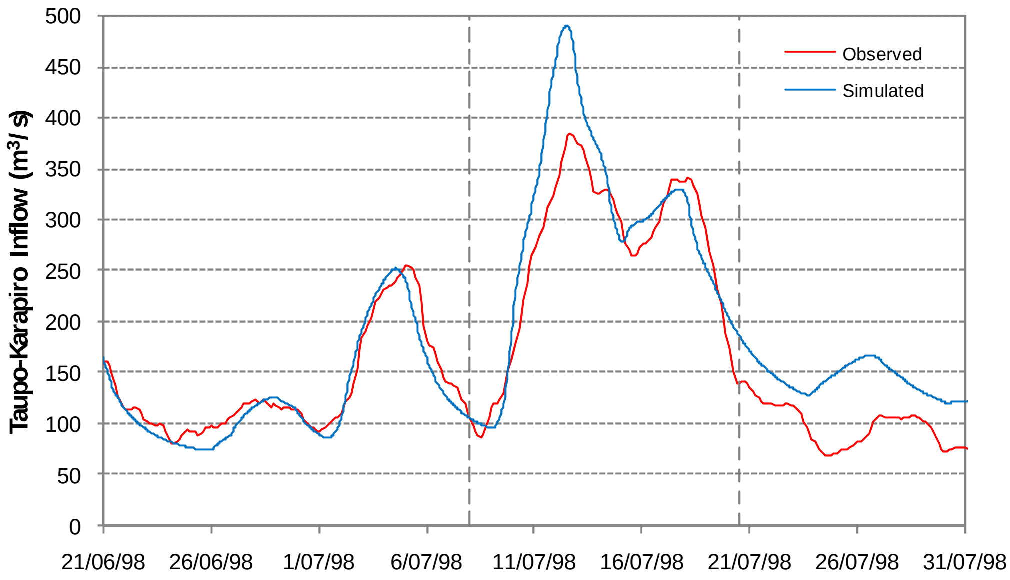


Figure 40: Observed difference between Taupo and Karapiro outflows and simulated catchment flow for the 1998 flood event (72-hour moving means).

The graph shows the following:

- The difference between simulated and observed 72-hour flood peaks is 28% over the July 1998 event;
- The simulated 72-hour peak of the event is 490 m^3/s compared to the observed 384 m^3/s; and,
- The total simulated flood volume over the event (8 to 20 July; marked by dashed vertical lines) is 314 million m^3 compared to the observed 288 million m^3 (a difference of 9%).

The same comparison was made for the February 2004 flood event. This flood occurred during summer months, meaning that the potential for the hydrolakes to buffer the peak flows is greater because the storm had a smaller flow volume and lake levels are more likely to be lower.

The comparison of simulated to uncorrected observed total catchment inflow is provided in **Figure 41**.

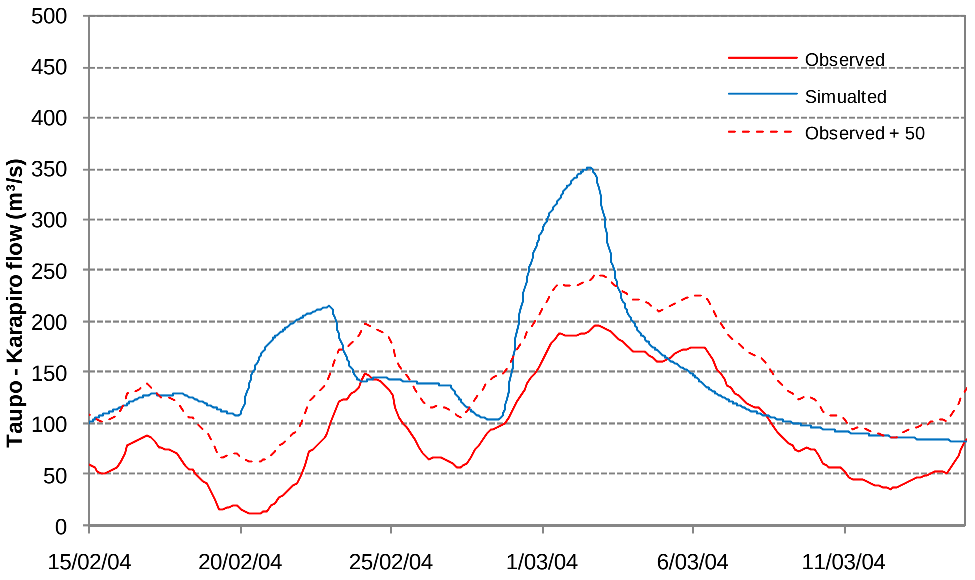


Figure 41: Observed difference between Taupo and Karapiro outflows and simulated catchment flow for the February 2004 flood event (72-hour moving means).

The difference between simulated and uncorrected observed total catchment inflows are greater for this event compared to the July 1998 event. A possible explanation for this is that more accession to lake storage occurred during the summer 2004 event. The dashed line represents the equivalent catchment inflow if a constant 50 m^3/s were being taken into storage. In this scenario, the volumes of observed and simulated catchment inflow match reasonably well.

Additional lake outflow information was sourced for Lake Whakamaru and incremental catchment inflows for Taupo – Whakamaru and Whakamaru to Karapiro were calculated. These records were processed to correct for operational storage changes within the hydrolakes (Jowett, pers. comm.).

Analysis of the difference in flows between Lakes Taupo and Whakamaru suggests a shortfall compared to gauged catchment flows at Waiotapu and Tahunaatara. There are two possible explanations for this: (1) the Taupo – Whakamaru catchment inflow data may be under-reported, and/or (2) tributary inflows are too small to be measured accurately by the Taupo-Whakamaru flow difference, on account of measurement error, river storage and time delay effects

Given the potential data quality issues discussed above, there is significant doubt relating to the calculated Taupo to Whakamaru incremental inflows. This is supported by the fact that differences between the lake outflows are on average very small, and often become negative (as shown in **Figure 42**). The reported average Taupo – Whakamaru catchment flow equates to a long term runoff coefficient of approximately 10% of rainfall. As such, the Taupo – Whakamaru incremental flow has been ignored.

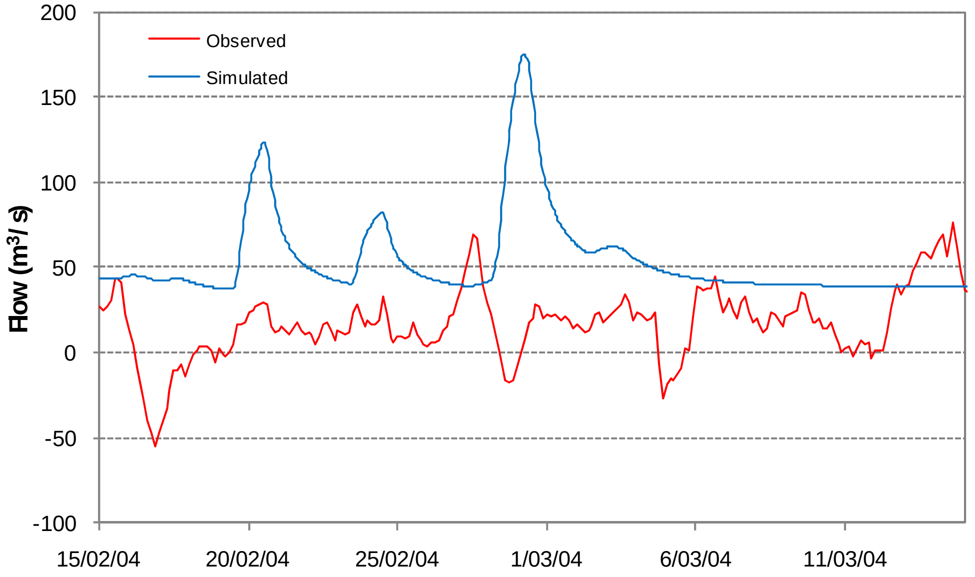


Figure 42: Simulated and "observed" inflow to the catchment between Lakes Taupo and Whakamaru for the February 2004 flood event (24-hour moving mean).

Incremental flows from the catchment between lakes Whakamaru and Karapiro are greater and travel times less, so that estimates of storage-corrected inflows are more closely defined. **Figure 43** and **Figure 44** compare the observed and simulated Whakamaru – Karapiro flow for the July 1998 and February 2004 floods, respectively. The figures show a strong match between observed and simulated for both the 1998 and 2004 events. Simulated flow volume over the peak July 1998 storm period (8 to 20 July) is 202 million m^3 compared to the observed 194 million m^3 (i.e. a difference of 4%).

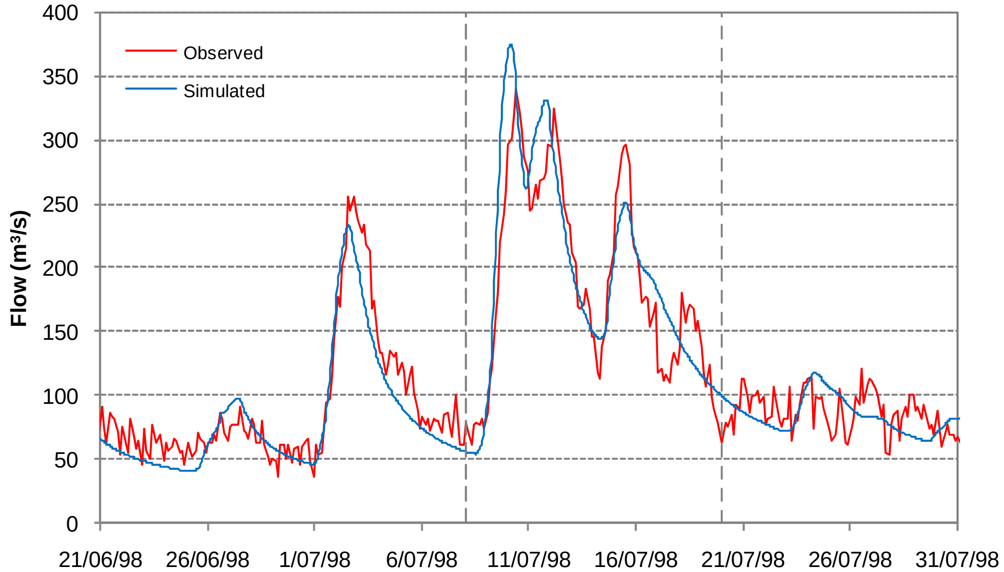


Figure 43: Simulated and observed inflow to the catchment between Lakes Whakamaru and Karapiro for the July 1998 flood event (24-hour moving mean).

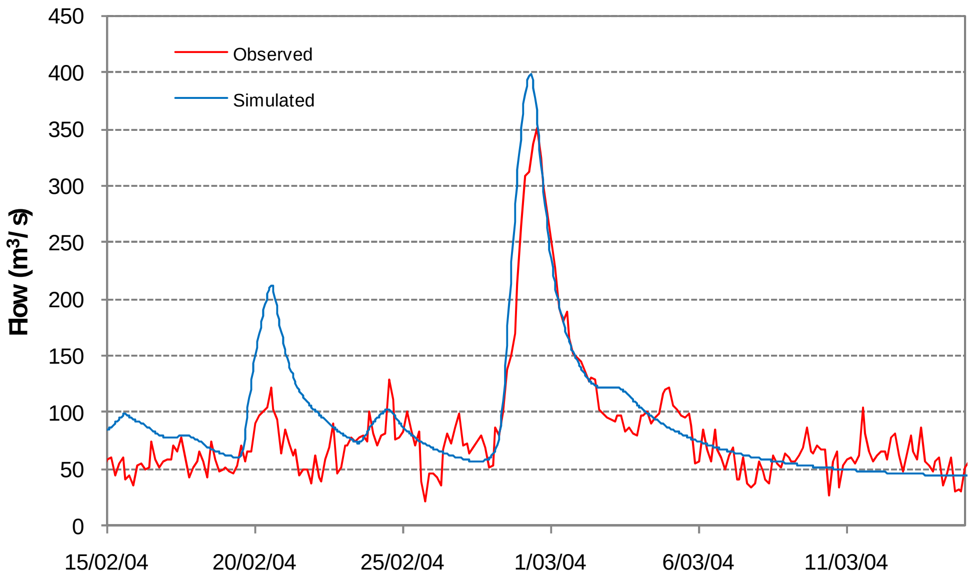


Figure 44: Simulated and observed inflow to the catchment between Lakes Whakamaru and Karapiro for the February 2004 flood event (24-hour moving mean).

7.4 Rainfall-runoff response of TopNet and HEC-HMS Models

In addition to the calibration and validation steps outlined above, sub-catchment runoff generated for the different size storms, and under existing land cover, may also be placed within a broader historical context (Jowett, 2009a).

The flows in the major tributary streams flowing into the Waikato hydro lakes have been monitored since 1964 and every major flood in these catchments up until July 2004 has been examined to determine the total storm rainfall and flood runoff. A plot of the amount of runoff produced by the storm rainfall shows the response of the catchment to rainfall. The analyses of storm rainfall and runoff are described by Jowett (1999), who derived runoff-rainfall design curves that were used to estimate the maximum amount of runoff for the probable maximum flood. These curves enveloped most of the recorded runoff/rainfall events and are shown in the graphs below.

These historical observations and design flow estimates are compared to the TopNet and HEC-HMS results is the following figures, with simulated flows corresponding to storm rainfalls of nominally 5 to 500 year ARI. It must be stressed that the rainfall-runoff design curves calculated by Jowett (1999) are empirical fits to extreme historical floods whereas the storms used in the present study are synthetic storms with a particular initial condition and particular temporal pattern of rainfall. This is important because, as will be demonstrated in subsequent sections, the distribution of rainfall within a storm plays a substantial role in the flood response, over and above the amount of rainfall. Furthermore, the models predict inflows into dam sub-catchments rather than at the flow gauging sites, but in most cases the gauged tributary streams represent a high proportion of the area draining into the hydro lakes.

Ohakuri and Waiotapu Stream

The Waiotapu is a right bank tributary that flows into Lake Ohakuri and only represents about 15% of the contributing area. The remaining area is thought to produce very little runoff (Jowett 1999). The HEC-HMS model results plot through the centre of the measured runoff/rainfall points at low rainfalls, but high rainfall model results exceed measured events (**Figure 45**). The slope of the HEC-HMS relationship is steeper than the maximum design relationship for the Waiotapu Stream. When the characteristics of the remaining catchment are considered, the HEC-HMS predicts flows towards the higher end of historical observations, and for the larger flows are higher still. The TopNet model predicts flows towards the lower end of historical observations, but will probably predict Ohakuri sub-catchment runoff well considering the low runoff characteristics of the remaining catchment.

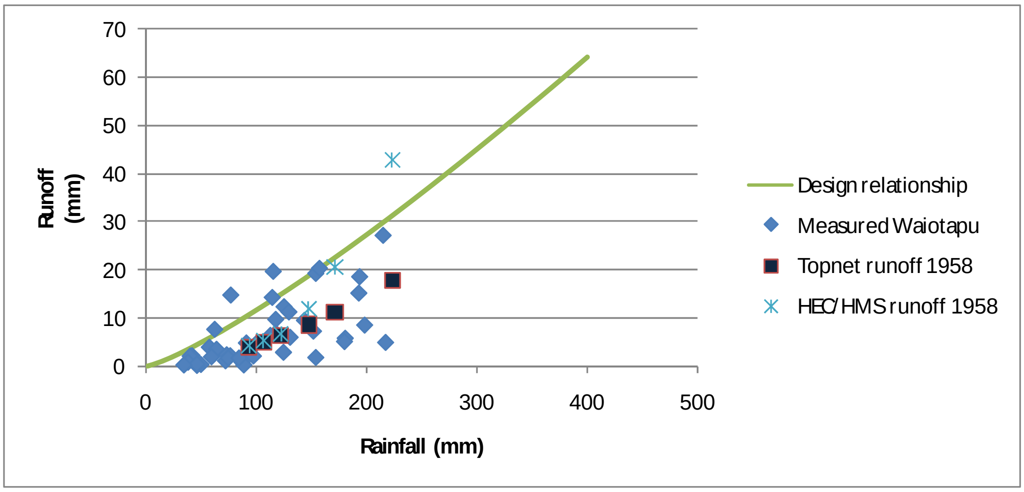


Figure 45: Measured storm runoff produced by total storm rainfalls and maximum design relationship in the Waiotapu Stream compared to storm runoff into Ohakuri reservoir predicted by HEC-HMS and TopNet models for rainfalls of 5 to 500 year ARI with 1958 temporal pattern.

Atiamuri and Tahunaatara Stream

The Tahunaatara Stream is a right bank tributary than flows into Lake Atiamiuri and forms most of the drainage of that reservoir. The HEC-HMS model results plot through the centre of the measured runoff/rainfall points at low rainfalls, but high rainfall model results exceed measured events (**Figure 46**). The slope of the HEC-HMS relationship is steeper than the maximum design relationship for the Tahunaatara Stream. The TopNet model predicts flows at the lower bound of historical observations.

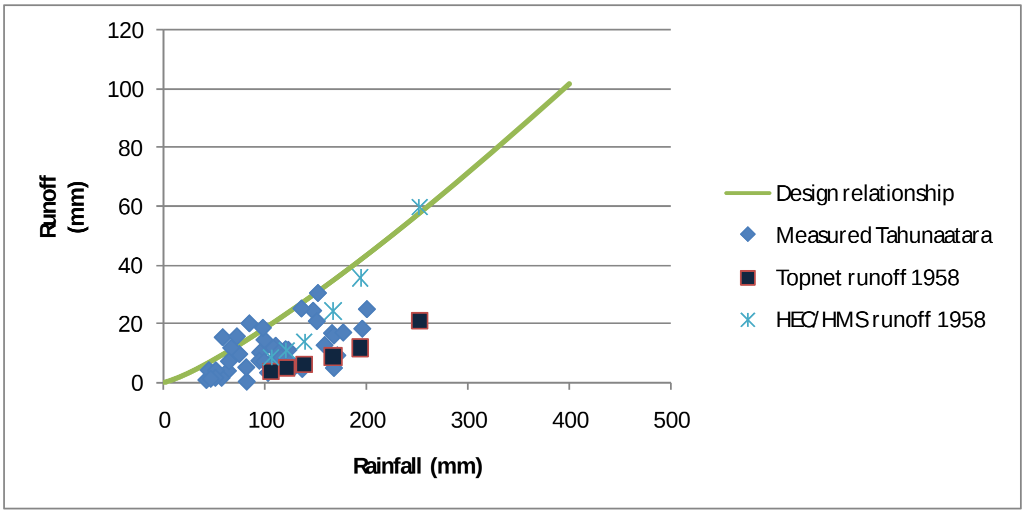


Figure 46: Measured storm runoff produced by total storm rainfalls and maximum design relationship in the Tahunaatara Stream compared to storm runoff into Atiamuri reservoir predicted by HEC-HMS and TopNet models for rainfalls of 5 to 500 year ARI with 1958 temporal pattern.

Maraetai and Mangakino Stream

The Mangakino Stream flows into Lake Maraetai from the left bank. The remaining catchment is considered to be less responsive than the Mangakino Stream (Jowett, 1999). The HEC-HMS model results plot towards the top of the measured runoff-rainfall points and the slope of the HEC-HMS relationship is similar to that for the Mangakino Stream (**Figure 47**). The TopNet model results plot towards the lower of the measured rainfall/runoff points, but may be a reasonable model of the whole Maraetai catchment.

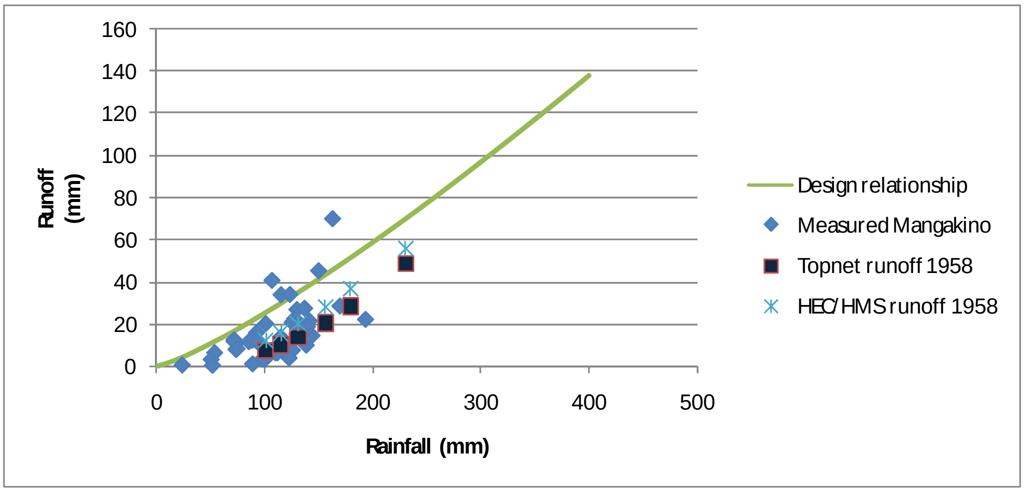


Figure 47: Measured storm runoff produced by total storm rainfalls and maximum design relationship in the Mangakino Stream compared to storm runoff into Maraetai reservoir predicted by HEC-HMS and TopNet models for rainfalls of 5 to 500 year ARI with 1958 temporal pattern.

Waipapa and Waipapa River

This Waipapa River is a left bank tributary that has a greater response to rainfall than any other upper Waikato tributary. The small area on the right bank of the Waipapa reservoir is less responsive than the

Waipapa River. The HEC-HMS model results plot through the centre of the measured runoff-rainfall points and the slope of the HEC-HMS relationship is similar to that for the Waipapa River (**Figure 48**). This probably is a good estimate of the sub-catchment response. The TopNet model predicts flows at the lower range of historical observations.

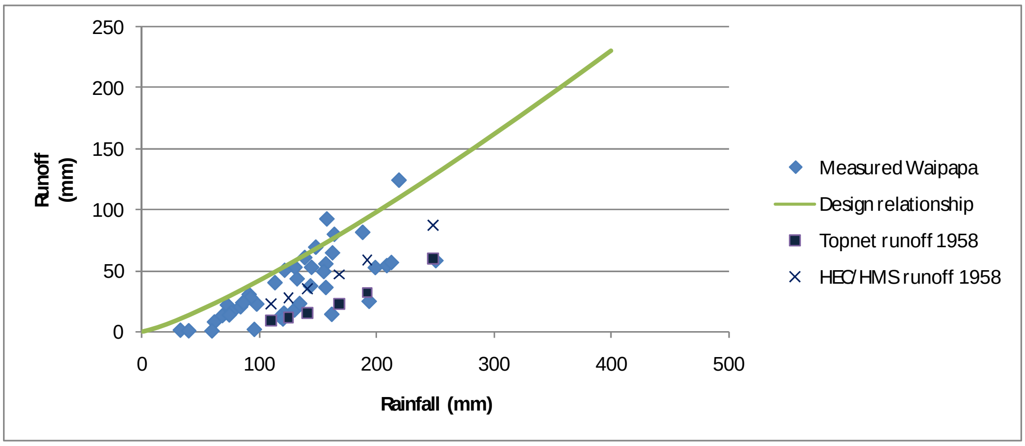


Figure 48: Measured storm runoff produced by total storm rainfalls and maximum design relationship in the Waipapa River compared to storm runoff into Waipapa reservoir predicted by HEC-HMS and TopNet models for rainfalls of 5 to 500 year ARI with 1958 temporal pattern.

Karapiro and Pokaiwhenua Stream

This catchment is one of the most difficult to model because the Pokaiwhenua Stream has a small and variable response to rainfall. For example, the largest flood in the stream occurred in June 2002 when a storm rainfall of 67 mm produced a flood peak of 121 m^3s^{-1} with 13% of the rainfall appearing as flood runoff. In contrast, a storm rainfall of 179 mm in February 1967 produced a peak discharge of 41 m^3s^{-1} with only 4% runoff. Most of the Waikato right bank (e.g., Little Waipa) has a similar response to the Pokaiwhenua, but the left bank (about 20% of the Karapiro catchment) will generate more runoff with characteristics similar to those of the Waipapa River. The runoff-rainfall predictions in the HEC-HMS and TopNet models exceed most measured Pokaiwhenua Stream events (**Figure 49**), but this may partly be the effect of the left bank tributaries that represent about 20% of the Karapiro sub-catchment. Although no rainfall events have occurred that produce the runoff amounts predicted by the models, there is a high degree of uncertainty about the response of this sub-catchment to rainfall.

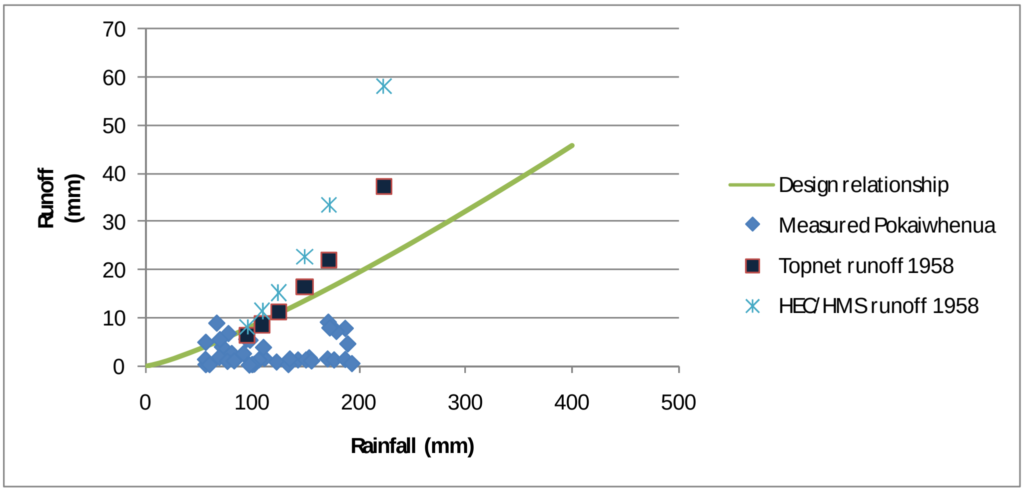


Figure 49: Measured storm runoff produced by total storm rainfalls and maximum design relationship in the Pokaiwhenua Stream compared to storm runoff into Karapiro reservoir predicted by HEC-HMS and TopNet models for rainfalls of 5 to 500 year ARI with 1958 temporal pattern.

Summary of runoff-rainfall relationships

It is expected that model results under the current land use should fall roughly within the range of scatter of measured data, assuming that the tributaries represent the catchment area contributing to dam inflows, and assuming that the initial conditions used by the flood models for these events are realistic..

In general, the HEC-HMS model predictions compare well with the measured tributary data, particularly for the Waipapa catchment. However for Ohakuri, and to a lesser extend Atiamuri, the model tends to predict flows at or above the higher range of historical data for more extreme and intense rainfalls. Overall, the response to low rainfall events seems to have been modelled very well in all catchments, but the predicted response to large and intense rainfall events is often greater than has been recorded in the tributary catchments.

The TopNet model predicts runoff in the Atiamuri and Waipapa sub-catchments towards the low side of historical observations, but predicts runoff well in the Ohakuri and Maraetai catchments. For high intense rainfalls, the TopNet model runoff predictions appear to be closer to measured events than HEC-HMS predictions. The slopes of the predicted rainfall-runoff relationships seem to be close to the maximum design relationships, though given the differences in rainfall timing during the design and simulated storms, an exact match should not be expected.

The variability of the model results should not be construed as uninformative. They provide a range of plausible impacts of future land use change, while also stressing the inherent uncertainty in any such predictions. The collective results should thus be used as a guide, rather than using any one simulation to prescribe design flood conditions.

7.5 WaikatoFlood

A level-pool routing model of the Waikato hydro dams had previously been checked against a complex hydrodynamic model of the same system, and found to produce similar results. No further calibration was undertaken during this study.

7.6 MIKE11-NAM

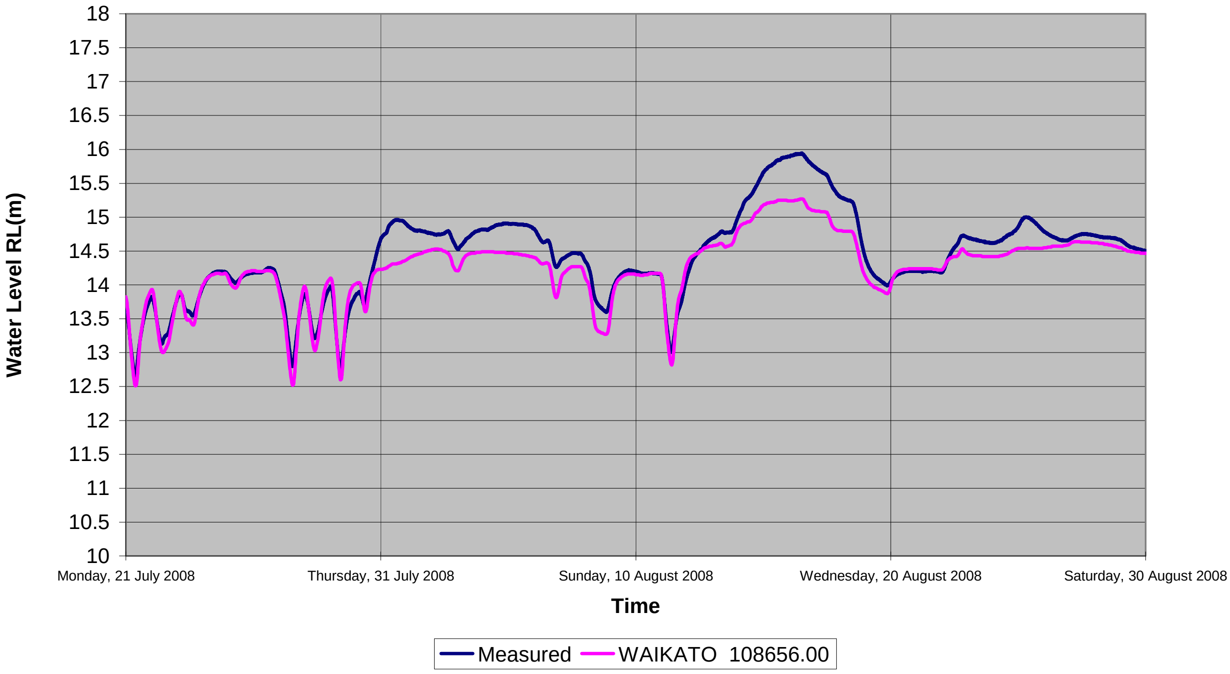
As with TopNet and HEC-HMS, MIKE11-NAM's parameters are varied within plausible ranges so that model results for the lower Waikato River sufficiently approximated observational data (Joynes, 2009). In this case, only the reach bed roughness (Manning roughness) was used for calibration. Model results were calibrated against a suite of observations, including flows, water levels, rating curves, and flow ratios at Ngaruawahia. Three historical flood events were chosen from July 1998, February 2004 and August 2008. These floods were selected to represent a range of flood sizes. In terms of flood peak return periods, these correspond to a range of 10 to 100 years, though these cannot be compared to storm return periods of similar values. Calibration results for the August 2008 flood are shown in **Figure 50**.

The calibration results were mixed but considering the number of calibration points and by using the same hydrological parameters the results were considered adequate for the purposes of this study. In every case the curves matched at the peak or the modelled curve was below the measured curve. Potential errors during the flood peak at Hamilton and Rangiriri are presented in **Table 7**. Each of these errors are of lesser importance than in typical flood impact studies given that the focus is on the relative impact of land cover change, not the absolute impact.

Table 7: Potential errors at the peak of a flood due to model / measured rating curve differentials

Location	**Event**	**Potential Error**
Hamilton	1998	Very little
	2004	Very little
	2008	Very little
Rangiriri	1998	200mm or 35m^3/s
	2004	150mm or 100m^3/s
	2008	very little

Hamilton



Rangiriri

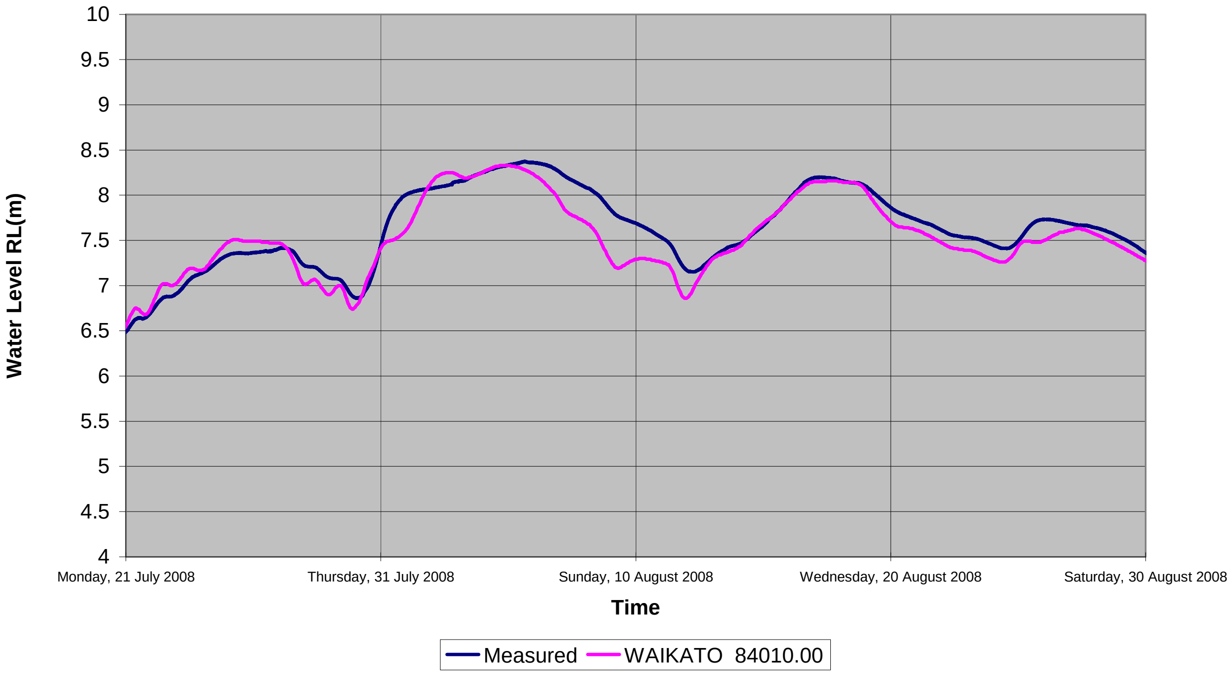


Figure 50: Measured and modelled flood levels at Hamilton and Rangiriri, for August 2008 calibration event.

8 Scenario Modelling

8.1 Test Events Simulations

The impact of land use change was assessed by running the models under test events which represent the current land use and the scenario for conversion of forest to intensive pasture. This section describes the rainfall information used in the test, and explains how the models represented the changes in land use.

The effects that land use change has on flooding are modulated by a variety of factors, especially the meteorological conditions prior to and during the storm itself. To assess how altered flooding may depend on these conditions, two types of storms were simulated, each represented by six magnitudes. The storm types are both historical, dating from 1958 and 1998, and lasted three days, which is typical of storms that produce severe flooding in the upper Waikato.

The magnitudes of the synthetic storms used in the simulations were chosen to reflect annual recurrence intervals (ARIs) of approximately 5, 10, 20, 50, 100 and 500 years in terms of the total 72-hour rainfall depths. Given the purpose of the analysis, these storms are not design events per se, but rather case studies used for the purpose of illustration. The magnitudes of the synthetic storms, specifically their 72-hr total rainfall, were obtained from NIWA's High Intensity Rainfall Design System (HIRDS) (Thompson 2002). **Figure 51** depicts the gridded data over the Waikato catchment for ARI of 100 years.

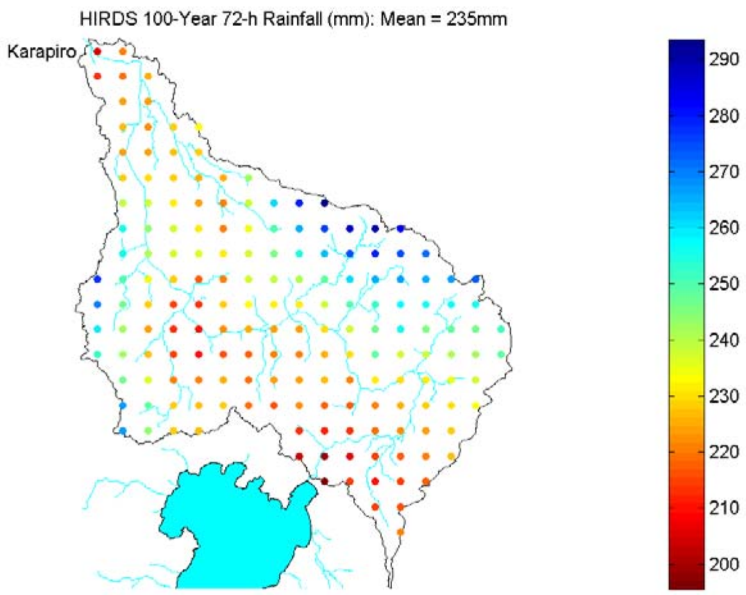


Figure 51: HIRDS 100-year 72-h rainfalls over the upper Waikato

The 1998 Event

The July 1998 storm was a long duration winter storm with rainfall distributed throughout the event. It was estimated to have a return period of between 10 and 25 years. During the simulations, rainfall was distributed in space and time according to historical observations, while the 72-hr total is scaled up or down to approximate the 6 different return periods of interest. Scaling factors were determined by NIWA based on HIRDS data with an areal reduction factor of 0.6, were agreed upon by the TEP, and applied to both HEC-HMS and TopNet. **Table 8** details the catchment-wide 72-hr rainfall totals for each ARI and both models.

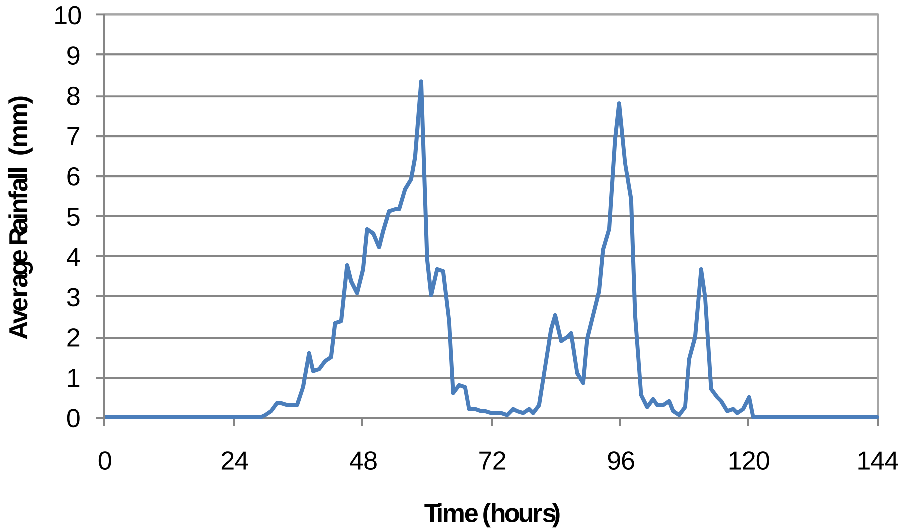


Figure 52: Average catchment rainfall (Starting at 09:00 on 7 July 1998)

The 1958 Event

The February 1958 storm resulted from a late summer tropical weather system that moved across the catchment from the north-west before becoming stationary over the centre of the North Island. The storm was considered to have a reasonably uniform rainfall distribution across the catchment, though not in time (**Figure 53**).

In the simulations for this case study, an areal reduction factor (ARF) of 0.75 was applied to the HIRDS totals to account for the fact that single events are unlikely to represent the same return interval event uniformly across the catchment. The different value of 0.75 was used to explore sensitivity to this assumption, given that the depth-area characteristics of severe rainstorms are extremely variable (Tomlinson, 1978). Another contrast with the 1998 storm is that the meteorological conditions leading up to the synthetic 1958 event were not from the same year. Instead, the 3-day February storm was inserted into the corresponding 3 days of February 2004, so that soil conditions just at the beginning of the storm were particularly wet. **Table 8** details the catchment-wide 72-hr rainfall totals for each ARI and both models. Differences between models for the same storm ARI and year arise from different methods of applying climatic data to the model's spatial organisation. Although there are differences between the model results, it is the predicted change in flow caused by land use change that is important in this study.

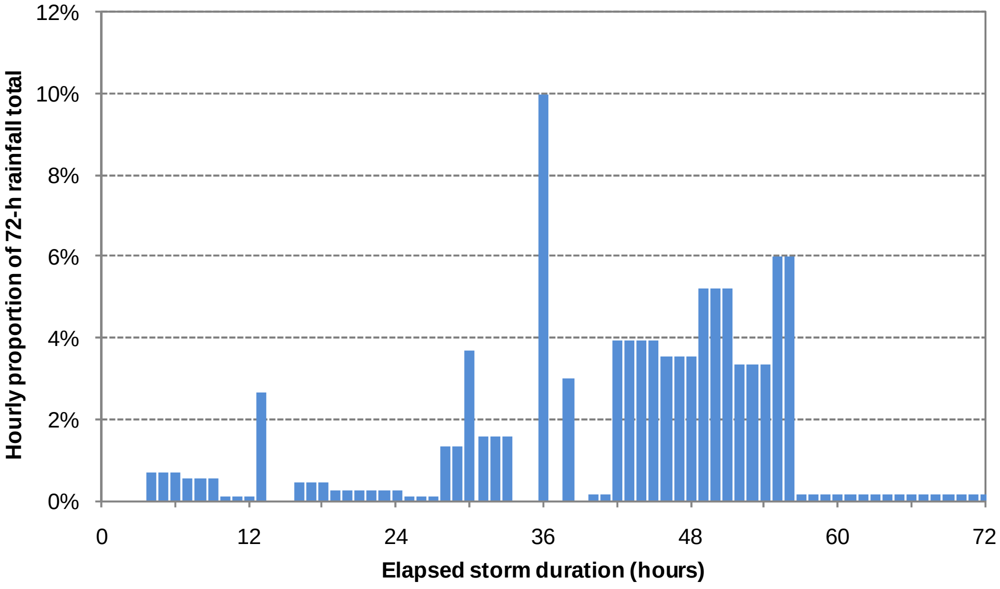


Figure 53: 72-hour temporal pattern of the February 1958 storm rainfall event.

Table 8: Total Waikato catchment rainfalls (mm) used in model simulations.

ARI	HEC-HMS 1958	HEC-HMS 1998	TOPNET 1958	TOPNET 1998
5 year	97	91	97	83
10 year	111	105	111	96
20 year	127	120	127	109
50 year	152	143	152	130
100 year	176	165	176	150
500 year	228	210	228	191

8.2 Land Use Change Predictive Analysis

To forecast the effects of land cover change on flood hydrology, two sets of simulations were performed for each model. Each set corresponded to one land cover scenario, either current conditions or projected future conditions. Within each set, climatic variables were varied as outlined previously. This gives us the crucial ability to isolate the effects of the land cover change.

For the future land cover scenario, model parameters associated with the areas outlined in black in **Figure 3** were changed to represent pastoral conditions, in accordance with each model's implementation of land cover hydrology.

8.2.1 TopNet

To mimic land cover conversion, sub-basin parameters falling within the projected conversion areas were adjusted to represent characteristics indicative of pasture hydrology rather than forest. Values of the hydraulic conductivity were altered according to values indicated by the Taylor et al. (2009) report for Agricultural and Horticultural Surfaces. The Taylor et al. (2009) mapping of hydraulic conductivity to combinations of soil type and land cover class was used as the basis of the map of hydraulic conductivity under future land use; it was not altered during the calibration process. The canopy storage capacity and canopy enhancement factors were also changed accordingly.

8.2.2 HEC-HMS

For HEC-HMS, the spatial analysis of soil type and land use combinations (homogeneous sub-basins) was reproduced following removal of forest for those areas identified in the land use change scenario. The resulting distribution of homogeneous sub-basins within each hydro lake sub-catchment is provided in **Table 9** for reference purposes.

Table 9: Homogeneous sub-basin areas (km^2) for hydro lake sub-catchments (land use change scenario).

	Forest			Pasture				
Sub-basin	**LOAM**	**POD**	**PUM**	**LOAM**	**POD**	**PUM**	**Open Water**	**Total**
Arapuni left*	9.8		11.3	26.8		118.9	8.8	**175.7**
Arapuni right	4.5		27.3	3.5		32.7	0.6	**68.5**
Aratiatia*	1.2	1.1	16.3	3.8	2.2	98.9		**123.5**
Atiamuri	30.2	9.2	95.9	31.2		137.9	2.3	**306.8**
Karapiro left*	2.7	19.1		117.9	6.9	0.9	4.2	**151.7**
Karapiro right	16.4	2.9	180.0	126.4		350.5	4.0	**680.2**
Maraetai left*	142.6	72.4	6.8	104.5	2.9	144.3	1.4	**474.8**
Maraetai right	27.0		95.9	1.8		58.2	3.3	**186.2**
Ohakuri left	7.9	12.4	35.2	9.6	14.2	183.6	5.1	**268.0**
Ohakuri right (a)			216.8			330.2	0.6	**547.5**
Ohakuri right (b)*	4.7	7.7	218.4	33.2		390.8	8.6	**663.6**
Waipapa	82.3	5.9	88.0	23.5	4.7	48.3	1.4	**254.1**
Whakamaru left	42.2	16.1	68.9	109.9	28.3	63.7	3.9	**332.8**
Whakamaru right	33.9		104.4	2.1		28.8	2.8	**171.8**

NB: Red numbers indicate a change in area from the base case scenario. * indicates no changes within sub-basin.

9 Results

9.1 Local flooding within the Upper Waikato Catchment

Local flooding refers to the magnitude of flood events on tributaries of the Upper Waikato, i.e. sub-catchments within the hydro-lake catchments. TopNet and HEC-HMS are both used, though in the case of HEC-HMS, artificial design storms specific to small catchment sizes were used, in contrast with TopNet's use of a rainfall pattern from a historical storm that affected the whole Waikato catchment.

9.1.1 TopNet

TopNet makes its calculations with model elements that are each about 10 km^2 in area, so the same simulations used for the dam sub-catchments also produce information on smaller catchments. It has not been calibrated on data from catchments of this size, so the results must be interpreted with caution.

Changes in local streamflow corresponding to the 100-year test event are depicted in **Figure 54** and summarised in **Table 10** along with the 10-year test event. In both cases only the 1958 temporal rainfall pattern was used, lasting three days.

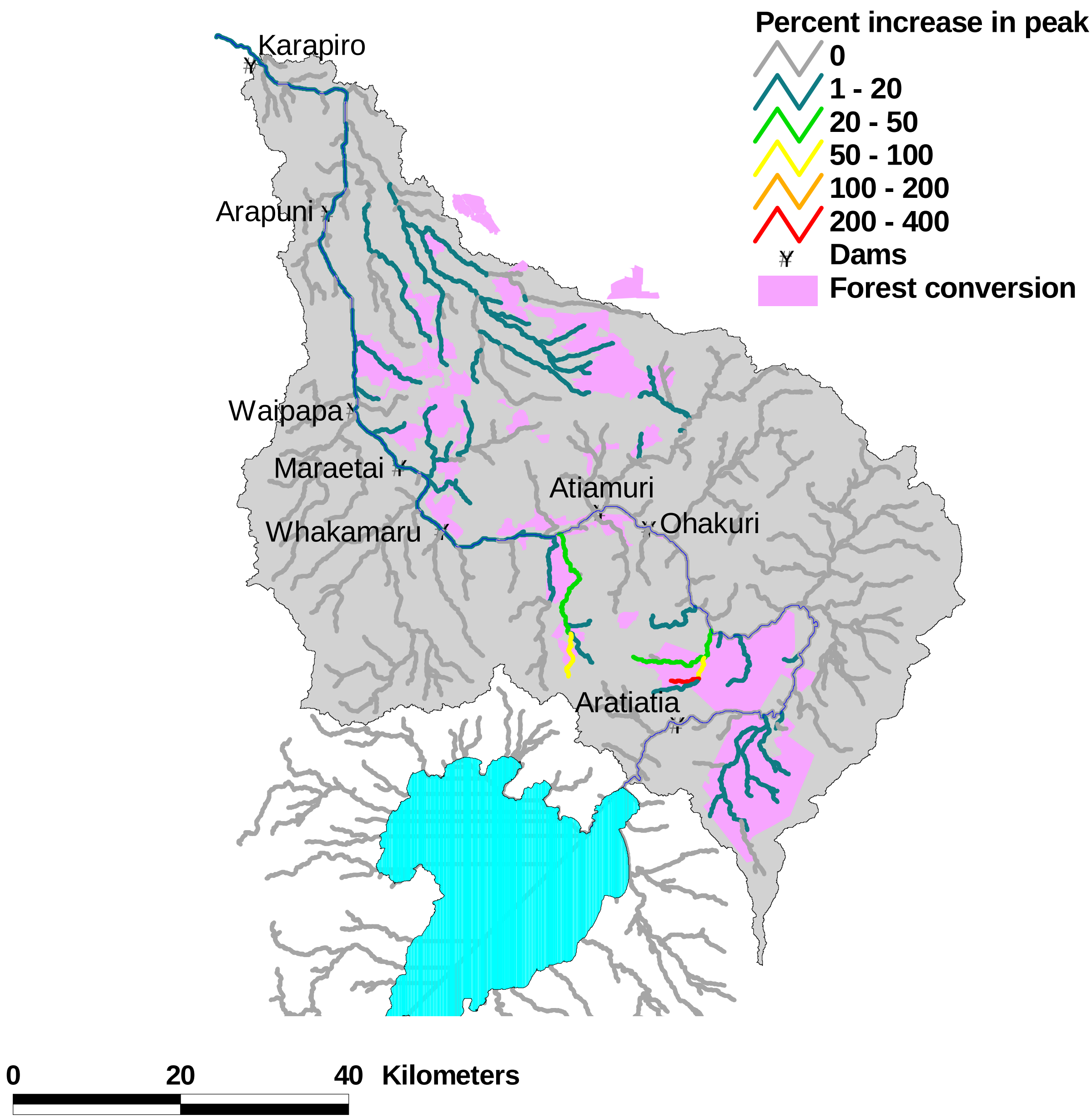


Figure 54: Percentage increase in peak flow for 100-year test rainfall event using the 1958 temporal pattern.

Table 10: Summary of local effects of land use change on flood peaks for the 10-year and 100-year test events

Location	Effect in 10-year test event	Effect in 100-year test event
Pokaiwhenua Stream	Up to 5% increases on some tributaries	Up to 5% increases on some tributaries
Ongarahu Stm and Mangatutu Stm (south of Lake Whakamaru)	Up to 5% increases in some tributaries, and up to 20% increases in a few cases	Increases of 20-100% in some tributaries
Orakonui Stm	Up to 5% increases on most tributaries	Increases of more than 50% in some tributaries
Pueto Stm and Sexton Stm	Up to 5% increases on most tributaries within conversion area	Up to 20% increases on some tributaries within conversion area

9.1.2 HEC-HMS

HEC-HMS was also used to assess local-scale effects of land cover change, but the focus was exclusively on the Pokaiwhenua sub-catchment, comprising an area of 105.3 km^2. The river flows from east to west under the SH1 approximately 2.5 km north of Parkdale before flowing into the Waikato River upstream of Lake Karapiro. The catchment was simulated as five lumped sub-basins, distinguished based on land use and soil type. The potential future land use was based on conversion to pasture of currently forested land with a Land Use Capability (LUC) rating of 6 or less.

Design storm rainfall depths for the 5-year and 100-year rainfall events were determined from the HIRDS database for the catchment centroid. The 5-year rainfall was determined by interpolation using an exponential function fitted through the HIRDS data. Six different storm durations were also investigated, maintaining total amount of rainfall in each and thus high intensities in the shorter storms. In contrast with the TopNet simulations, the temporal distribution was not the 3-day-long 1958 pattern, but an artificial pattern with most rain falling in the middle of the storm. Historical rainfall was used to determine suitable antecedent soil moisture conditions for the flood analysis.

HEC-HMS simulations were performed for both the 5- and 100-year rainfall events, and for both land use scenarios. Changes in flood volumes and flood peaks are depicted in **Figure 55** and **Figure 56**. The impact at the SH1 crossing of the Pokaiwhenua Stream of forest to pasture conversion is summarised as follows:

- Flood peaks will increase significantly;
- The highest percentage increase in flood discharge will be for storm duration of approximately 12 hours, twice the catchment time of concentration;
- The percentage increase in peak discharge will be greater for less frequent events; and
- The percentage of rainfall resulting in surface runoff will increase significantly.

These results suggest that after conversion of the catchment from 95% to 15% forest cover, the increase in flood runoff is expected to be significant. Comparisons with the TopNet results should be made using the 72-hr storm.

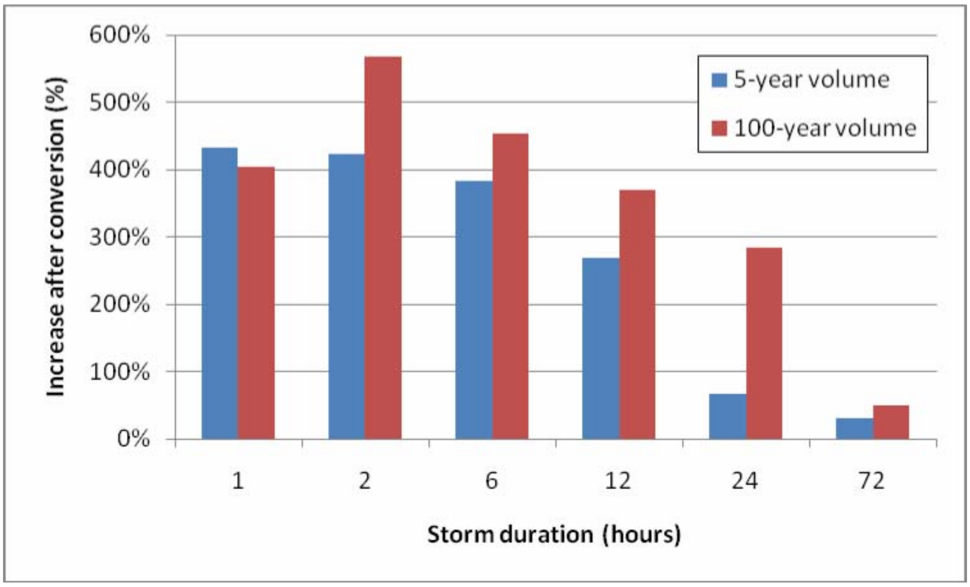


Figure 55: Pokaiwhenua at SH1: Increase in runoff volume after conversion on HEC-HMS.

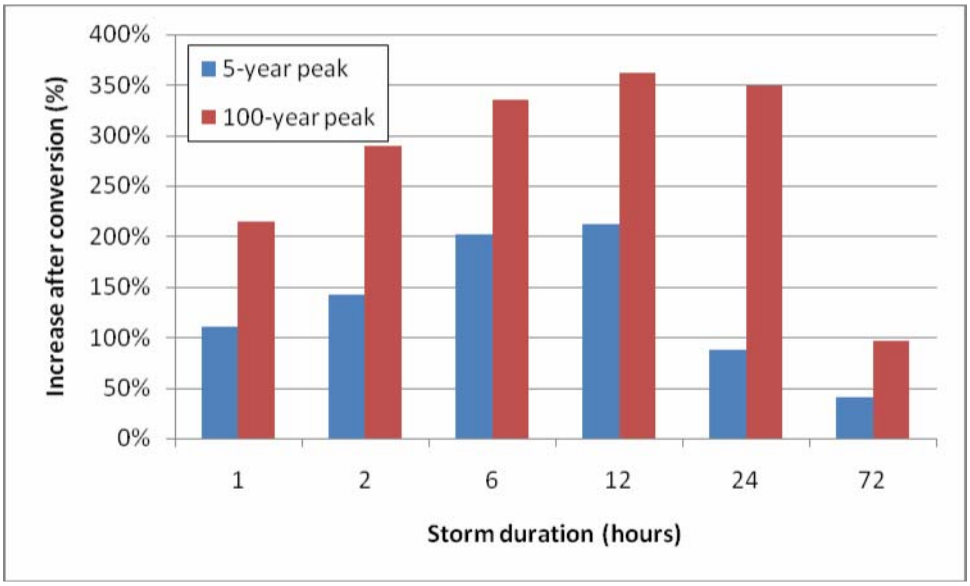


Figure 56: Pokaiwhenua at SH1: Increase in runoff peak after conversion based on HEC-HMS.

9.1.3 Discussion

With regards to the model results, differences in the prescribed rainfall prevent a direct inter-comparison - they are instead complementary. TopNet provides a more detailed examination of the spatial variability of the impacts, while HEC-HMS provides a richer conceptual understanding of what characteristics of storm (i.e., intensity, duration) are responsible for flooding changes. While some storms simulated by HEC-HMS may be indicative of short and intense thunderstorms, this is not the case of the 1958 event used by TopNet. In their entirety, then, the results indicate that variations in both landscape and storm characteristics are important in understanding how land cover change translates into flooding change.

These analyses may also be placed in a broader context by considering other small catchment studies. The Purukohukohu experimental catchment located on the slopes of the Paeroa Ranges near Reporoa and drains into the Waiotapu Stream. This pumice catchment includes the Puruki recorder (0.344 km^2), which provides us with a record of hydrological changes that have occurred in response to land use change. The catchment was in pasture between 1968 and 1973 when it was planted in exotic forestry. The forest was harvested in 1996-1997. Rowe (2003) found that small flood peaks from pasture were double those from mature forest, but for larger events flood peaks from pasture were an order of magnitude greater than those from forest. Mulholland (2006) found that, on average, flood peaks from an unforested neighbouring catchment were three times those from an equivalent area of the forested Puruki catchment. Mulholland (2006) also analysed storm runoff and rainfall for 17 storms in the Purukohukohu catchment at Puruki before and after afforestation and found that the average percentage of storm runoff from pasture (18%) was slightly less than that from forest (20%). There was little difference in average storm runoff percentages between winter (23%) and summer (17%) when the catchment was pasture, but when the catchment was forested average summer storm runoff (14%) was much less than winter (45%). Generally, these figures are consistent with the model evaluation carried out by TopNet (**Figure 54**) and HEC-HMS.

9.2 Inflows to Dams

9.2.1 TopNet

Figure 57 shows the simulated hyetographs and inflow hydrographs for the 7 dam catchments for the current and converted cases for the 100-year return period 1998 rainstorm. Four of the catchments show no appreciable change in the hydrographs due to land use conversion.

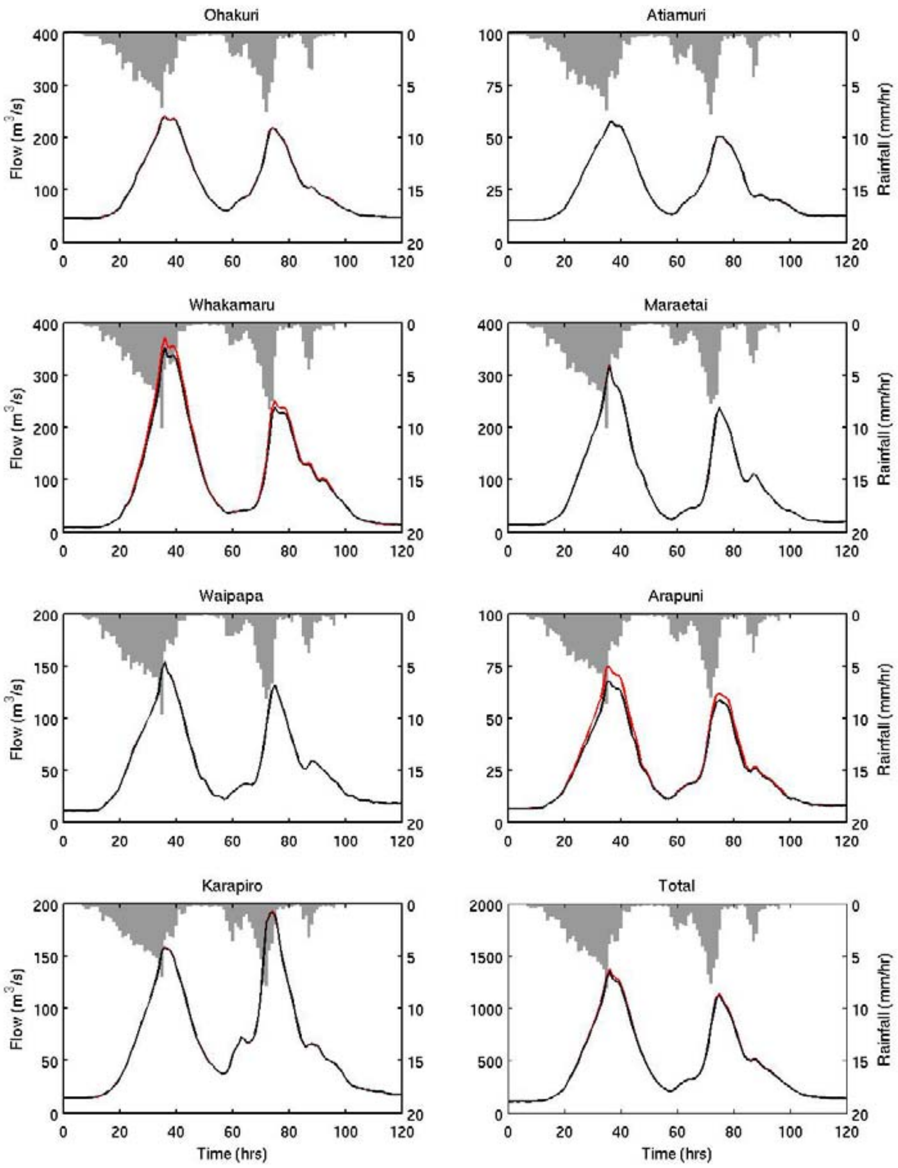


Figure 57: Simulated hydrographs for each of the dam catchments as simulated by TopNet for the 100-year rainfall event for 1998 under current (black lines) and converted (red lines) land use scenarios.

Figure 58 shows the simulated hyetographs and inflow hydrographs for the 7 dam catchments for the current and converted cases for the 100-year return period 1958 rainstorm. Again, four of the catchments show no appreciable change in the hydrographs due to land use conversion.

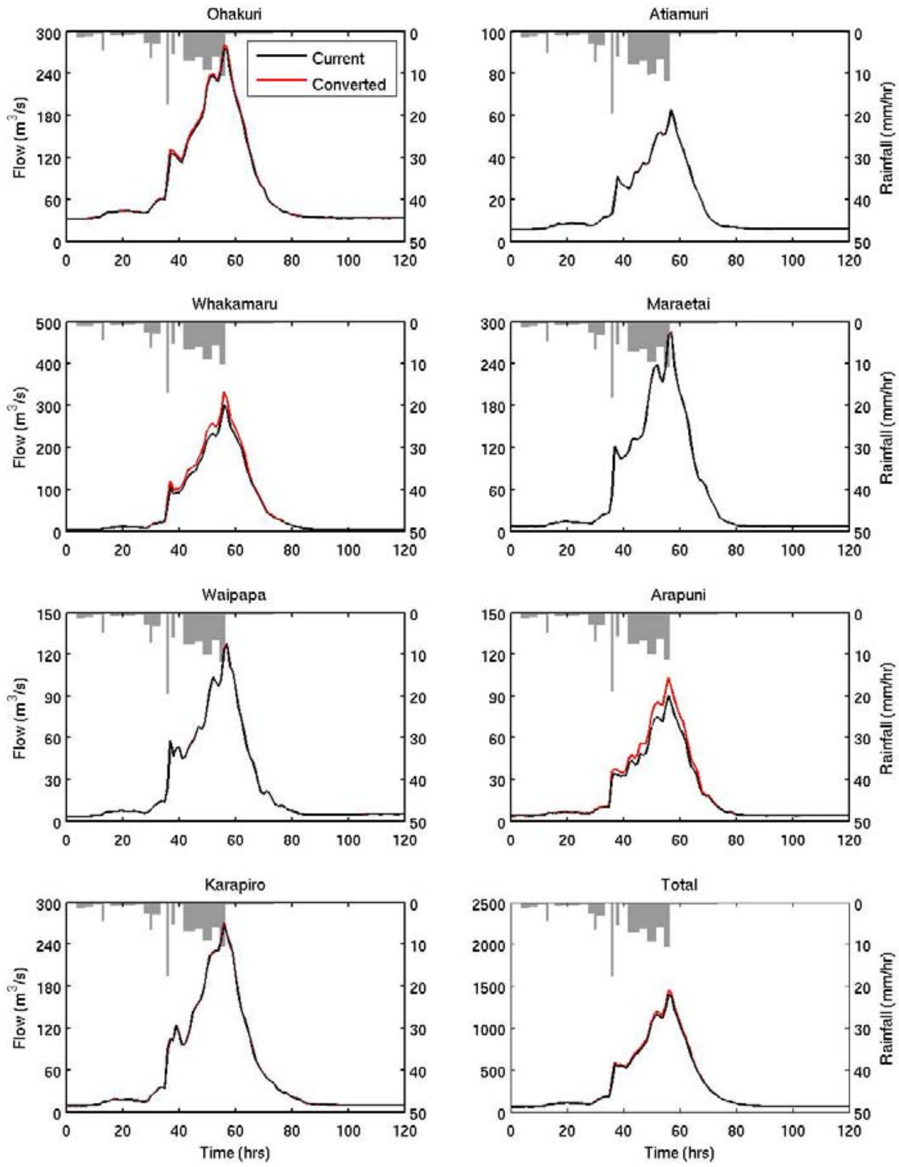


Figure 58: Simulated hydrographs for each of the dam catchments as simulated by TopNet for the 100-year rainfall event for 1958 under current (black lines) and converted (red lines) land use scenarios.

The spatial variability is more comprehensively illustrated in **Figure 59** and **Figure 60**, alongside sensitivity to storm ARI. The catchment response to land cover change is dominated by Arapuni and Whakamaru, though Ohakuri produces a detectable effect in the modelled peak flows. While the absolute changes in peak flow increase with increasing storm ARI, percentage differences for Arapuni and Whakamaru peak at intermediate storm ARIs (20 and 100 years, respectively). The effects of storm ARI on sub-catchment peak flow differences are similar to the effects on peak 72-hour flows, which are more representative of total flood volume.

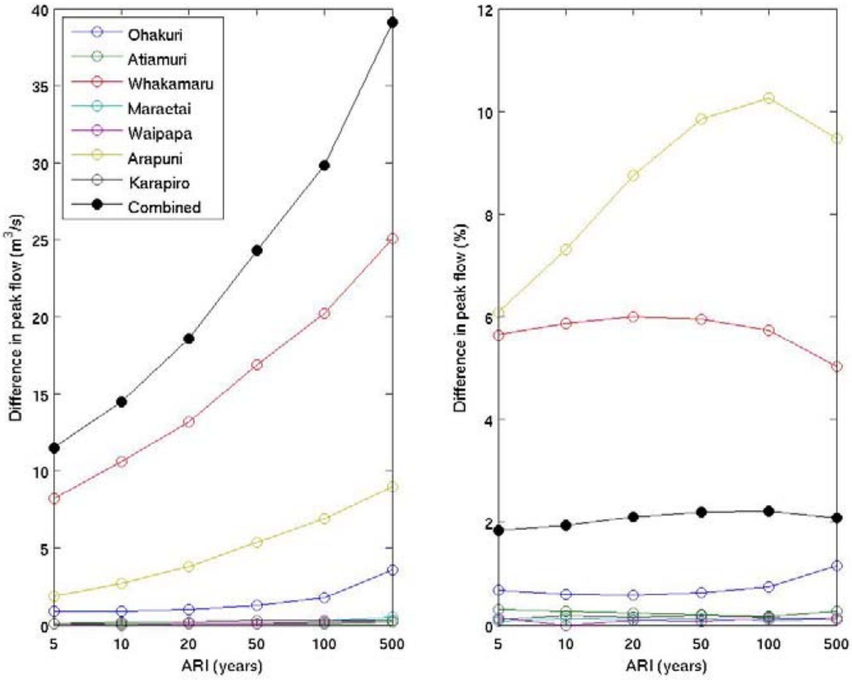


Figure 59: Peak flow differences in m^3/s (left) and percent (right) for the converted scenarios compared to current land use hydrographs (TopNet simulations, 1998 rainfall pattern). Results are displayed for different return intervals and the dam catchments as well as the outlet. “Combined” refers to the total Taupo-Karapiro inflows.

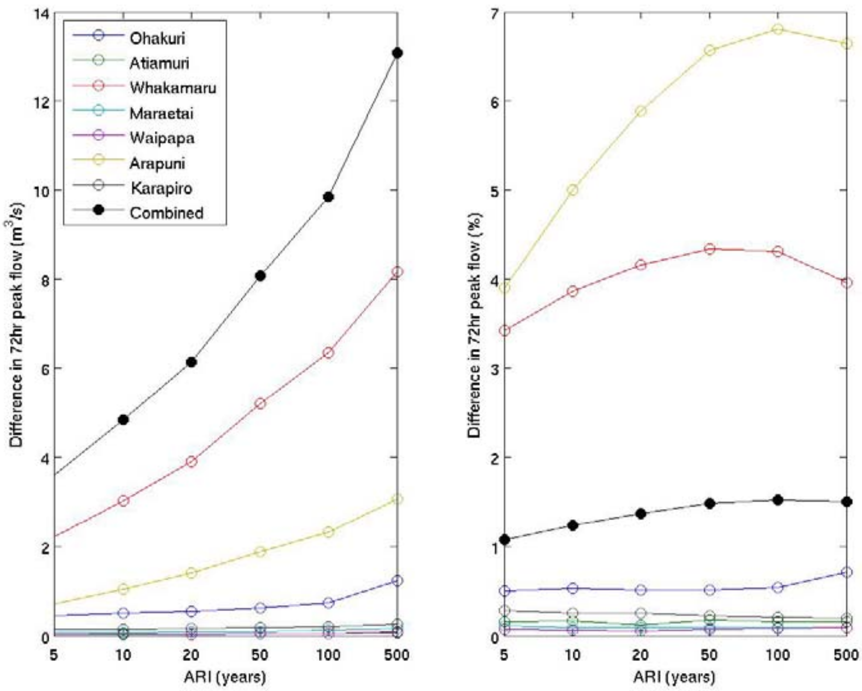


Figure 60: Peak 72-hr flow differences in m3/s (left) and percent (right) for the converted scenarios compared to current land use hydrographs (TopNet simulations, 1998 rainfall pattern). Results are displayed for different return intervals and the dam catchments as well as the outlet. “Combined” refers to the total Taupo-Karapiro inflows.

9.2.2 HEC-HMS

There was no discernable effect of land use change on flood flows for the 5, 10 and 20 year test events. Model results for the 50 and 100 year test events are shown for seven sub-catchments corresponding to the incremental hydrolake catchments (**Figure 61** and **Figure 62**). For the 100-yr storm ARI only two sub-catchments – Atiamuri and Karapiro – show no appreciable change in flow following land cover conversion.

Details for the 500 year test event are not shown here due to increased uncertainty in model results for this event. This is attributable to the following:

1) The rainfall intensities selected for the 500 year test event are beyond the range of those used during model calibration, therefore model functionality is untested to these imposed stresses;
2) Resulting simulated flows are outside the range of observed flows in the catchment; and
3) Test rainfall totals were extrapolated beyond the range of HIRDS values (the greatest being the 150 year event), meaning that there is an added degree of uncertainty relating to the magnitude of this event.

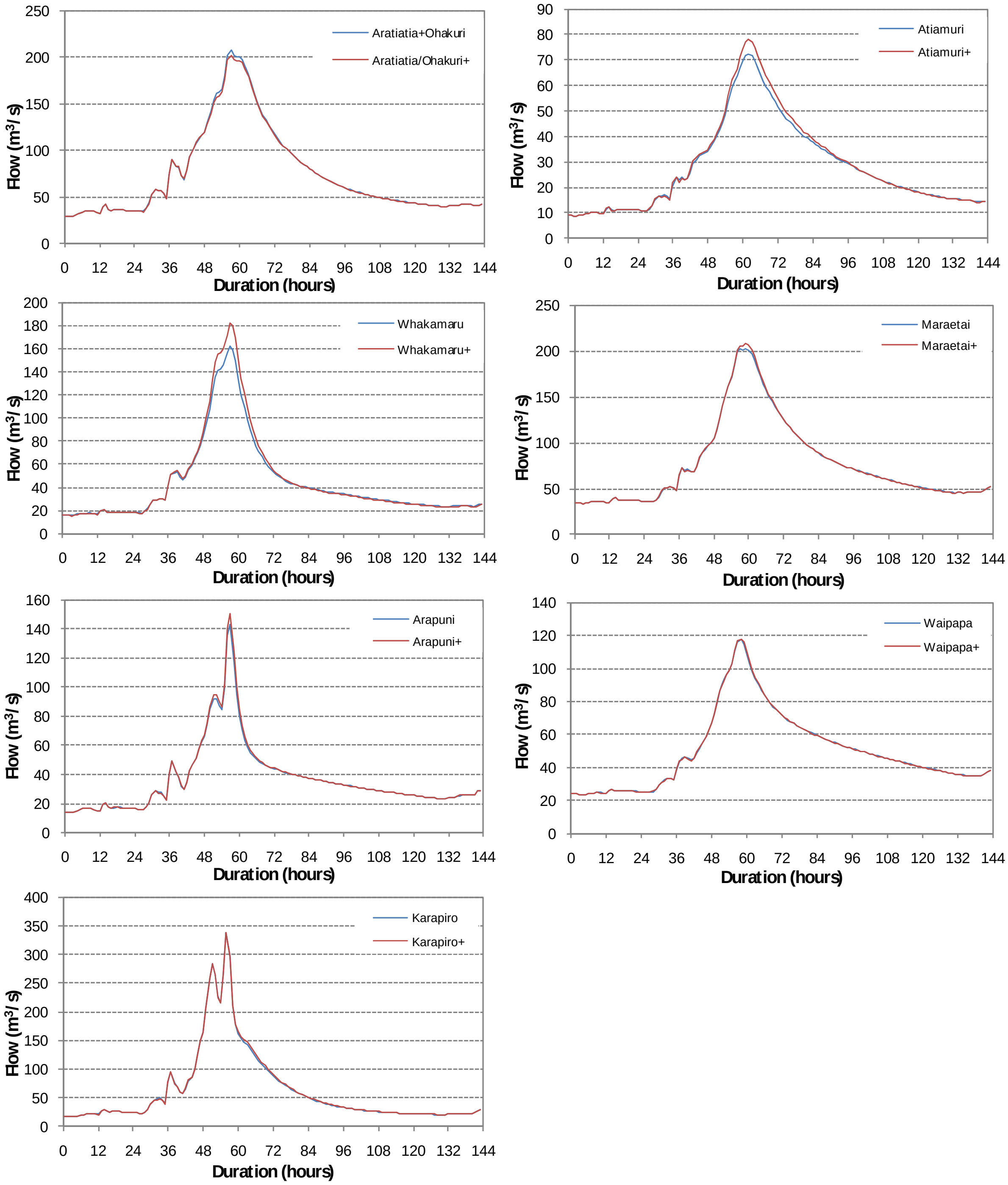


Figure 61: Effect of land use change (indicated by + symbol) on dam catchment inflows for 50-year test event for 1958 on 7 dam catchments, using HEC-HMS.

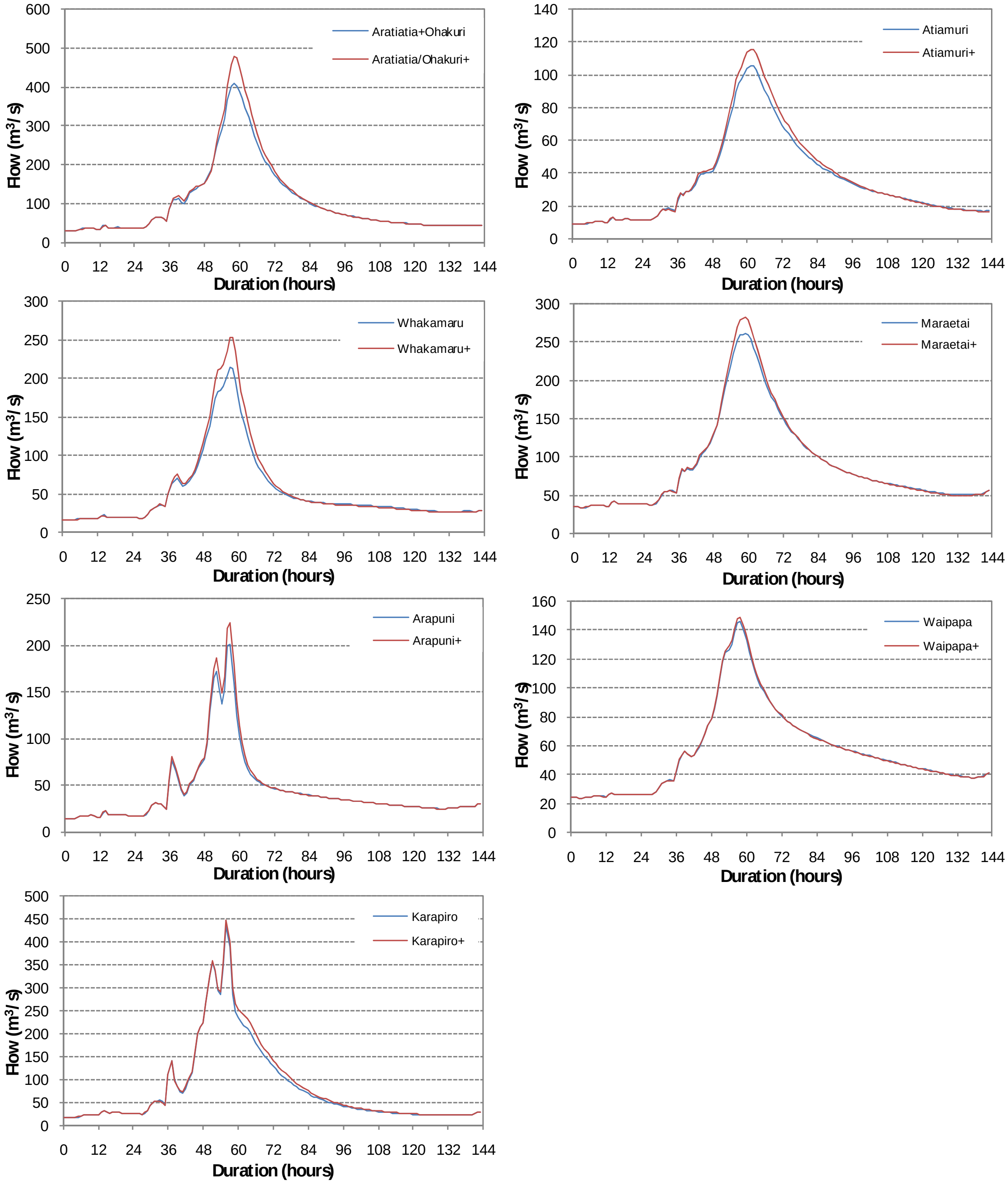


Figure 62: Effect of land use change (indicated by + symbol) on dam catchment inflows for 100-year test event for 1958 on 7 dam catchments, using HEC-HMS.

9.2.3 Summarising TopNet and HEC-HMS

Results of the modelling are summarised as follows, focussing on the cumulative tributary inflows between Taupo and Karapiro for the two storm events. Percentage increases in peak flows and flood volumes following conversion for each of the simulations are presented in **Table 11** and **Table 12**.

Table 11: Percent differences in simulated peak hourly Taupo – Karapiro inflows for the two storm types and two models.

Notional Storm Average Recurrence Interval	1998 Event		1958 Event	
	HEC-HMS	TopNet	HEC-HMS	TopNet
5 Year Rainfall	0.2	1.9	0.8	2.7
10 Year Rainfall	0.2	2.0	1.1	2.9
20 Year Rainfall	0.7	2.0	1.3	3.1
50 Year Rainfall	1.5	2.2	1.9	3.5
100 Year Rainfall	1.6	2.2	9.4	3.6
500 Year Rainfall	4.7	2.1	15.6	3.0

Table 12: Percent differences in simulated 72-hr peak hourly Taupo – Karapiro inflows for the two storm types and two models.

Notional Storm Average Recurrence Interval	1998 Event		1958 Event	
	HEC-HMS	TopNet	HEC-HMS	TopNet
5 Year Rainfall	0.0	1.2	0.0	2.1
10 Year Rainfall	0.0	1.0	0.0	2.2
20 Year Rainfall	0.0	1.6	0.0	2.6
50 Year Rainfall	0.0	1.5	1.0	2.8
100 Year Rainfall	0.0	1.6	5.2	3.0
500 Year Rainfall	2.0	1.5	9.5	3.0

9.2.3.1 1998 Event

Peak flood flow differences for each of the 1998 six storms, integrated from Taupo to Karapiro without consideration of dam operations are presented in **Table 11**. The corresponding hydrographs and percent differences are depicted in **Figure 63** and **Figure 64**. For HEC-HMS, differences in peak flow rise from 0.2% for the 5-yr ARI to 4.7% for the 500-yr. For TopNet, the differences are consistently very close to 2%.

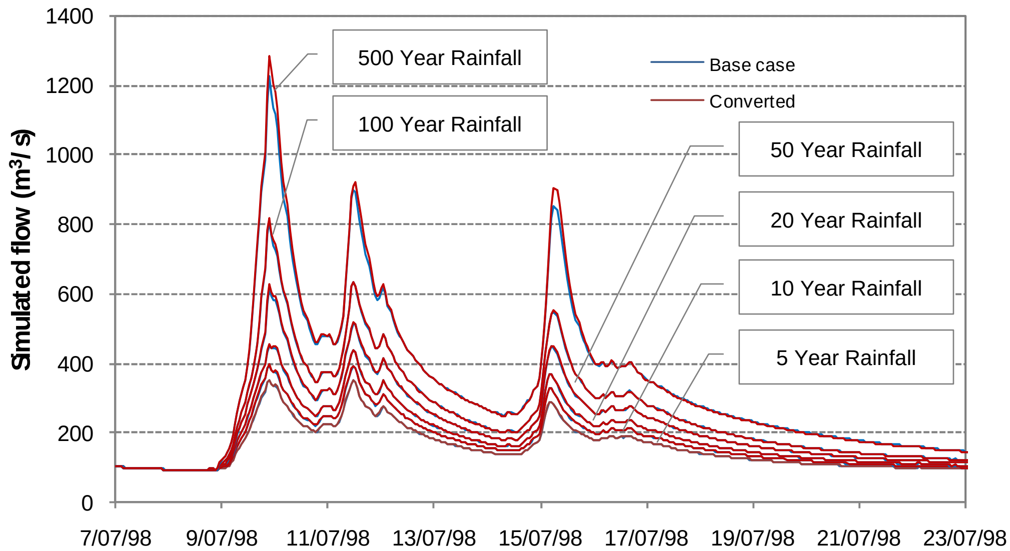


Figure 63: Simulated Taupo – Karapiro inflow hydrographs of six notional magnitude storm events under base case and converted land use scenarios, HEC-HMS, 1998 events.

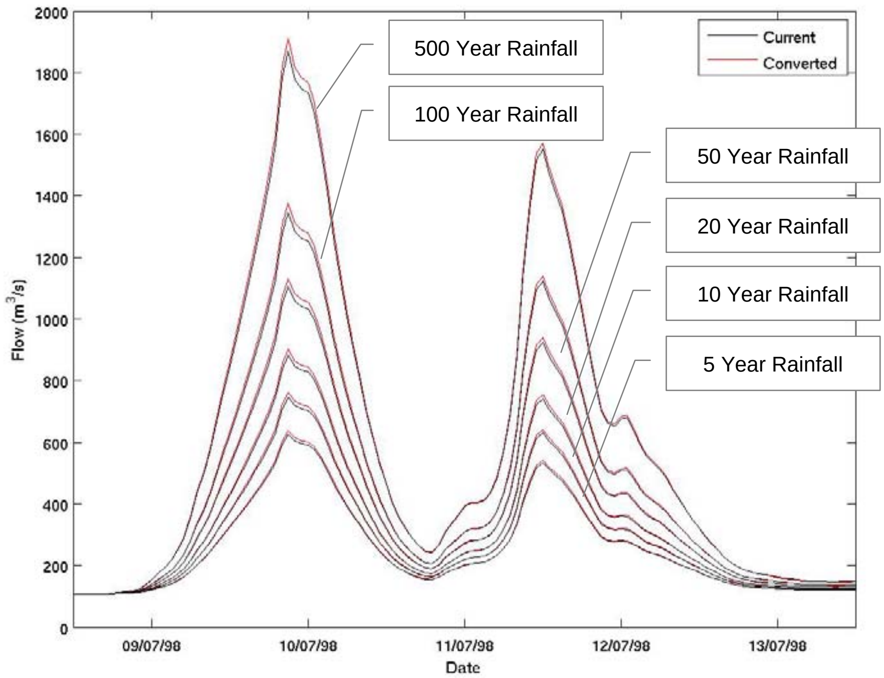


Figure 64: Simulated Taupo-Karapiro inflow hydrographs for the 6 synthetic rainfall events under current (black) and converted (red) land use scenarios, TopNet, 1998 events.

9.2.3.2 1958 Event

Peak flood flow differences for each of the six 1958 storms, integrated from Taupo to Karapiro without consideration of dam operations, are presented in **Table 11**. The corresponding hydrographs and percent differences are depicted in **Figure 65** and **Figure 66**. For HEC-HMS, differences in peak flow rise from 0.8% for the 5-yr ARI to 15.6% for the 500-yr, showing a similar response to rainfall intensity as the 1998 event, though greater in magnitude. For TopNet, the differences are again consistent, varying between 3-4%. In terms of absolute flows, those simulated by HEC-HMS far exceed those by TopNet. Given that the main difference between the two storms lies in their peak intensities, it is important to note that storm intensity is central to changes in flood response simulated by HEC-HMS, though less so for TopNet.

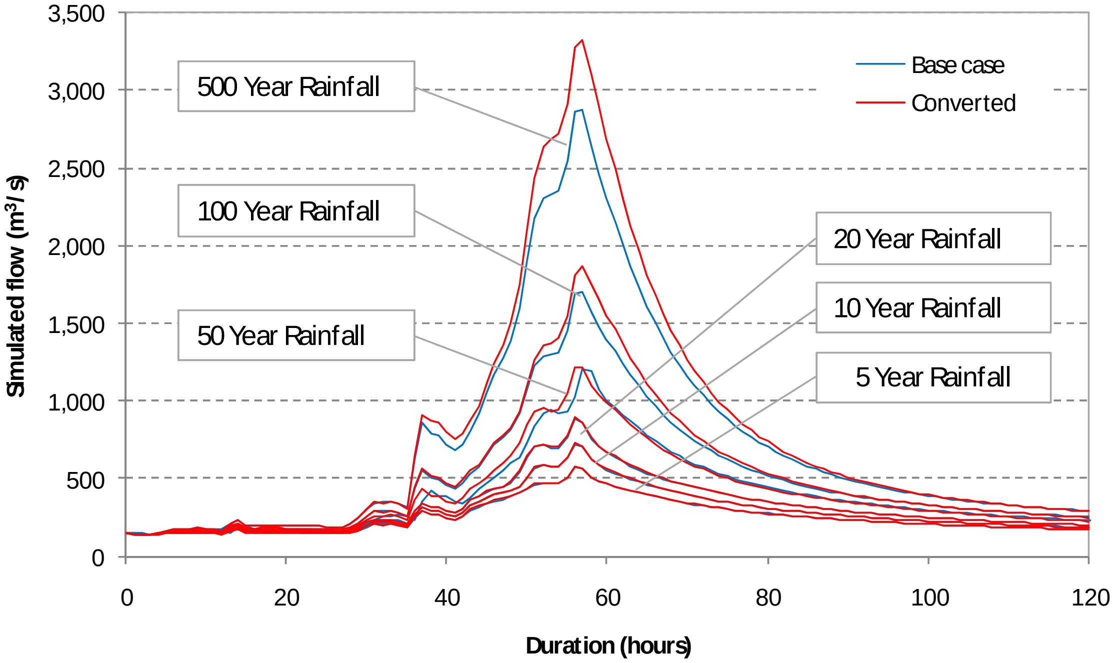


Figure 65: Simulated Taupo – Karapiro inflow hydrographs of six notional magnitude storm rainfall events under base case and converted land use scenarios, 1958 events.

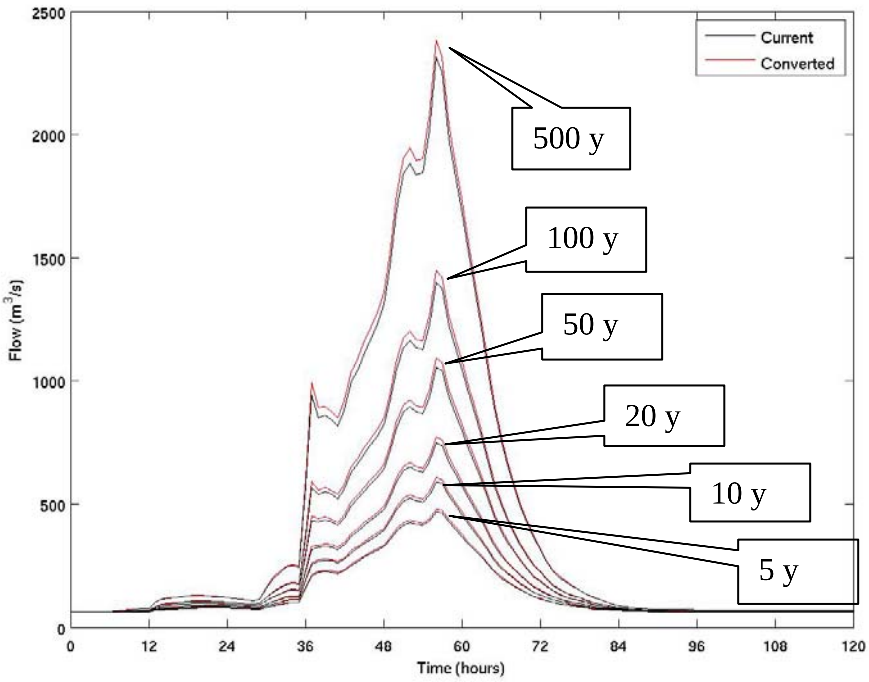


Figure 66: Simulated Taupo-Karapiro inflow hydrographs (TopNet) for the 6 synthetic rainfall events under current (black) and converted (red) land use scenarios, 1958 events.

9.3 Effects of Dam Operations

As stated previously, neither HEC-HMS nor TopNet considered the influence of dam operations in the propagation of the flood hydrographs down main stem of the Waikato River. This element of the analysis was conducted by Jowett (2009a).

The effects of hydro-dam operations were accounted for by taking the tributary inflow hydrographs, as generated by HEC-HMS and TopNet for the two storm events and six storm ARIs, and routing them down the Waikato subject to prescribed dam operational rules.

Figure 67 illustrates the inflow hydrographs at Karapiro for each storm ARI under the two land cover scenarios, based on the HEC-HMS tributary inflows. The temporal patterns differ substantially from those generated in the absence of dam operational rules (c.f., **Figure 65**). It is also possible to begin to see the effects of higher peak flows under land cover change. **Table 13-Table 16** list the percentage increases in hydro-dam discharge, according to storm ARI, storm type and model. Note that these lake outflows cannot be compared to the individual tributary inflows reported above. As the land cover change effects are accumulated downstream, lake outflows respond accordingly.

Percentage increases in peak discharge at Karapiro tend to increase with storm ARI, and resemble the hydrological sensitivity of the sub-catchments as depicted above. We examined the sensitivity of these results to the initial lake levels. Because of the operational rules in place, using the 90th percentile lake levels as opposed to the median values has very little effect on predicted flow changes under land cover conversion. The predicted flow changes are more sensitive to differences in storm magnitude, storm type, and model used.

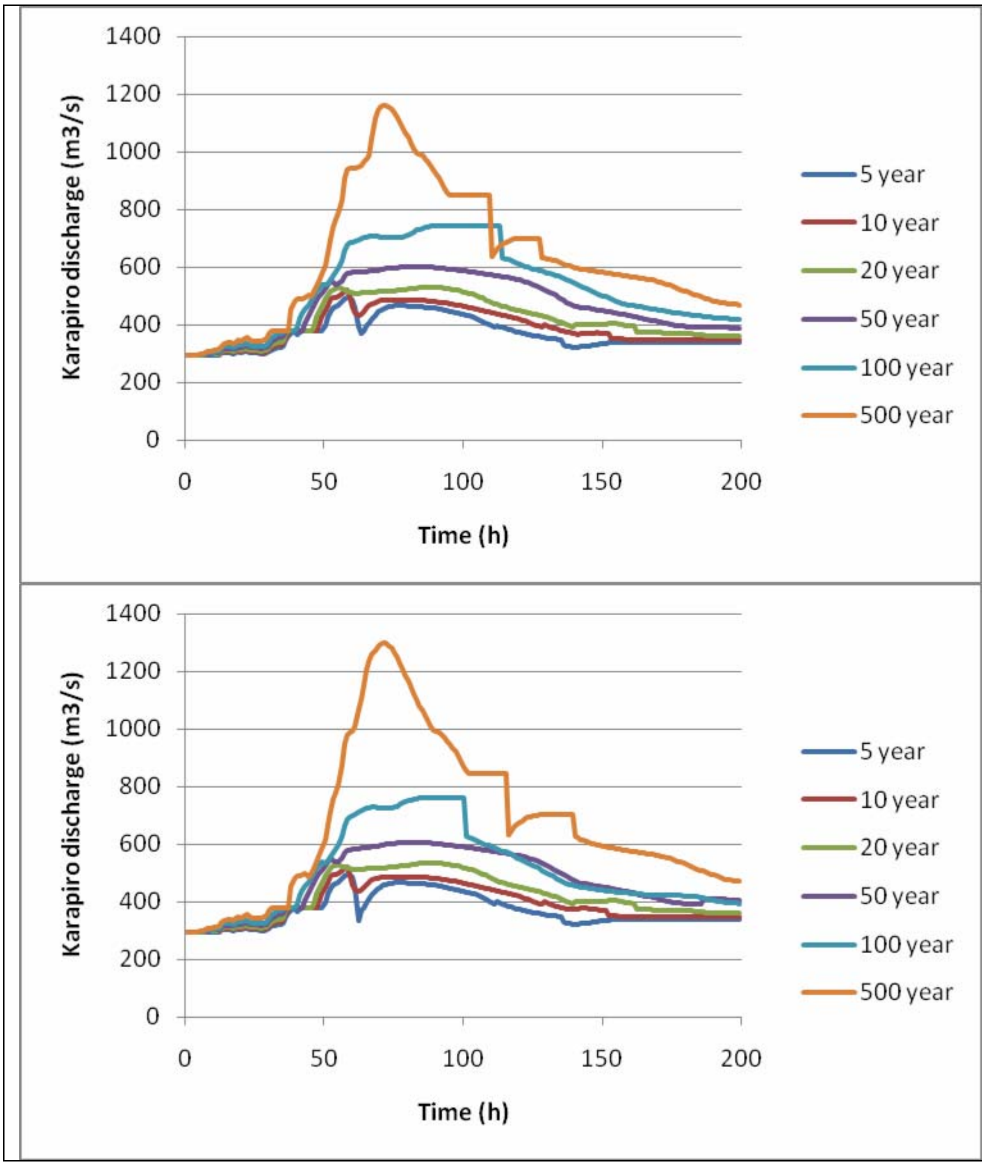


Figure 67: Hydrographs of Karapiro discharge simulated using HEC-HMS model inflow hydrographs for 5-500 year rainfalls with 1958 temporal pattern with current land use (above) and with future land use (below) scenarios.

Table 13: Percentage increase in hydro dam discharges simulated using HEC-HMS model inflows for future land use scenario and 1998 temporal pattern.

Rainfall magnitude	Ohakuri	Atiamuri	Whakamaru	Maraetai	Waipapa	Arapuni	Karapiro
5 year	0.5	0.0	0.3	0.3	0.0	0.0	0.0
10 year	0.0	0.4	0.3	0.3	0.0	0.0	-0.2
20 year	0.4	0.4	0.0	0.0	0.0	0.0	0.0
50 year	0.0	0.0	0.0	0.0	0.0	0.2	0.0
100 year	-0.7	-0.7	0.9	1.6	1.0	0.4	0.5
500 year	-0.9	-0.5	1.1	1.3	1.4	1.5	2.2

Table 14: Percentage increase in hydro dam discharges simulated using TopNet model inflows for future land use scenario and 1998 temporal pattern.

Rainfall magnitude	Ohakuri	Atiamuri	Whakamaru	Maraetai	Waipapa	Arapuni	Karapiro
5 year	0.3	0.3	0.0	0.0	0.2	0.2	0.2
10 year	0.3	0.3	0.3	0.2	0.4	0.9	0.2
20 year	0.3	0.0	3.3	0.2	0.2	0.6	0.7
50 year	0.3	0.3	1.6	0.9	0.2	0.9	1.0
100 year	0.0	0.3	3.1	1.8	0.3	0.8	1.7
500 year	0.0	0.2	5.4	3.4	3.5	3.2	1.2

Table 15: Percentage increase in hydro dam discharges simulated using HEC-HMS model inflows for future land use scenario and 1958 temporal pattern.

Rainfall magnitude	Ohakuri	Atiamuri	Whakamaru	Maraetai	Waipapa	Arapuni	Karapiro
5 year	0.4	0.3	0.0	0.0	0.0	0.0	0.0
10 year	-0.4	0.0	0.6	0.2	0.0	0.2	0.0
20 year	-0.7	-0.6	1.8	1.3	1.2	0.8	0.2
50 year	-1.7	0.0	0.6	1.0	0.8	0.5	0.7
100 year	0.0	-8.8	-8.1	1.2	1.9	0.7	2.7
500 year	1.8	17.4	20.6	11.9	10.5	11.3	12.1

Table 16: Percentage increase in hydro dam discharges simulated using TopNet model inflows for future land use scenario and 1958 temporal pattern.

Rainfall magnitude	Ohakuri	Atiamuri	Whakamaru	Maraetai	Waipapa	Arapuni	Karapiro
5 year	0.7	0.7	0.0	0.0	0.0	0.0	0.4
10 year	0.7	0.6	2.8	0.0	0.5	0.0	0.2
20 year	0.6	0.6	0.3	1.2	-0.4	1.5	-0.2
50 year	0.8	0.0	4.5	1.4	0.4	2.9	0.2
100 year	0.0	0.5	3.6	1.9	0.9	3.2	1.2
500 year	0.0	1.9	7.2	8.2	7.2	5.3	6.3

9.4 Karapiro Daily Discharges

Karapiro discharges simulated using inflows from the two models, under current land use with two temporal rainfall patterns, were compared with the annual maximum daily discharges recorded at Arapuni and Karapiro since 1921 to show the relative effect of storm intensity on predictions and to check whether the simulated discharges were similar to those that have been recorded (Figure 68).

Discharges resulting from the TopNet and HEC-HMS flood simulations under the current land use are both generally in accord with recorded discharges at Karapiro. The HEC/HMS model is more sensitive to the temporal rainfall pattern than TopNet, and so HEC-HMS has a wider range of flows for most recurrence intervals. The wide range of flows for the 500-year rainfall highlights the great uncertainty inherent in predicting discharge from storms with ARIs longer than 100 years.

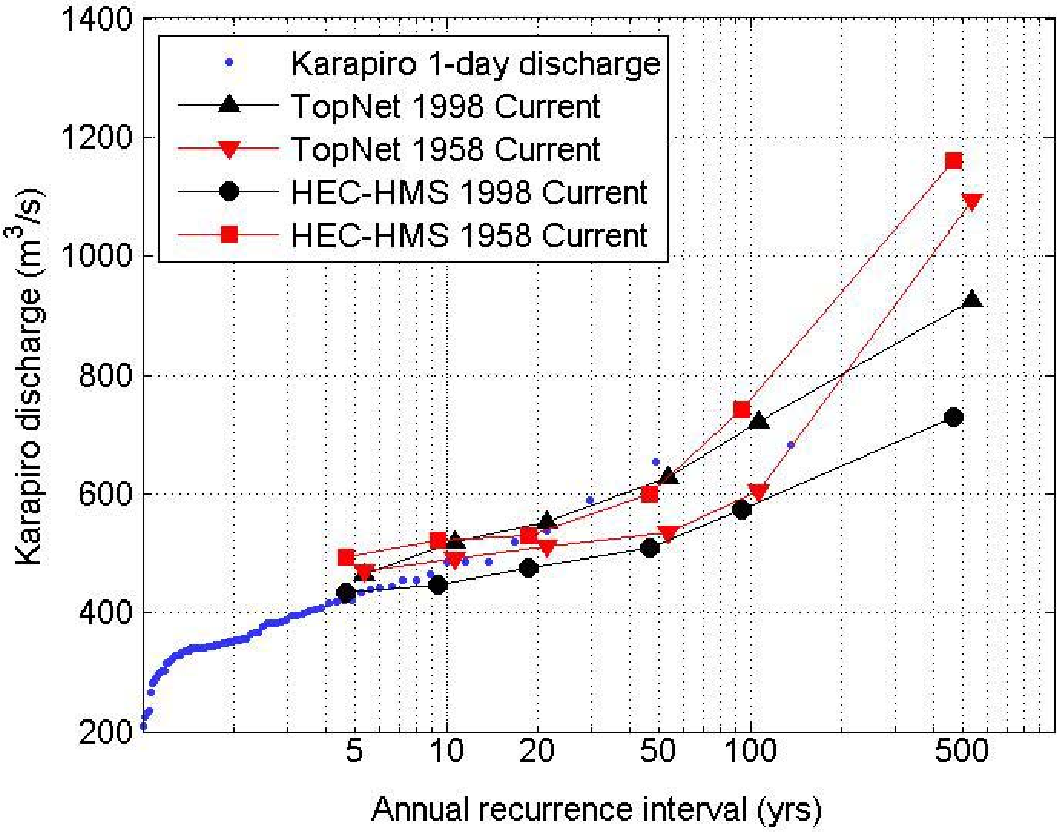


Figure 68: Recorded annual maximum 1 day discharges and associated annual recurrence intervals from Karapiro compared with simulated discharges resulting from HEC-HMS and TopNet simulated inflows for the current land use, and with temporal patterns matching both the 1998 and 1958 storms. TopNet and HEC-HMS results are horizontally offset from the exact ARI for the sake of clarity.

It is important to note the limitations of Figure 68, so that it is not interpreted as a method for selecting preferred models. The measured flows are shown with their correct average recurrence interval (ARI) values, but the ARI values of the modelled floods are not known. The modelled floods have instead been plotted using the nominal ARI values for the rain used in the models. As will be seen in the next section, the same nominal return period has been assigned to different rainfall depths, and different rainfall patterns. Using the ARI of the rainfall to plot the modelled floods is a convenient approximation, but it is a gross simplification. The uncertainty in return period of the modelled floods is more than a factor of two.

In spite of the significant limitations of Figure 68, it is included because it allows a review of the models in the context of the whole-catchment response to a very long time series of observed flood responses.

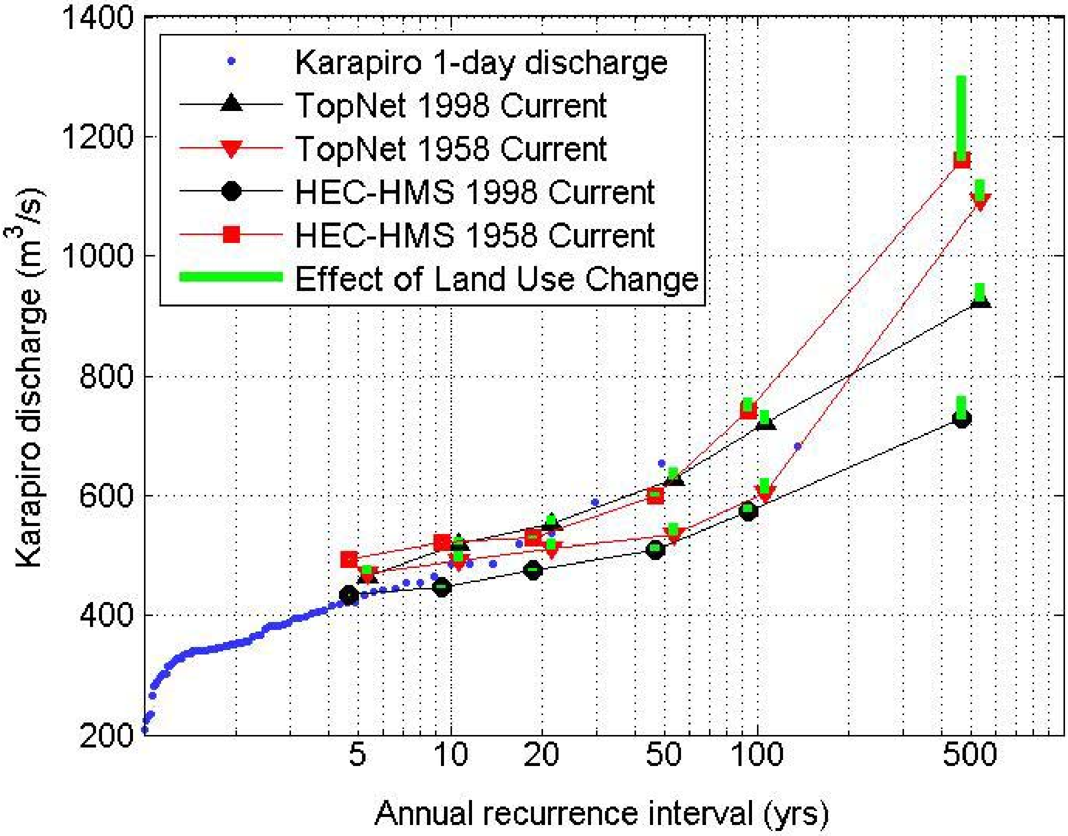


Figure 69: The data and model results as in Figure 68 but with the future land use scenarios added (green bars).

The simulated effects of land use change on Karapiro discharge are shown in Figure 69. Table 17 shows the percentage increases in Karapiro peak discharge due to land use change, for both models and both temporal patterns. Both models predicted that the change in land use would slightly increase (by up to 1%) the magnitude of flood discharges from Karapiro for a rainfall magnitude of 50 years ARI. For smaller rainfall events of up to 20 years ARI, the magnitude of the flood increase was negligible.

Karapiro discharges resulting from the two sets of model inflows began to diverge slightly for large rainfalls (> 50 year ARI), with HEC-HMS increases about double those of TopNet, for the 500-year rainfall.

Taking both models and temporal patterns into consideration, the potential change in land use could increase flood discharges at Karapiro by 1.9% for rainfalls with a 100 year ARI, and 6.5% for rainfalls with a 500 year ARI.

Table 17: Percentage increase in Karapiro peak discharge simulated using HEC-HMS and TOPNET model inflows with future land use scenario and 1998 and 1958 temporal patterns.

Rainfall magnitude	Karapiro (HEC-HMS 1998)	Karapiro (TOPNET 1998)	Karapiro (HEC-HMS 1958)	Karapiro (TOPNET 1958)	Average percent increase
5 year	0.0	0.2	0.0	0.4	**0.1**
10 year	-0.2	0.2	0.0	0.2	**0.1**
20 year	0.0	0.7	0.2	-0.2	**0.3**
50 year	0.0	1.0	0.7	0.2	**0.5**
100 year	0.5	1.7	2.7	1.2	**1.9**
500 year	2.2	1.2	12.1	6.3	**6.5**

9.5 Lower Waikato flooding

The model results presented in the previous section were used in a MIKE11-NAM model of water levels and flows along the lower Waikato River for the different design storms (Joynes 2009).

The 1958 and 1998 rainfall style floods were modelled for the full set of return periods using both TopNet and HEC-HMS hydrological models. A clear difference in flood levels occurs due to the land conversion under the 1958 rainfall pattern. **Table 18** reports the changes in peak flood discharge and peak flood water level at two key sites for the current and converted land-use case, according to the input flows simulated by HEC-HMS and TopNet, and routed through Waikato Flood (see previous section).

It would be prudent to treat the flood predictions stemming from the 500-year storm with caution because of the wide range of predictions from the catchment models. The flows and levels for the 100 year storm event are in accord with the measured data and thus should be reasonable. Due to the nature of the storm and dam operations, the 1998-style events produced very little effect of land cover change at Karapiro (c.f. **Table 13-Table 14**), so only the 1958 storm results are shown in **Table 18**.

Table 18: Effect of land use change on flows and water levels at key locations, based on HEC-HMS and TopNet models for the 1958 storm (from Joynes 2009).

		HEC-HMS				TopNet			
		Return Period (years)							
Location	**Model Chainage**	**20**	**50**	**100**	**500**	**20**	**50**	**100**	**500**
Water Level Differences (m)									
Hamilton	WAIKATO 33806.00	0.02	0.03	0.11	0.53	-0.04	0.04	0.04	0.28
Ngaruawahia	WAIKATO 53730.00	0.00	0.00	0.04	0.27	0.03	0.02	0.03	0.22
Huntly	WAIKATO 67661.00	0.00	0.00	0.04	0.22	0.02	0.02	0.03	0.17
Rangiriri	WAIKATO 84010.00	0.00	0.01	0.03	0.07	0.02	0.01	0.02	0.05
Flow Differences (m^3/s)									
Hamilton	WAIKATO 33566.00	3	5	21	145	-5	7	6	68
Ngaruawahia	WAIKATO 53730.00	-1	1	18	154	9	6	11	132
Huntly	WAIKATO 67661.00	0	1	17	147	8	6	12	115
Rangiriri	WAIKATO 84319.50	0	2	17	52	7	6	12	42

The most significant feature of **Table 18** is that for the 1958 100-yr ARI storm the water level increases due to land use change ranged from 40-110 mm at Hamilton and 30-40 mm at Rangiriri. Results for other locations downstream of Rangiriri and on tributaries are given by Joynes (2009).

For the 1958 500-yr ARI storm, the modelled water level increases due to land use change ranged from 280 mm (TopNet) to 530 mm (HEC-HMS) at Hamilton (Bridge St). For the same storm, the modelled water level increases due to land use change ranged from 170 mm (TopNet) to 210 mm (HEC-HMS) at Huntly. For sites further downstream, the modelled 500 year storms overtopped the stopbanks under both the current and future land uses. None of the stopbanks are designed to provide protection against events of that severity.

It is important to note that we have presented information on the predicted *changes* in flood levels due to land use change, but not the levels themselves. The objective of this project is to estimate changes, rather than estimate design floods. The levels that are predicted using results from the two hydrological models (TopNet and HEC-HMS) are different, as would be expected from the results already presented in Section 7.4 and Section 9.2.

9.6 Summary of Key Modelling Results

From the detailed results above in Section 9.1 to Section 9.5, we now draw together a selection of key results into a single table (Table 19) showing the predicted changes in flood magnitude, for the different locations of interest. For each row of the table, there is a reference to an earlier section of the report, so the sources of the numbers can be traced.

Table 19: Summary of Results on the Predicted Effect of Land Use Change on Flood Magnitude

	Small flood (5-year rainstorm)	**Medium flood (20-year rainstorm)**	**Large flood (100-year rainstorm)**	**Extreme flood (500-year rainstorm)**
Local flooding within Upper Waikato[1] **10-100 km^2 catchment area, 0-80% upstream land use conversion**	Significant increase (5-50%) for streams where most of catchment has land use change	Significant increase (5-50%) for streams where most of catchment has land use change	Very significant increase (more than 50%) for streams where most of catchment has land use change	Very significant increase (more than doubled) for streams where most of catchment has land use change
Upper Waikato[2] Taupo-Karapiro inflow **4405 km^2 area, 542 km^2 land use conversion**	Little or no change	Little or no change	From 2-9% increase in peak flow rate (mean of 4%) From 0-5% increase in 72-h flood volume (average 2%)	From 2-16% increase in peak flow rate (mean of 6%) From 2-10% increase in 72-h flood volume (average 4%)
Upper Waikato[3] Karapiro outflow **7852 km^2 area**	Little or no change	Little or no change	From 0.5-3% increase in peak flow rate (average 2%)	From 1-12% increase in peak flow rate (average 7%)
Waikato River at Hamilton[4] **8230 km^2 area**	Little or no change	Little or no change	0-110 mm water level increase 0-21 m^{3}s^{-1} peak flow increase	0-530 mm water level increase 0-140 m^{3}s^{-1} peak flow increase
Waikato River at Ngaruawahia[4] **11395 km^2 area**	Little or no change	Little or no change	0-40 mm water level increase 0-18 m^{3}s^{-1} peak flow increase	0-270 mm water level increase 0-150 m^{3}s^{-1} peak flow increase
Waikato River at Huntly[4] **12066 km^2 area**	Little or no change	Little or no change	0-40 mm water level increase 0-17 m^{3}s^{-1} peak flow increase	0-220 mm water level increase 0-150 m^{3}s^{-1} peak flow increase
Waikato River at Rangiriri[4] **12420 km^2 area**	Little or no change	Little or no change	0-30 mm water level increase 0-17 m^{3}s^{-1} peak flow increase	Flood exceeds design standards even under current land use; stopbanks overtopped

[1] Sources: Figure 54 Table 10 Figure 55 Figure 56

[2] Sources: Table 11 Table 12

[3] Sources: Table 17

[4] Sources: Table 18

10 Discussion and Interpretation

The results presented above show that the prescribed scenarios of land cover change may have a significant effect on flood flows, depending on sub-catchment characteristics and storm magnitudes. In order to better interpret these results, it is useful to understand why flood responses vary spatially as they do. It is also useful to convey how confident we can be in these results.

10.1 Sub-Catchment Variation of Effects

The TopNet model results above show that the effects of land cover change are not uniform across the Waikato catchment, but are concentrated in two to three sub-catchments, particularly Arapuni and Whakamaru (**Figure 70**, **Table 20**). This is broadly similar to HEC-HMS's results. There are several possible factors that control this spatial variability, and thus can help us understand what factors control the hydrological response to land cover change. Among these are the amount of land cover converted, and the hydrological responsiveness of the soils where the land use change occurs. **Figure 70** depicts these factors alongside both models' simulated changes in peak flow from the 1958 and 1998 events, with a storm ARI of 100 years. These results show no simple relationship – they are particularly variable and suggest multiple factors are jointly at play. To assist interpreting these results, **Figure 71** depicts the spatial distribution of soils and converted area alongside the seven dam sub-catchments.

The first impression is that there is considerable variability for some sub-catchments. This stems from differences in the model and storm characteristics. The small negative changes in peak flow are attributed to changes in the timing and duration of the flood hydrograph. More focused inspection, however, does suggest some controlling factors. Arapuni and Whakamaru exhibit the greatest changes in peak flow, but neither underwent the greatest amount of land cover change, which occurred for Ohakuri. What is unique for Arapuni and Whakamaru is that much of the forest cover change occurred on less permeable, non-pumice soils, in contrast with Ohakuri, in which very little land cover change occurred on non-pumice soils. On the other hand, it appears that catchment area, or any correlate such as slope, does not have a pronounced effect on peak flow changes; large and small catchments alike can exhibit both large and small responses to land cover change.

Results thus suggest that a greater flood response in the region studied will arise from greater cover change, and that flood response would generally be greater still where deforestation occurs on non-pumiceous soils This is consistent with the studies at local scales – both modelling and observational – as outlined in **Section 9.1**.

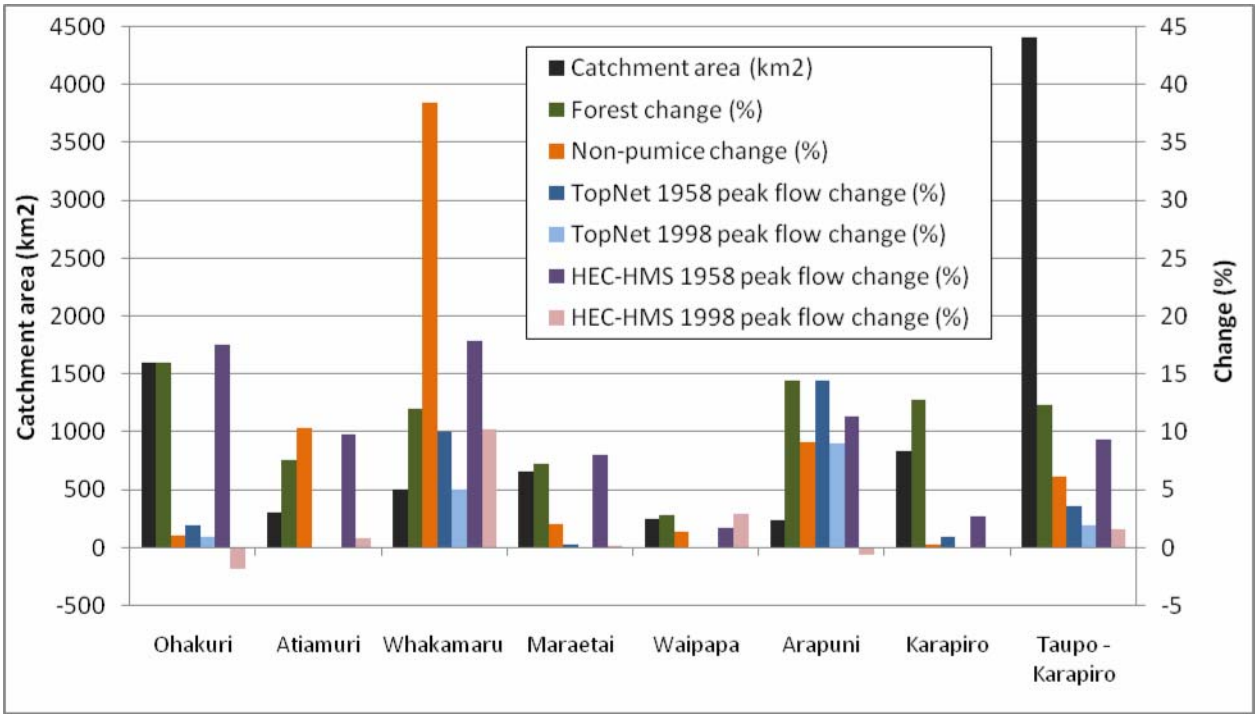


Figure 70: Landscape determinants of, and flooding response to, land cover change based on 100-year ARI storms modelled by TopNet and HEC-HMS. Depicted are: catchment area (black); percent of catchment area converted from forest to pasture (green); percent of converted forest underlain by non-pumice soils (orange); percent change in peak flood flow for 1958 (dark blue); and percent change in peak flood flow for 1998 (light blue). Post-conversion flood peaks are higher where more forest is converted, and where pumice is less extensive, all other factors being equal.

Table 20: Landscape descriptors and models results for the 1958 and 1998 events with the 100-yr storm ARI.

Catchment	Area	Forest area			Non-pumice within converted forest	Peak flow change			
		Current	Converted	Change		TopNet		HEC-HMS	
						1958	1998	1958	1998
	(km²)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
Ohakuri	1602.6	49	33	16	1	2	1	17	-2
Atiamuri	306.8	52	44	8	10	0	0	10	1
Whakamaru	504.6	65	53	12	38	10	6	18	10
Maraetai	661.0	59	52	7	2	0	0	8	0
Waipapa	254.1	72	69	3	1	0	0	2	3
Arapuni	244.2	36	22	14	9	14	10	11	-1
Karapiro	831.9	39	27	13	0	1	0	3	0
Taupo-Karapiro	4405.2	51	39	12	6	4	2	9	2

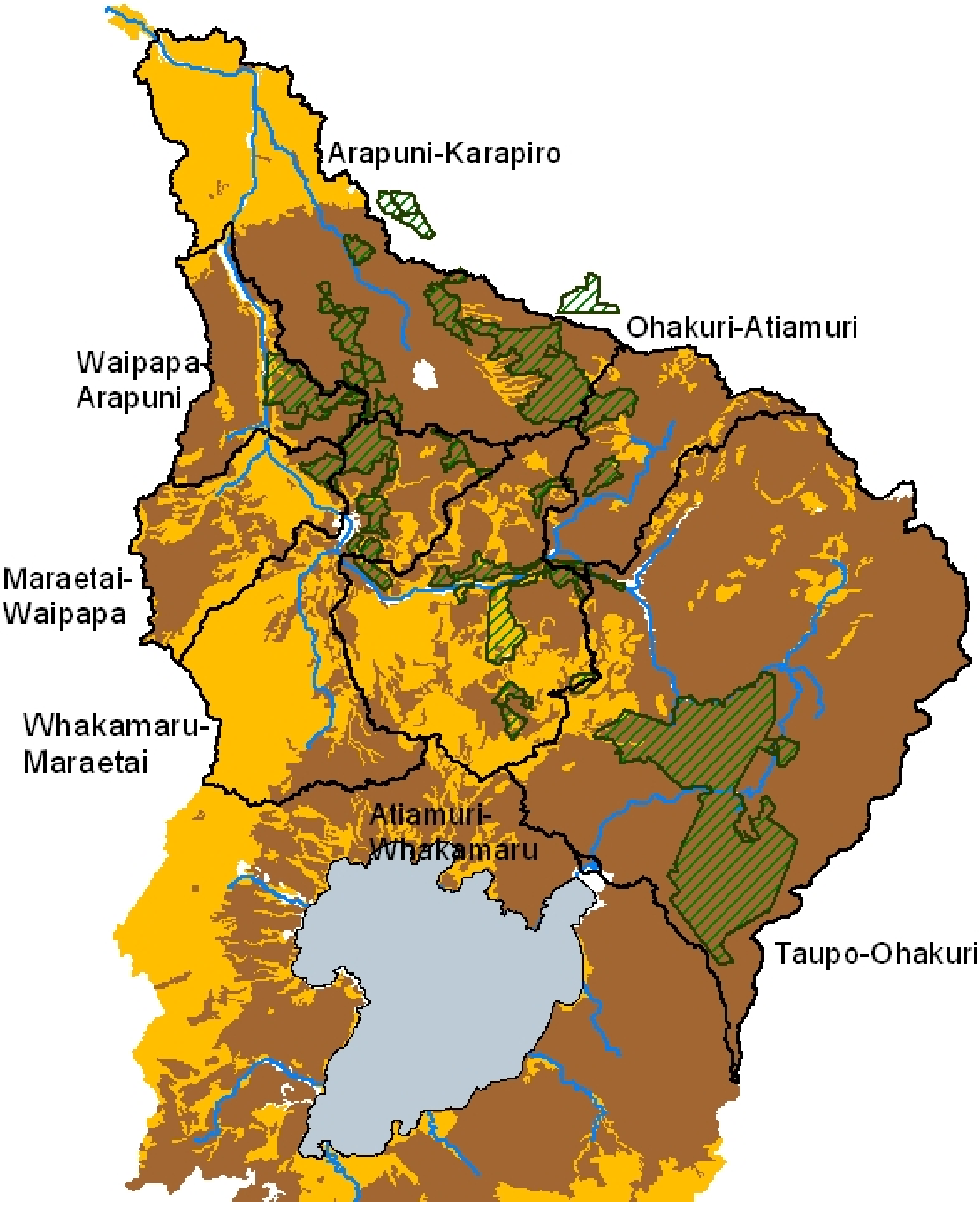


Figure 71: Regional map of general soil type, dam sub-catchment and areas of potential conversion. Dark brown is pumice soils; orange is non-pumice soils. Green striped regions indicate forest areas potentially subject to conversion to pasture.

10.2 Effects of Land Use Change on Flood Volume and Annual Runoff

The impacts of conversion from forest to pastoral agriculture on the volume of water runoff volume are relevant both for understanding flood response and for long term water yield, though the latter is outside the scope of this report. Here we briefly describe the similarities and differences between volume changes for floods and water yield.

This report found that the modelled volume of flood runoff is predicted to stay the same or increase, after conversion from forest to pasture (Table 12). The percentage increases are slightly larger for 100-year and 500-year rainstorms. These increases are mainly because less water infiltrated into the pasture land during the modelled flood, and thus more modelled surface runoff occurred during the flood. The change in modelled evaporation during floods is negligible.

In the long term, conversion from forest to pasture causes significant changes in evaporation, and thus in water runoff (Rowe, 2003). Average annual water yields are expected to increase after conversion to pasture, because of those changes in evaporation (Scotter and Kelliher, 2004). This evaporation effect is mainly due to evaporation of water that is intercepted by the plant canopy; in New Zealand the differences in transpiration between forest and pasture are relatively small by comparison. The changes in flood volume during large rare floods make only a very small contribution to the expected changes in the long term water yield that will result from evaporation changes.

10.3 The Role of Catchment Size and Storm Duration

It is expected that the magnitude of the effect of land use change on flood peaks will be dependent on the intensity of the rainfalls within the storm event. This is because the main effect of land use change is to reduce the infiltration capacity of the soil. As a consequence, large catchments, which are not as susceptible to short high intensity rain storms as are small catchments, are likely to be less effected by land use change. This is borne out in the results shown in Table 19.

The main results of this study are based on 72 hour duration storm events, as this is representative of the range of critical storm durations for the overall catchment. When considering the effects for different catchment scales/different rainfall intensities, two specific cases are discussed, the first for medium scale catchments (~ 100 km^2), and the second for small scales (< 1km^2).

The work reported in Section 9.1.2 on modelling the land use change effects on the Pokaiwhenua Stream catchment at State Highway One (with a catchment area of 105 km^2) for a range of different rainfall intensities and durations, indicates that the increases in peak flows due to land use change are expected to be four to five times greater for the 12 hour storm than for the 72 hour storm.

For assessing effects at very small scales, the data summarised by Rowe (2003) for floods in the Purukohukohu Stream at Puruki is useful (catchment area of 0.34 km^2). Flood peaks appear to have been reduced by around an order of magnitude following planting in forest.

10.4 Uncertainties and Confidence Limits

The calibration and validation sections of this report indicate that the models employed provide useful representations of the hydrological processes at play, though the models are imperfect. The uncertainties stem from many factors, as listed throughout the report, but largely distil down to two: a lack of relevant observational data, and limitations in how the models represent reality.

All models, by their very nature, will have some degree of inaccuracy; they are designed to be simplifications of reality, not perfect replicas. However, by being based on a physical understanding of nature and by being calibrated to observations, they are not completely inaccurate either. Furthermore, just as the models cannot be completely certain, nor can we exactly quantify their degree of uncertainty. They are, in a way, informed judgements, and given the lack of observational data, they are the most informed judgements available. Our confidence in the results should resemble our confidence in the models' abilities to mimic known observations, and is further bolstered if they also mimic one another.

That being said, what is important here is not how certain we are in the effects of storm magnitude *per se*, but how certain we are in the effects of the land use change. The replication of many of the land cover change effects between TopNet and HEC-HMS provides reasonable confidence in the following results:

1. The majority of percentage increases in peak flows due to land use conversion are below 5%;
2. Absolute differences in peak flows increase with increasing storm magnitude; and
3. The sub-catchments that show the greatest change in peak flows are sub-catchments with appreciable land cover change on non-pumice soils (loam or podsol).

One the other hand, differences in modelled results indicate a high degree of uncertainty in the following:

1. The exact magnitude of conversion effects on extreme flood peaks;
2. Whether the percentage change in flood peaks increases with storm magnitude or remains steady; and
3. The exact magnitude of the change in flood stage in the Lower Waikato.

Differences in model results stem from the very nature of the models themselves. Recalling **Section 6.2**, each model represents environmental data and hydrological processes in slightly different ways. Little more can be stated regarding the cause of these differences without a very detailed inter-model comparison, which is beyond the scope of the present study. It is thus expected that the models' results should differ. Indeed, the project was designed so that the results could be different, because it is in the results' convergence that we can have greater confidence.

Another issue that requires consideration is how percentage differences in flood peaks vary as storms magnitudes increase. There is a common expectation that as storm magnitude increases, the effect of land cover differences decreases. The widely-held perception is that extremely large storms can easily saturate the landscape's temporary stores, and convert rainfall efficiently into runoff – any difference in storage due to land cover would be overwhelmed by the rainfall, and the larger the rainstorm, the less would be the effect of the land use change. The rainfall-runoff data reported by Jowett (1999) do not support the idea that large observed storms saturate storage – in the most extreme recorded events, less than 50% of rain becomes runoff, because most of the catchment has permeable soils and very large soil water storage capacity. In addition, there are parts of the catchment for which the channel network is poorly defined, so that if runoff is generated, it is unclear how it will reach the river.

Similarly, most of the model results do not support the view that land use change has less effect in larger storms. TopNet predicts a roughly steady percentage difference, because (i) TopNet's modelled runoff for the Waikato only changes significantly in the 6% of land area where land cover change occurs on non-pumice soils, and (ii) Topnet's prediction of rainfall-runoff processes (i.e., the relative proportions of surface runoff, rapid sub-surface runoff, storage) doesn't change significantly with return period, for a given rainfall pattern.

By contrast, HEC-HMS predicts an increasing percentage difference as rainfall increases, because HEC-HMS predicts that rainfall-runoff processes in pasture catchments change between small events and large events, specifically that infiltration excess is not active in small events on pasture, but is active in large events on pasture. This point is illustrated in more detail in SKM and EW (2009).

It is not possible at this stage to declare which of the two modelled patterns is correct, because of a lack of suitable observational data, but it is certainly reasonable for the model results to differ from conventional understanding because of the very pervious soils in the Waikato. Both models, if run with unrealistically intense rain events, would follow the common expectation that land use change had little impacts on flood peaks for large rainfalls.

The uncertainty ranges presented in Table 19 reflect the range of model results and rainfall inputs chosen. The two models were chosen as two plausible representations of the hydrological conditions of the Waikato catchment, and indeed two of the most plausible representations. This encapsulates the physical representations embodied in the models, the choice of landscape and hydrological data, and the calibrations. The two rainfall inputs were chosen as examples of extreme storms, but with very different storm characteristics – long and steady for the 1998-style event, and short and intense for the 1958-style event. The uncertainty ranges presented in the report thus reflect a combination of uncertainty in our knowledge of hydrological behaviour and of assumed natural variability. The methods we have adopted provide the best available bounds for what could happen.

10.5 Assessment

The authors consider that this report presents a reasonably defensible approach to the estimation of land-use change impacts on floods at the catchment scale of interest, where the salient weaknesses include:

- Variability in the standard of calibration, from poor to good over a range of catchment scales;
- Limitations in the data that confound our ability to parameterise the different models;
- Residual concerns with the model performance that without further investigation might be ascribed to poor conceptualisation, poor parameterisation, or poor quality data;
- The need to adopt a number of simplifying assumptions in the specification of test event inputs which could be improved upon with further effort; and,
- A limited assessment of model sensitivity to different flood producing factors.

Overall, the amount of effort expended on this study to date is considerable and it is considered that the results obtained are largely consistent with physical reasoning.

10.6 Future Data Collection

The recommendations that this report offers are limited to some extent by the data on which they are ultimately based. It is thus further recommended that this report be complemented by continued and targeted data collection. While longer periods of observation are highly valuable, it is particularly important to differentiate the effects of pasture and forest. A modelling approach was in part necessary because flood data on land use impacts at relevant scales were lacking.

The most appropriate monitoring campaign would use a paired catchment basis. This involves the deployment of streamflow and rainfall gauges in coupled catchments that differ only in land cover (i.e., all other climatic and landscape features of the two catchments are very similar), and whose land cover differences are stark. While these paired observations may be made for catchments that already have different land covers, it is especially worthwhile to begin monitoring before land cover conversion takes place, so careful selection of study catchments is needed. It should be appreciated that this monitoring campaign would not yield immediate results. Many years would be required to make statistically robust conclusions. It is thus an investment to inform any adaptive management that may be adopted.

11 Conclusions

Approximately 24% of the existing forested land area within the catchment of the Waikato River between Karapiro and Taupo may be converted from forest to pastoral agriculture in the next 15 years. The potential land use change represents 12% of the total land area of the Taupo to Karapiro catchment. This may lead to increases in flood risk within the Waikato River and its tributaries, extending downstream of Karapiro dam and to the flood protection works of the Lower Waikato Waipa Control Scheme. The present report was commissioned by Environment Waikato to assess the potential effects of the anticipated land cover conversion.

This report synthesises several modelling efforts in order to assess potential changes in both tributary inflows and flood propagation along the Waikato River. The study comprised three steps:

1. Modelling of the flood response of the seven hydrolake sub-catchments, using two separate models;
2. The propagation of the resulting flood responses through the hydrodam system; and
3. Assessment of how these flood pulses affect inundation in the Lower Waikato.

The first step provided the basis for the study. It comprised the use of two distinct catchment hydrology models (TopNet and HEC-HMS) to predict the flood response to storms of different magnitude, with annual return intervals ranging from 5 to 500 years. This range of event sizes enables the study to produce assessments that are relevant to a wide range of possible impacts, ranging from small relatively frequent floods to design and over-design events. These will assist stakeholders in their respective responsibilities for long-term planning. The predictions were made twice, for each model: once for the current land cover, and once for potential future cover following forest-pasture conversion. The differences between the pre- and post-conversion scenarios thus provided an estimate of how the forest conversion might affect flooding, depending on storm magnitude.

The study found that:

- Existing scientific studies within the Waikato catchment on the effects on flood size of conversion from forest to pastoral agriculture indicate that both the rate and total volume of flood runoff increase. The studies were in very small catchments and cannot be extrapolated to large catchments. The magnitude of these observed increases in flood peaks ranged from a factor of two to ten. The explanation given for this change is the reduction in the infiltration capacities of the soil following conversion to pastoral agriculture.

- Significant to very significant increases in peak flow rate for local flooding in small catchments where full conversion is expected.

- While the 72 hour storm simulated is appropriate for defining the effects of land use change over the whole catchment, the effects on the local tributary sub-catchments are larger for storms with shorter durations. To make assessments of impacts on local flooding in specific cases, a range of design storms with different durations need to be considered, to assist in identifying the magnitude of the local effects and appropriate mitigation measures

- At Hamilton, insignificant impacts during small to medium floods, increases of up to 0-110 mm in peak water level for large floods, and increases of 0-530 mm for extreme floods

- From Ngaruawahia to Rangiriri, insignificant impacts during small to medium floods, increases in the peak flood water level of 0-40 mm during large floods, and increases of 0-270 mm in extreme floods;

- Any forecasts for flood changes in extreme events are highly uncertain;

- At a sub-catchment scale, increases in peak flood flow following conversion are more likely to be greater in the following circumstances:

    - Where a greater percentage of total area is converted from forest to pasture; and

    - Where a greater percentage of the converted forest is underlain by loam or podsol soils.

The uncertainty ranges presented in Table 19 and noted above reflect the range of model results and rainfall inputs chosen. The uncertainty ranges presented in the report thus reflect a combination of uncertainty in our knowledge of hydrological behaviour and of assumed natural variability. The methods we have adopted provide the best available bounds for what could happen.

The assumption that land use change will take place on 567 km^2 is a realistic scenario, rather than a precise prediction of what future land use changes will occur. When further information becomes available on actual or planned forest conversion in the catchment, the methods developed here can readily be applied with the new land use information.

Mitigation measures such as flood detention dams can reduce increases in flood size associated with conversion from forest to intensive agriculture, and are being used in the Waikato catchment. The methods used in this study could be extended to include effects of mitigation, if required, but this was outside the scope of the study.

When considering these results it is important to understand that the flooding studied herein were not design floods, and the significance of the forecasted changes has not been assessed in terms of design and policy considerations.

12 References

Bennett, T.H.; and Peters, J.C. (2000). Continuous Soil Moisture Accounting in the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS). In: Proceedings of the 2000 Joint Conference on Water Resources Engineering and the Water Resources Planning and Management, Hyatt Regency Minneapolis, ASCE.

Beven, K.J.; and Kirkby R.J. (1979). A physically based variable contributing area model of basin hydrology. Hydrol Sci Bull 1979:43–69.

Environment Waikato (2007). Hydrological Land Cover Classification – GIS Layer. Data Management Coordinator. Hamilton, Environment Waikato. EWDOCS# 1233221: 8 p.

Fowlds, S. (2007). Effects of Land Use Change on the Flood Hydrology of the Waikato River Catchment Between Karapiro and Taupo. Environment Waikato document 1147112, April 2007, Hamilton.

Goring, D.G. (1994). Kinematic shocks and monoclinal waves in the Waimakariri, a steep, braided, gravel-bed river. In: Proceedings of the International Symposium on waves: Physical and numerical modelling, University of British Columbia, Vancouver, Canada, 1994, p. 336-45.

Henderson, F.M. (1966). Open channel flow. MacMillan, New York. 522 p.

Jackson, R. J. (1973). Catchment hydrology and some of its problems. Proceedings of Soil and Plant Water Symposium, Palmerston North, NZ DSIR Information Series 96: 73-80.

Jackson, R. J. (1999). Hydrology and hydraulics review for the Piako River Scheme differential rating project: Storm runoff from Forest and Pasture. Landcare Research New Zealand Ltd.

Joynes, S.A. (2009). Effects of land use change in the Waikato River catchment between Karapiro and Taupo: Hydrological and hydraulic modelling of the Waikato and Waipa catchments north of Karapiro dam. November 2009. 60 p.

Jowett, I.G. (1999). Maximum Flood Inflow Estimates for Hydroelectric Dams on the Waikato River Volume I. *NIWA Client Report No. MWA80201*. 50 p.

Jowett, I.G. (2009a). Review of Waikato Flood Modelling with Land Use Change. Client Report No. IJC907. December 2009. 17 p.

Jowett, I.G. (2009b). Waikato Flood Routing with Land Use Change. Client Report No. IJC906. December 2009. 30 p.

Mulholland, M. (2006). Effect of land uses change on the flood hydrology of pumice catchments. Environment Waikato document 1080643, February 2006, Hamilton.

Newsome, P.F.J.; Wilde, R.H.; Willoughby, E.J. (2000). Land Resource Information System Spatial Data Layers. *Landcare Research Technical Report No.* 84 p.

Rowe, L. (2003). Land use and water resources: A comparison of streamflow from New Zealand catchments with different vegetation covers. SMF2167: Report No. 6. Landcare Research for the Ministry for the Environment, LC0203/188. 139 p.

Scotter, D.; Kelliher, F. (2004). Evaporation and transpiration. In: Harding, J.; Mosley, M.P.; Pearson, C.P.; Sorrell, B.K. (eds). Freshwaters of New Zealand, pp. 3.1-3.10. New Zealand Hydrological Society and New Zealand Limnological Society, Wellington.

Selby, M.J. (1972). The relationships between land use and erosion in the Central North Island, New Zealand. Journal of Hydrology (NZ) 11:73-85.

Sinclair Knight Merz (2008). Impact of Land Use Change on Floods in the Upper Waikato – Data Collection and Selection of a Second Model. Report prepared for Environment Waikato.

Sinclair Knight Merz and Environment Waikato (2009). Impact of Land Use Change on Floods in the Upper Waikato PHASE 2: MODEL CALIBRATION AND FLOOD HYDROGRAPH GENERATION. Sinclair Knight Merz report to Environment Waikato, Project AE03513.2. Draft C, 7 May 2009.

Tait, A.; Henderson, R.D.; Turner, R.; Zheng, X. (2006). Thin plate smoothing spline interpolation of daily rainfall for New Zealand using a climatological rainfall surface. International Journal of Climatology 26(14): 2097-2115.

Taylor, M.; Mulholland, M.; Thornburrow, D. (2009). Infiltration characteristics of soils under forestry and agriculture in the upper Waikato catchment. Environment Waikato Technical Report No. 2009/18, 28p.

Technical Expert Panel, (2007). Effects of Land Use Change on the Flood Hydrology of the Waikato River Catchment Between Taupo and Karapiro - Specification of Study Programme. Environment Waikato document 1346813, November 2007, Hamilton.

Thompson, C. (2002). High Intensity Design System v 2.0. NIWA. Christchurch.

Tomlinson, A. I. (1978). Storm rainfalls. Journal of Hydrology (NZ) 17(2):57-77.

Woods, R. A.; Schmidt, J.; Collins, D. B. G. (2009), Estimating the Potential Effect of Land Use Change on Waikato Tributary Floods – TopNet Model Development, NIWA Client Report CHC2009-155, October 2009, Christchurch, 78pp.

13 Appendix 1: TEC Member Profiles

Ghassan Basheer BSc. CE (Tech.), HD Urban and Regional Planning

Ghassan is the Technical Services Programme Manager of Environment Waikato's River and Catchment Services Group. He has more than 30 years of experience covering a wide range of civil and water resources engineering fields, of which the last 13 years was within the Waikato Region. His expertise included investigations, design, implementation and maintenance of irrigation, flood control and drainage projects, as well as leading the hydraulic reviews of the major flood schemes in the region.

Ian Jowett B.Sc. (Hons)

Ian has worked for Ministry of Works, Power Division on the derivation and review of design floods for all major New Zealand hydro-electric schemes between 1967 and 1984. He started working on the hydrology of the Waikato River 40 years ago, when he developed the first estimates of probable maximum flood and flood routing procedures for the Waikato hydro-electric dams. Since then, he has been involved various flood studies for hydro-electric dams and reviewed the Waikato flood hydrology in 1999 and flood routing procedures in 2008.

Murray Mulholland BE, ME, MIPENZ, CPEng

Murray Mulholland has over 25 years of experience in river and catchment engineering in the Waikato River Catchment. He has been involved a diverse range of water resources related projects throughout the Waikato including flood control, drainage, water supply and hydrological, and hydraulic investigations.

Rory Nathan BE, DIC, MSci, PhD, FIEAust

Dr Nathan is a Principal with Sinclair Knight Merz. He has around 30 years experience in academic and consulting positions, with specialist expertise in the characterisation of hydrologic risk. He was the senior author of the Australian national guidelines on the estimation of large to extreme floods, and is an Honorary Fellow at both the University of Melbourne and Monash University. He has published around 150 papers in refereed journals and conference proceedings, and has won several national and international awards for his research.

Alan Pattle BE, ME, MIPENZ

Mr Pattle is a Director of Pattle Delamore Partners Ltd and has over 30 years of experience as an environmental engineer in Europe, Asia, the Pacific and New Zealand. He has undertaken a wide range of water resources related projects throughout the Waikato Basin covering irrigation, mining, water supply, wastewater, contaminated sites and landfills.

Jon Williamson B.Sc., M.Sc. (Tech) (Hons).

Jon is Senior Water Resource Specialist with over 14 years professional experience and an Associate of the firm Sinclair Knight Merz. Jon has specialist technical expertise in Hydrogeology and Hydrology, with his key area of interest and speciality being the application of numerical models to natural resource management issues.

Ross Woods B.Sc. (Hons), M.Comm (Hons), PhD

Ross is a Principal Scientist and Group Manager with 23 years professional experience at NIWA and its predecessors. Ross has extensive experience in the development and application of spatially distributed hydrological models, and in the leadership of multi-agency research projects. He is also an active member of the international research community, including leadership of research on classification and similarity within the Prediction in Ungauged Basins programme of the International Association of Hydrological Sciences.

14 Appendix 2: Project Brief

Project Brief

Effects of Land Use Change on the Flood Hydrology of the Waikato River Catchment Between Karapiro and Taupo

1. Background

Increasing pressure is being exerted for conversion of established areas of plantation forest to pastoral farming in the Waikato River Catchment. Such conversion is already well underway in some parts of the catchment.These areas consist of a variety of geological soils, whose hydrological and erosion characteristics vary with changes in land use. In particular the flood hydrology of the pumice soils of the central North Island is known to be particularly sensitive to changes in land use.

Conversion of forested areas to pasture within the Waikato region is currently unregulated by statutory planning instruments and can occur 'as of right'. Currently known areas of forestry conversion are assessed at up to approximately 70,000ha.

2. Aim

This project is aimed at assessing the effect that the anticipated potential changes in land use within the catchment of the Waikato River between Karapiro and Taupo, may have on the flood hydrology of the Waikato River and its tributaries.

In addition it is intended to identify the subsequent effects downstream of Karapiro dam and impacts on the flood protection works of the Lower Waikato Waipa Control Scheme.

A key aspect of the project will involve consultation with key stakeholders and their technical advisors to ensure the outcomes of the technical investigations are based on robust methodology and information, and the results can be used to inform future planning and decision making processes.

3. Objectives

1. To provide a robust assessment of the effect of forestry to pasture conversion on the flood hydrology of the tributary catchments to the Waikato Hydro Lakes covering the spectrum of risk/return period events.

2. To determine how changes in the source hydrology of the tributary catchments are transformed as they pass through the Waikato hydro lake system.

3. Following on from 2 above, determine the expected impacts of the changes in land use on the flood risks in the Lower Waikato River including protection standards for the LWWCS flood protection scheme.

4. To seek input from from a panel of suitably qualified technical experts to ensure that robust methodology and results are achieved, and that key stakeholders support the investigation outcomes. Note: The technical expert panel will include nominees from parties involved in, or potentially significantly effected by, the effects of forest conversion, and also at least one expert independent of the these parties.

5. To consult with a range of key stakeholders, in order that those parties have the opportunity to understand, discuss and input, and support the outcomes of this investigation.

6. Prepare a technical report setting out the methodology and results of the investigation that will inform Council's policy decision making and direction.

4 Project Framework

The project is being undertaken by Environment Waikato for the purposes of establishing a robust understanding of the impact of landuse change on the flood hydrology of the Waikato River system, for input into its future planning and policy decision making, and operational work programmes. Environment Waikato will provide overall leadership and support for the project, and the project ultimately reports to Environment Waikato.

Environment Waikato's Project Watershed Liaison subcommittees, and in particular the Upper Waikato, Middle Waikato, and Lower Waikato Subcommittees, also have a significant interest and responsibility for river and catchment management in this area. The project will report through these subcommittees to Council. The subcommittees have broad representation across key stakeholders and landowners in these areas.

Within this overall framework, the project requires effective project oversight and leadership, project management, appropriate technical and expert input, and liaison with key stakeholders. To achieve these ends, a project structure including several key working groups are proposed as outlined below.

4.1 Project Control Group

A Project Control Group has been set up to provide oversight and recommendations on the scope, direction, communication, and delivery of the project. Membership will include staff from Environment Waikato (Project sponsors and project managers), Upper river representation, Middle river representation, Lower river representation, and Mighty River Power (hydro system). Appointments for the Upper/Middle/Lower river representatives were made in consultation with the three Project Watershed liaison subcommittee chairs (Upper/Middle/Lower). The membership of the PCG is shown in section 4.4 below.

4.2 Technical Expert Panel

It is proposed to establish a technical expert panel to provide input and assist the implementation of the technical investigation, including assisting in confirmation of:

- The appropriate scope of the project.
- The approach taken and methodology followed in the investigation.
- The appropriateness of any assumptions and qualifications associated with the results.

Provisionally, the panel is proposed to include technical expert advisors from Environment Waikato, Mighty River Power, major land developers, and independent expert input (such as from NIWA).. This panel needs to be able to provide expert advice and contribute effectively and objectively to the investigation.

4.3 Key Stakeholders

The focus of this Project is a technical investigation of the flood hydrology of a significant part of the Waikato catchment and the impact of landuse change on this flood hydrology. The Project Control Group and technical expert panel is expected to be the primary groupings to guide the project, and ensure a robust understanding and outcome is achieved.

There are also a number of key stakeholders with a significant interest and/or involvement in the project and its outcomes. It is proposed that a liaison forum of identified key stakeholders be established, to enable development of a collective understanding of the Project and its subsequent outcomes, an open sharing of relevant information and issues, and to enable key stakeholders to be kept informed of progress. Identified key stakeholders include the following:

- Territorial Local Authorities
- Carter Holt Harvey
- Wairakei Pastoral Ltd
- Mighty River Power
- Relevant Environment Waikato Liaison Subcommittees
- Federated Farmers
- Iwi

4.4 Project Structure and Resources

Project Sponsor

- Scott Fowlds

Project Control Group

- Scott Fowlds
- Dennis Crequer
- Ghassan Basheer
- V Clark (Deputy Chair - Upper Waikato CLSC)
- S Kneebone (Chair - Middle Waikato CLSC)
- M Lumsden (Chair Lower Waikato CLSC)
- Leroy Leach (MRP)

Project Management

- Ghassan Basheer (Project manager and coordinator)
- Murray Mulholland.(Technical programme manager)

Technical Expert Panel

- A panel of five to six people with expertise in flood hydrology, the hydrological effect of land use changes, and hydrological modelling.

Investigations

- Murray Mulholland other internal resources and external contractors as required.

Data Supply and Communications

- Environmental Monitoring Programme
- Communications Programme

Potential Scope of Investigation

The scope of the investigation is to be confirmed by Environment Waikato, in conjunction with the Project Control Group, and Technical Expert Panel. It is designed to assess the hydrological implications of proposed forest to pasture conversions on flood flows within the Waikato River catchment between Karapiro and Taupo. The following are a preliminary identification of the investigative tasks which will be carried out to undertake the project. It is proposed that the Technical Expert Panel will consider each task and provide recommendations on the methodology, assumptions and results to ensure a robust outcome is achieved at the end of the investigation.

Investigation Outline

a) Finalise one or more scenarios defining the spatial and temporal extent of the forest to pasture conversions based on known and expected conversion areas within the Upper/Middle Waikato Zone (The Waikato River Catchment between Lake Taupo and Karapiro) over the next 25 years..

b) Define the geological make-up of the Waikato River Catchment and interpret rainfall-runoff relationships with respect to the geological, slope and land use differences to show potential effects of geology and land use on the relationships.

c) Recalculate the hydrological analyses for each of the sub-catchments entering the hydro-lakes to estimate current and expected future flood inflow hydrographs for a range of return periods.

d) Review the findings of the MRP study, “Forest Conversion - Flow Effects on Hydraulic Structures”, currently underway.

e) Route the flood inflow hydrographs through each of the hydro lakes based on defined lake levels, to obtain outflows from Lake Karapiro for a range of return periods under both current and expected future scenarios.

f) Route the flow hydrographs obtained in (e) to the Lower Waikato, using a model agreed to by the Technical Expert Panel, for the Waikato River from Karapiro to Port Waikato. This will require estimates, agreed to by the Technical Expert Panel, of inflows hydrographs from the Waipa and other significant tributaries downstream of Karapiro.

g) Examine the impacts of increased flows in the lower Waikato on design standards for the Lower Waikato Scheme stopbanks and structures, and Lower Waikato river system.

Programme

A target programme for the project is set out in the attached Gantt Chart. Key milestones are identified as follows:

Milestone	Date
1) Confirm Project Brief	April 07
2) Establish project control group, and confirm scope and objectives of project	May 07
3) Establish technical expert panel and prepare scope of investigation	June 07
4) Final confirmation of scope	July 07
5) Technical Investigations a) Spatial and temporal extent of forest to pasture conversions b) Review of MRP study of effects on extreme events c) Source hydrology and inflows to hydro system d) Hydro system management and routing e) Kapapiro to Lower Waikato Hydraulic Modelling f) Lower Waikato Scheme Impacts g) Local (on site) effects	July 07 to Dec 07
6) Draft Report	Dec 07
7) Peer Review of Draft Report	Jan 08
8) Final Report	March 08

Reporting

Reporting will be monthly from the Project Manager to the Project Control Group.

Briefings to Environment Waikato and key stakeholders at commencement and end of project, and at key stages during the project will occur as appropriate.

Project Costs

To be confirmed following confirmation of project scope and investigation programme.

Relationship to Other Projects

1) This project has synergies with and important implications for the Waikato River above Karapiro Policy Review Project.

15 Appendix 3: Study Specification

Effects of Land Use Change on the Flood Hydrology of the Waikato River Catchment Between Taupo and Karapiro

Specification of Study Programme for modification/approval by Expert Panel

Final Version by Ross Woods, 16 November 2007, in response to Panel comments

INTRODUCTION

The overall goal of the study programme is to predict and evaluate changes in flood magnitude for the Waikato River and its tributaries, as a result of forest-to-pasture land use conversion in the Waikato River catchment between Taupo and Karapiro.

Specifically, to estimate, where identified areas of land currently in forestry are converted to pasture, the change in flood hydrology for small, large and extreme floods (peak magnitudes of average recurrence interval approximately 5 years, 20 years and 100 years, as well as the 500 year Flood, at 3 spatial scales:

(i) Upper Waikato hydropower lakes

(ii) lower Waikato flood protection works

(iii) local flooding within Upper Waikato

OVERVIEW OF TECHNICAL PROJECTS

1 Summarise data and international research on floods and land use.

2 Build models (use more than one) that can predict how floods on middle Waikato tributaries will change with land use change

3 Apply models to predict impacts on flood hydrology:

3.a Apply both a statistical model and a rainfall-runoff model to estimate impact on local flooding.

3.b Route small and large floods along the Upper Waikato under present and future land use scenarios, and combine with Waipa flows to run hydraulic model of lower Waikato.

3.c Route extreme floods along middle Waikato under present and future land use scenarios.

4 Write final technical report

PROJECT STEPS AND METHODS:

1 Summarise hydrometeorological and land-use data

1.a Compile and summarise data on historical floods in the Upper Waikato catchments.

The work on compiling and summarising floods has been done in a flood frequency report (Mulholland 2006), although there is not a comprehensive data set for flood volumes - this needs to be added to the dataset, and also the corresponding rainfall depths at raingauges and as interpolated from the raingauge network. Much of the required data might already be available from Mighty River Power. If not, then the recommended provider for that data is Roddy Henderson of NIWA, who has extensive relevant experience and data processing scripts for these data sets.

The end result is a table of flood data, to be used for further analysis

1.b Create a time series of land use data

Digital mapped land use and land cover information is available from at least 3 sources: NZLRI (~mid-1970s), LCDB1 (~mid-1990s) and LCDB2 (~mid-2000s) (LCDB=Land Cover Data Base).

Land cover data is important because it will be used to provide calibration for models that seek to predict land use change effects. If the %forest data is not reliable, then the model predictions of floods for the future land use scenarios are much less reliable.

(i) Assess feasibility of using aerial photography to validate the 3 sets of digital mapped data. Specifically, identify availability of photography over Upper Waikato in 1970s, 1990s, and 2000s. Estimate the cost per 10 sq km of doing a comparison of % of photograph in forest vs % of digital map in forest. If at least 10 comparison can be done for any one of the three maps, then proceed, and document the inferred uncertainty in mapped %forest area that arises from finding disagreements between the maps and the photos.

(ii) Compare the values of %forest for relevant gauged catchments in the Upper Waikato, across the 3 mapped data sources. If change in %forest over time is significant (e.g. >20% of catchment area) for a gauged catchment, then attempt to verify from aerial photography.

(iii) Summarise the decade-to-decade changes for all gauged catchments. For catchments where no change in forest cover has taken place, this will also provide an indication of the "noise" in the mapped data. The decade-to-decade variability will also help clarify whether it is reasonable to assume a single %forest over the historical flood record for a given catchment. If there is evidence of significant change in % forest over the decades, then attempt to estimate %forest in the mid-1960s and mid-1980s for each gauged catchment, using aerial photography, or records of plantation forest area from the forest industry or Statistics New Zealand or MAF. By having reliable land cover data for the 1960s and 1980s, it will be possible to do a comprehensive trend analysis listed in 1.c below.

This land cover verification work is being undertaken by Environment Waikato.

1.c Statistical correlation between flood size and vegetation cover

If there is very little evidence from Step 1b of significant decadal change in %forest cover for some gauged catchments, then carry out a correlation analysis to test for an association between flood size (e.g. Mean Annual Flood peak, mean annual flood runoff volume) for each catchment and %forest for each catchment. Check for possible confounding influences (e.g. other spatial differences such as soil type or rainfall, independent of forest area differences) that might have had this impact, especially if the sample size is small. Possible provider: McKerchar or Mulholland

If there is evidence from Step 1b of significant decadal change in %forest for some gauged catchments, then carry out a correlation analysis for each gauged catchment, to test for an association between flood size (both peak and runoff depth) in each decade (independent of trends in rainfall) and % forest in that decade. Check for possible confounding influences (e.g. other temporal changes such as changes in farm drainage which occurred independently of forest area changes) that might have had this impact, especially if the sample size is small. Possible provider: McKerchar or Mulholland

1.d Data on soil properties

Obtain measured infiltration data for soils in the study area, using a stratified sampling approach which compares infiltration for paired sites with the same soil type but different land uses (forest and dairy pasture).

Quantify and summarise the infiltration rates so that this information can be used in process-based hydrological models outlined in section 2 of this document.

1.e Summarise links between floods and land use.

Assess the predictive power of results from studies above on links between floods and land use.

Review existing scientific literature and knowledge of relevant hydrological processes.

If there is no reliable empirical evidence to indicate that flood magnitudes on Upper Waikato catchments have been affected by land use change, then use the literature review to define likely range of impacts of forest removal on flood magnitude.

Use the review information to check results (decade-to-decade and catchment-to-catchment) of model studies in Step 2 below. Possible provider: McKerchar or Mulholland

2 Build models (use more than one) that can predict how floods will change with land use change on Upper Waikato tributaries.

To assess changes in local flooding and provide suitable input to flood routing models on the Upper Waikato, we need to predict the impacts of vegetation change on the flood hydrology of tributary catchments. Given the relatively underdeveloped science of impacts of landuse change on floods, it is prudent to use at least two modelling approaches.

2.a Assemble data for models

Assemble continuous hourly rainfall and river flow data for all relevant catchments. Also assemble the daily rainfall data, for use in estimating event rainfall totals. For the event-based models, select flood events of interest (e.g. >2 year average recurrence interval). Possible provider: Mulholland or Henderson or SKM

2.b Calibrate models

Calibrate at least one event-based model (e.g. the modified SCS+unit hydrograph model of Mulholland (2006), the runoff-coefficient+unit hydrograph model of Jowett (1999), or RORB, e.g. used by SKM), as well as a continuous simulation model (e.g. Topnet, by NIWA). All models need to produce hydrographs representing ungauged and gauged catchmentcatchments, and need to be capable of simulating the effects on floods of a change of vegetation.

With each model, calibrate the model parameters to multiple catchments at once in a way that reveals any impacts of vegetation change. Calibration strategies include: separating catchments into groups with similar %forest, and subdividing flow times series into periods with relatively constant %forest. Model calibration should address uncertainty in parameter estimates, so that predictions include assessment of uncertainty. An assessment of the uncertainty associated with extrapolation to ungauged catchments should also be made.

Model validation should be carried out by comparing predictions and measurements of (i) tributary flood hydrographs (ii) tributary flood event runoff depths (iii) Taupo-Karapiro flood event runoff depths. A model which is unable to reproduce observed effects of land cover change on flood hydrology should not be used in later stages of the project. If models are spatially distributed (e.g. RORB, Topnet) and flow data are available for subcatchments of main tributaries, include the subcatchments in calibration/validation process, to provide more reliable results for local effects (Step 5).

2.c Compute flood hydrographs for current conditions

Compute flood hydrographs for agreed design events for small, large and extreme floods (i.e., average recurrence interval approximately 5 years, 20 years and 100 years, and PMF), using each model, under current land use. It is not easy to assign a specific return period to the combination of flood-producing circumstances used in making a model estimate of an extreme flood. However, the goal of this study is to determine land use change impacts on floods of a given magnitude, rather than to develop design floods for a specific need. The determination of design events to meet particular engineering objectives is outside the scope of this study. This study will however provide information and models that are relevant to future design studies on the Waikato River.

2.d Checkpoint: Are the models developed above suitable for the purpose of this study?

Assess whether the models developed above are suitable for making estimates of land use change on flood hydrology. At this point it may be necessary to modify the methods in Section 3 below, to accommodate new knowledge during the project.

3 Apply models to predict impacts on flood hydrology

3.a Apply both a statistical model and a rainfall-runoff model to estimate impact on local flooding within Upper Waikato.

3.a.i Statistical model of local effects

From the correlation analysis in steps 1.c, 1.d, 1.f, develop a statistical model of the relationship between %forest and flood peak magnitude, for Upper Waikato tributaries. Generate small and large flood peaks for all subcatchments, under current and future land use scenarios. Compare current and future predictions to estimate magnitude of change. Provider: Mulholland and/or McKerchar

3.a.ii Rainfall-runoff model of local effects

Using any of the rainfall-runoff models from Step 2 which have subcatchment flows (e.g. RORB, Topnet), generate small and large flood hydrographs for all subcatchments, under current and future land use scenarios. Compare current and future predictions to estimate magnitude of change. Note that some subcatchments may experience much larger changes in %forest than the gauged catchments, and that caution is needed in extrapolating in this way. Provider: those from Step 2b

3.a.iii Prediction of local effects

Predict the increase in flood magnitude for a selection of Upper Waikato streams draining at least 10 sq km (this size to be based on the smallest area of the catchments in the calibration data set), by synthesising the results from *3a.i* and *3a.ii*, and resolving any inconsistencies. Provider: Mulholland, McKerchar and Provider: those from Step 2b

3.b Route 5-100 year floods along Waikato River

Route small and large floods along middle Waikato under present and future land use scenarios, and combine with Waipa flows to run hydraulic model of Lower Waikato. Possible providers: MRP and Environment Waikato.

3.b.i Middle Waikato

Use a model of Upper Waikato reservoirs based on flood rules (Mulholland 2007) and sound hydro baselines to route tributary inflow hydrographs for events of each size, under current and future land use scenarios. Use a Taupo inflow series which is consistent with the return period of the event being considered. Output is flood hydrograph at Karapiro for each return period. Possible providers: Environment Waikato with assistance from MRP (via Jowett), or SKM using RORB. A first pass at this work has been drafted by Mulholland (2007) to provide a rough order of change under a 1 in 100 year event. Specification to be developed by TEP and confirmed by the PCG for implementation of actual routing study

Lower Waikato

Run Environment Waikato's hydraulic model of the Lower Waikato to determine effect of change in land use on flood risk. As described in 3.a where possible use recorded flood events on the Waipa River as input to the hydraulic model, along with the modelled Karapiro flows for current and future land use scenarios. Summarise the change in Lower

Waikato flood risk by comparing simulation results for current and future land use scenarios. Possible provider: EW hydraulic modeller. Specification to be developed by TEP and confirmed by the PCG for implementation of actual routing study

3.c Route PMF floods along Upper Waikato

Route PMF floods along Upper Waikato under present and future land use scenarios. Specification to be developed by TEP and confirmed by the PCG for implementation of actual routing study

Rainfall for PMF

Use previous PMF studies (Jowett 1999; Jowett, Thompson et al. 1999) to specify spatial rainfall patterns for PMF events. Provider: Jowett?

3.c.i Run the rainfall-runoff models to get tributary inflow for PMF

Run the calibrated rainfall-runoff models from Step 2.b with the spatial rainfall patterns from the previous step, to simulate tributary PMF inflow hydrographs for all Upper Waikato tributaries. Providers: those from Step 2b

3.c.ii Route tributary inflow along Waikato River

Use the same routing model in item 3.b above to route Taupo outflows (specified as per previous studies) and modelled Upper Waikato tributary flows down to Karapiro.

Provider: Environment Waikato with assistance from MRP (via Jowett). A first pass at this work is reported in Mulholland (2007).

Write final technical report

Summarise results of Steps 1- 3, including uncertainty, and indicate some potential implications for Lower Waikato flood risk, and local flooding risk.

3.d Write first draft

3.e Review comments by panel

3.f Write final draft

3.g Final review comments by panel

3.h Consultation

3.i Finalised report

Lead Provider: Woods (NIWA)

References

Jowett, I. G. (1999). Maximum Flood Inflow Estimates for Hydroelectric Dams on the Waikato River Volume I. NIWA Client Report. Hamilton, NIWA. **MWA80201:** 50.

Jowett, I. G., S. M. Thompson, et al. (1999). Supplementary Information for Maximum Flood Inflow Estimates to Hydroelectric Dams on the Waikato River Volume II. NIWA Client Report. Hamilton, NIWA. **MWA80201:** 50.

Mulholland, M. (2006). The effect of land use change on the flood hydrology of pumice catchments. Hamilton, Environment Waikato**:** 49.

Mulholland, M. (2007). Upper Waikato River Catchment: Effect of Land Use Changes on Flood Hydrology:- Hydro Lake Flood Routing - DRAFT. Hamilton, Environment Waikato**:** 28.

Thompson, C. (2002). High Intensity Design System v 2.0. NIWA. Christchurch.

TIMETABLE

Task	#######	30-Oct-07	#######	#######	31-Jan-07	#######	#######
1 Summarise data on floods and land use.							
1.a Compile and summarise data on floods							
1.b Create a time series of land use data	Start		End				
1.c Statistical correlation between flood size and vegetation cover							
1.d Data on soil properties	Start		End				
1.e Summarise links between floods and land use.				End			
2 Build models for how tributary floods will change with land use change							
2.a Assemble data for models							
2.b Calibrate models			End				
2.c Compute flood hydrographs				End			
3 Apply models to predict impacts on flood hydrology:							
3.a Apply models to estimate impact on local flooding					End		
3.a.i Statistical model of local effects					End		
3.a.ii Rainfall-runoff model of local effects					End		
3.a.iii Prediction of local effects					End		
3.b Route 5-100 year floods along Waikato River					End		
3.b.i Middle Waikato					End		
3.b.ii Lower Waikato					End		
3.c Route PMF floods along middle Waikato					End		
3.c.i Rainfall for PMF					End		
3.c.ii Run the rainfall-runoff models to get PMF tributary inflow					End		
3.c.iii Route tributary inflow along Waikato River					End		
4. Write summary report							
4.a Write first draft						Start & End	
4.b Review comments by panel						Start & End	
4.c Write final draft						Start & End	
4.d Final review comments by panel						Start & End	
4.e Finalised report						Start & End	