Estimating the potential effect of land use change on Waikato tributary floods – TopNet model development

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Executive Summary

This report documents the development and application of a hydrology simulation model for tributaries of the middle Waikato catchment. The purpose of the model is to estimate the potential effect of land use change on flood magnitude. The TopNet modelling system is used to simulate hourly flow rates at several hundred locations on tributaries throughout the middle Waikato catchment, that is, downstream of Lake Taupo and upstream of Lake Karapiro.

This modelling approach is one of two being undertaken under the leadership of a Technical Expert Panel assembled by Environment Waikato. The panel's Study Specification has been approved by a Project Control Group which provides guidance for the project. The work in this report contributes to item 2 of the Study Specification "Build models (use more than one) that can predict how floods will change with land use change on Upper Waikato tributaries".

Data have been assembled for a wide range of catchment properties. These include mapped spatial data such as catchment boundaries, river networks, soils and vegetation, as well as time-varying data such as rainfall, other climate data and streamflow.

A simulation modelling approach is used for this problem, because direct inferences from measured data are not practical (see separate report on land cover data). The areas that have been identified as likely candidates for conversion from forest to pasture lie mainly outside the network of gauged catchments in the study area. Previous studies of observed floods from the gauged catchments have shown that the flood response varies significantly within the study area. From this it is reasonable to expect the change in flood response after forest removal could also vary. Therefore, a key technical challenge is to identify the previously unknown factors that control the measured place-to-place variation in flood response. With that knowledge, more robust projections can be made for the impacts of land use change on floods than would otherwise be possible.

The methodology used in this report is to develop a computer model that adequately simulates flood response throughout the study area. This model is used to produce a control simulation, i.e., characterising present-day catchment response. It includes the current place-to-place variations in rainfall, soils and vegetation. The model is then altered to represent the projected future changes from forest to pasture land use, and the model is run again, with all other factors (including climate) unchanged. The modelling has been based on a conversion of about 56,000 ha of forested area. The differences between the floods generated by the two model runs are interpreted as representing the effects of the projected vegetation change.

An adequate model calibration was achieved, striking a balance between realism and minimal distortion of parameter vales. Some catchments are poorly simulated by the resulting model, and some are reasonably well simulated. The purpose of the model and the degree of extrapolation must be borne in mind when assessing the acceptability of the calibration. This remains a topic for the Technical Expert Panel to assess.

Increases in tributary flood peaks of the order 10-15% were simulated in the more sensitive sub-catchments, where conversion was extensive and there was a greater proportion of lower-permeability soils, namely Whakamaru and Arapuni. These tributary-scale effects were damped when integrated over the larger basin, as other catchments showed no appreciable flow responses. Thus differences in peak flows showed greater sensitivity to landscape characteristics than to the magnitude of the storm. Those flow changes that did occur were focussed, percentage-wise on the rising limb of the flood hydrograph. Total flood inflow volumes to the Taupo-Karapiro catchment were predicted to increase by up to 3% as a consequence of land use change. Local-scale flood peaks within the tributary catchments were predicted to increase by up to 5% for small rain events, and by 5-100% for large rain events.

This study does not draw any conclusions about the impact of land use change on flood magnitude on the main-stem of the Waikato River. This study only addresses changes in tributary flows: the results of this modelling study will be used as input to a separate flood routing study which will quantify those changes.

1. Introduction

This report documents the development and application of a hydrology simulation model for tributaries of the middle Waikato catchment. The purpose of the model is to estimate the potential effect of land use change on flood magnitude. The TopNet modelling system is used to simulate hourly flow rates at several hundred locations on tributaries throughout the middle Waikato catchment, that is, downstream of Lake Taupo and upstream of Lake Karapiro.

This modelling approach is one of two being undertaken under the leadership of a Technical Expert Panel assembled by Environment Waikato. The panel's Study Specification has been approved by a Project Control Group which provides guidance for the project. The work in this report contributes to item 2 of the Study Specification "Build models (use more than one) that can predict how floods will change with land use change on Upper Waikato tributaries".

A companion report (Jowett 2009) provides a review of some aspects of the performance of the two modelling approaches used for tributary catchments.

An estimate of the impacts of these potential land use changes on flood magnitudes for the mainstem of the Waikato River is outside the scope of this report, and is being addressed separately in a companion project, to which this report contributes.

2. TopNet hydrological model

TopNet is a catchment model designed for continuous simulation of catchment water balance and river flow. It can provide flow predictions at many locations in a catchment, and is used for operational flood forecasting (Bandaragoda et al. 2004, Clark et al. 2008, Ibbitt et al. 2001), as well as for water resource modelling (Henderson et al. 2007). The same modelling system can also be used to simulate the potential effects of changes in vegetation and climate (Woods et al. 2008).

The model inputs are rainfall and temperature time series (e.g. at hourly timesteps, with rain from one or more locations), 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). The development of model parameter files is done using TauDEM, a suite of computer software developed by Professor David Tarboton at Utah State University, in collaboration with NIWA (http://moose.cee.usu.edu/taudem/taudem.html). TopNet has been used with rain input from raingauges, weather radar, and atmospheric models. The TauDEM software automatically identifies sub-watersheds and river networks from digital elevation data, and automatically generates the TopNet model parameter file.

TopNet models a catchment as a collection of sub-watersheds, linked by a branched river network (

Figure 1). Flow is routed through the river network using kinematic waves using the shock-fitting technique of Goring (1994). We assume the channel is hydraulically wide, and that the water level depth *h* is a good approximation for the area of the channel. The discharge per unit channel width, *q*, is given by Manning's stage-discharge relationship.

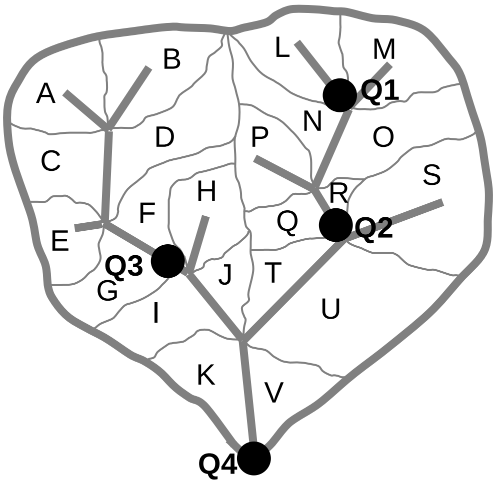


Figure 1: Schematic of TopNet model: Each letter indicates a sub-catchment, and the symbols Q1 – Q4 indicate the location of flow recording sites.

Each sub-watershed is modelled (Figure 2) using an adaptation of Topmodel (after Beven and Kirkby, 1979). Precipitation on each sub-watershed is modelled as either rain or snow, depending on the air temperature. Snow is added to a snowpack for each sub-watershed, and is later melted when air temperature is warm enough (degree-day method). Each sub-watershed has 4 stores: the snow store, a plant canopy store, a root-zone store and a saturated zone store. 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 water storage equals its capacity (partial area or 'Dunne runoff', indicated by SATXS)
- rain rate exceeds infiltration rate ('Hortonian runoff', indicated by INFXS)
- saturated zone discharge into stream (both subsurface storm runoff and baseflow, indicated by SSF)

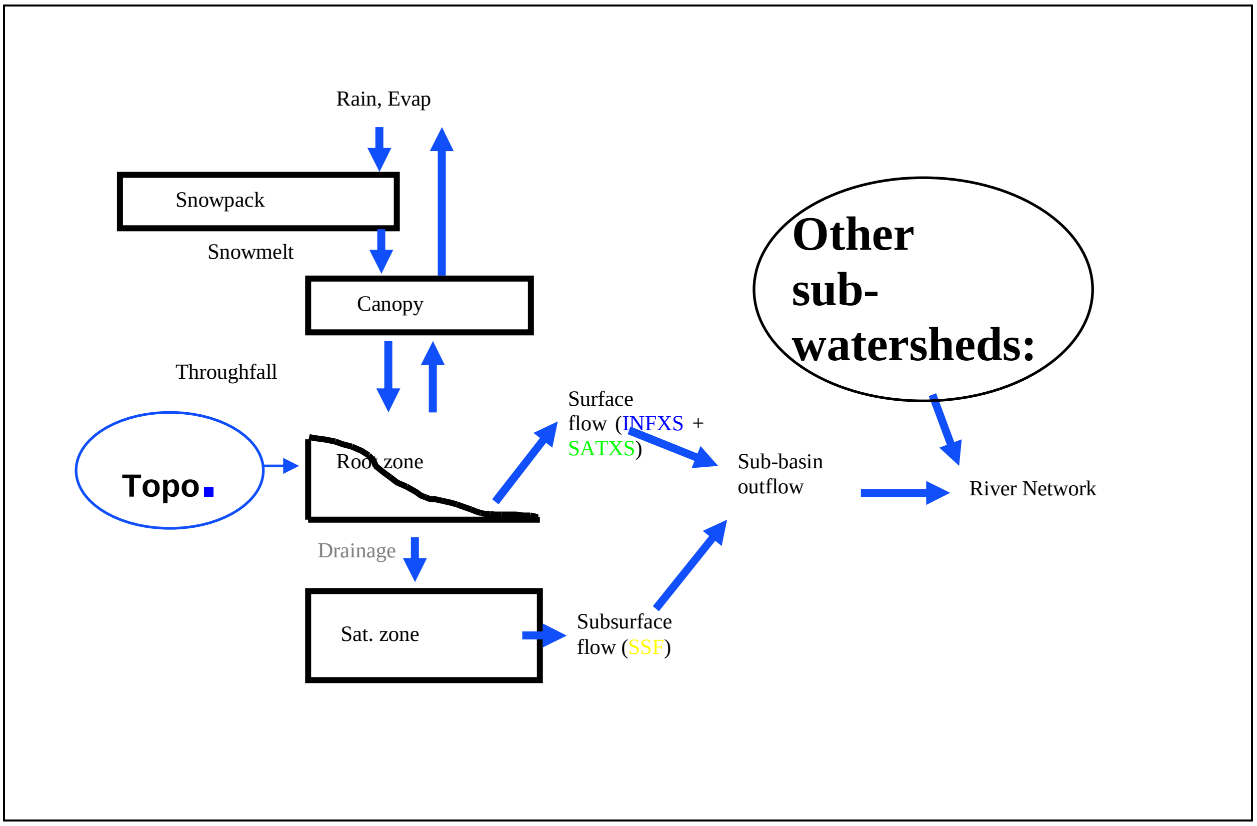


Figure 2: **Overview of TopNet model structure, showing the snowpack, canopy, root zone, saturated zone and river network components of the model. Arrows indicate flows of water from one model component to another. The abbreviations INFXS, SATXS and SSF (and associated colour-coding) are used later in the report.**

TopNet assumes that available soil water storage can vary within a sub-watershed because of topographic effects - valley bottoms and flat places are wetter than ridges. TopNet uses a topographic index to measure the propensity for soil wetness at each location in a sub-watershed. 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. 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. Table 1 and Table 2 provide a full list of model parameters and the data sources used to estimate them.

Table 1: Parameters of the basin model component of TopNet.

Parameter	Symbol [Unit]	Description	Data source
*Albedo	α		EW land cover map for 2001/02
Atmospheric lapse rate	L [K m^{-1}]		Uniform
Wetness index (frequency distribution)	w_i		REC[1]
Stream distance (frequency distribution)	d_i		REC[1]
Saturated store sensitivity	f [m^{-1}]	Describes exponential decrease of conductivity with depth	Correlated with macroporosity
*Saturated hydraulic conductivity at ground surface	K_o [m s^{-1}]	Controls infiltration at surface	EW experiments, mapped by vegetation type
Saturated hydraulic conductivity within subsurface	K_s [m s^{-1}]	Controls subsurface redistribution of water, vertically and laterally	Correlated with macroporosity
Drainable soil water	θ_1	Range between saturation and field capacity	LRI[2]
Plant available soil water	θ_2	Range between field capacity and wilting point	LRI[2]
Depth of soil	D [m]		LRI[2]
Exponent in drainage function	C	Describes drainage into saturated zone	Uniform
Wetting front suction	ψ_f [m]	Parameter of Green-Ampt Infiltration capacity	Uniform
Overland flow velocity	V [m s^{-1}]		Uniform
*Canopy capacity	CC [m]		EW land cover map for 2001/02
*Evaporation enhancement	CR	Increasing evaporation losses by interception from taller vegetation	EW land cover map for 2001/02

* - affected by land use change

1. The REC is the New Zealand River Environment Classification (Snelder and Biggs 2002), which has spatial information about the river network and the catchments of New Zealand's rivers. The REC includes a digital network of approximately 600,000 river reaches and related sub-basins for New Zealand. Topographic reach and catchment properties in the REC were derived from a 30 metre digital elevation model (DEM).
2. The LRI is the New Zealand Land Resource Inventory (Newsome et al. 2000), which includes the Fundamental Soils Legend (FSL) data on soil properties for all of New Zealand
3. The LCDB is the New Zealand land cover database, which includes land cover, soil, and geological properties for all of New Zealand

Table 2: Parameters of the network model component of TopNet.

Model parameter	Symbol [unit]	Description	Data source
Network topology			REC
Reach length	L [m]		REC
Reach slope	S		REC
Upstream area	A [m^2]	Total upstream area above stream reach	REC
Reach Manning's n	N		Uniform
Hydraulic geometry parameters	a, b	Relationship between drainage area and channel width $W=aA^b$	Uniform

3. Data assembly

3.1. Spatial data

Under previously FRST-funded projects, NIWA has linked together national spatial data layers for river networks, sub-catchment boundaries, flow recorder locations, vegetation cover (from LCDB, New Zealand Land Cover Database), soils (from NZLRI, New Zealand Land Resource Inventory, (Newsome et al. 2000)) and topography into a very large single spatial database suitable for TopNet modelling for all of New Zealand. From this national dataset, spatial data for a TopNet model of a particular catchment can be extracted and correctly formatted, by specifying the river reach identifier of the New Zealand River Environment Classification (REC, Snelder & Biggs 2002) at the most downstream point of interest. The model developer must also specify the desired spatial resolution of the stream network, that is, order 1, order 2, order 3 etc. An order 1 stream network in the REC typically has sub-catchments of 0.7 km^2, and each larger order has catchments which are about four times as big.

The outlines of the Topnet catchments used for this study are shown in Figure 3, along with land cover for the catchment between Taupo and Karapiro, and the river network.

3.2. Project land use change

Forested areas totalling 567 km^2 in and near the middle Waikato have been identified by Environment Waikato as likely to be converted from forestry to intensive agriculture in the next 15 to 20 years. These areas are shown in red in Figure 4, along with the tributary catchments which have a long flood record. The majority of the projected land use change would take place outside the monitored catchments which provide our best understanding of middle Waikato flood hydrology e.g. Jowett (1999). There are some small areas on the northern boundary of the Pokaiwhenua catchment which lie outside the Waikato catchment: the effects of that conversion are not modelled in this report.

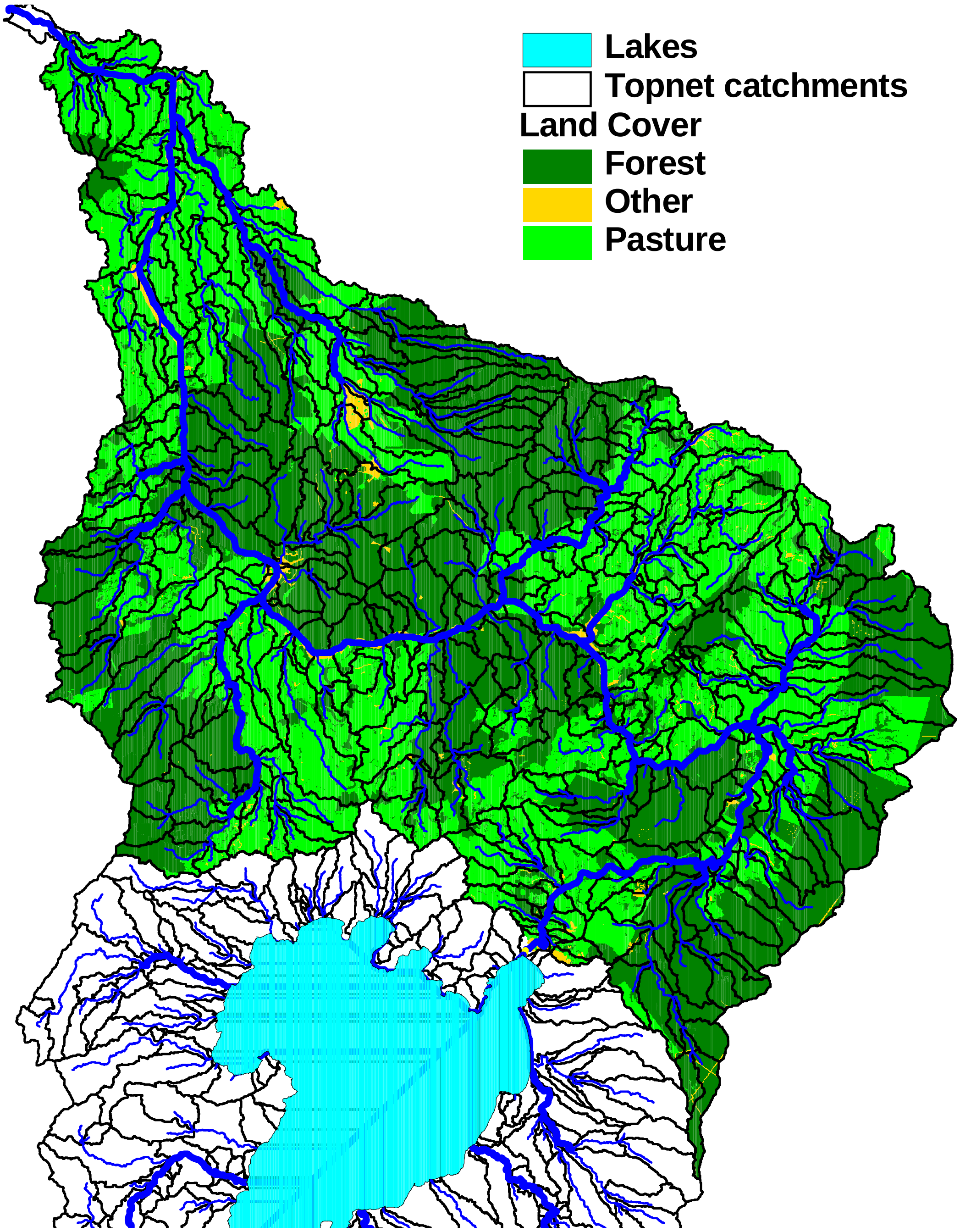


Figure 3: TopNet model (order 3) of the middle Waikato, with 2001-02 land cover (source: Environment Waikato) and river network also shown.

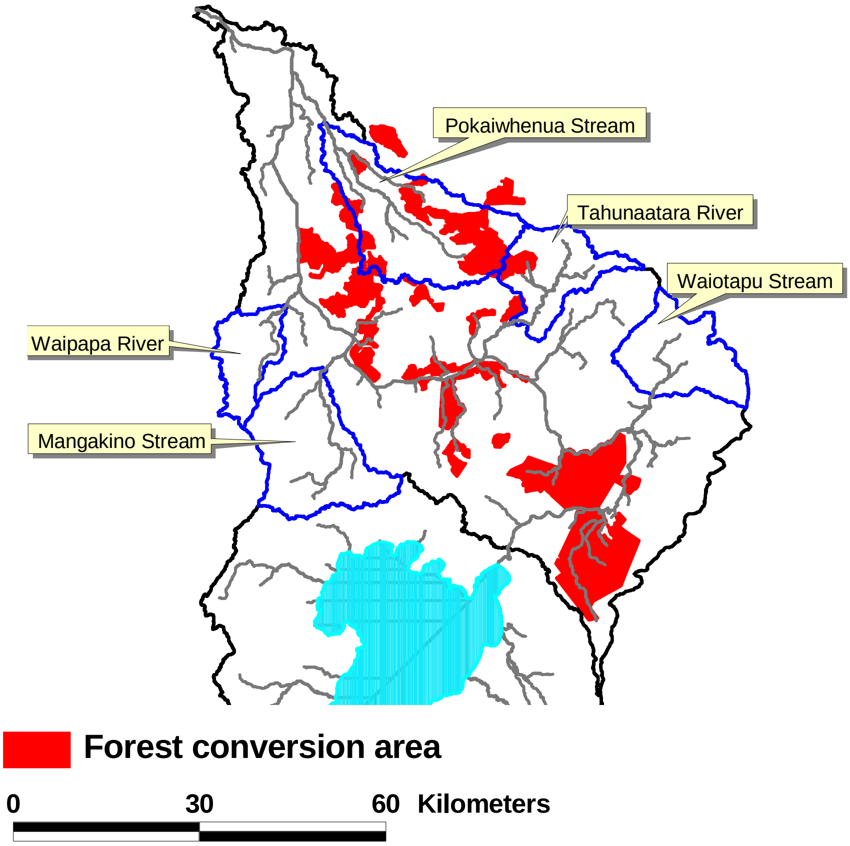


Figure 4: **Areas of the middle Waikato identified by Environment Waikato as likely to change from forest to intensive agriculture in the next 15 to 20 years (in red). The majority of the land use change areas are outside the well-monitored tributary catchments. Tributary catchments with long term flood monitoring are shown with blue outlines.**

3.3. Observed variations in flood response

The flood response to a given amount of rainfall varies significantly amongst the monitored tributary catchments. The observed catchment response has previously been summarised in two ways by Jowett (1999), as runoff ratios for floods (event runoff divided by event rainfall), and as the *b* divisor value in design runoff formulae $Runoff = Rainfall^{a}/b$. Lower values of *b* correspond to more responsive catchments. In Table 3 runoff ratios and *b* values are shown for five large tributary catchments with long flood records (also shown in Figure 4), and three other tributaries. The five large catchments range from the very damped responses of the Pokaiwhenua to the relatively flashy hydrographs at Waipapa River. The differences between a 5% runoff ratio and a 20% runoff ratio are very significant in determining the total tributary inflow to the middle Waikato. However, a quantitative understanding of the underlying causes is not available. For previous catchment runoff studies (Jowett 1999, MWD 1972), engineering judgement was used to decide how to estimate the runoff responses of the unmonitored tributaries, by associating them with similar monitored catchments, assigned on the basis of proximity, slope, drainage characteristics and land use. Data are also given in Table 3 for 3 additional catchments which are smaller or have shorter flood records

Table 3: Runoff response (divisor *b* as revised by Henderson and Thompson (2000), runoff ratios from Jowett (1999)).

Catchment	Divisor, b	Maximum % runoff	Mean % runoff
Pokaiwhenua Stream at Puketurua	34.75	8.5	2.2
Waiotapu Stream at Reporoa	24.7	19.2	5.3
Tahunaatara Stream at Ohakuri Rd	15.6	26.4	9.4
Mangakino Stream at Dillon Rd	7.7	29.7	12
Waipapa River at Ngaroma Rd	5.8	47	23.9
Waipapa Stream at Mulberry Rd	120.2	2.9	1.1
Pokaiwhenua at Forest Products	95	N/A	N/A
Mangahanene Stream at SH1	6.97	47.2	22.5

Since these runoff responses differ so markedly between catchments and the majority of the land use change is projected to take place in the unmonitored catchments, one of the most important steps in the prediction will be deciding how to represent unmonitored catchments.

3.4. Flow data

Time series data for river flows were included as hourly data from the stations listed in

Table 4, and mapped in Figure 5.

3.5. Rainfall data

Time series data for rainfall used in this study are an amalgam of daily rainfall data (Tait et al. 2006) from the Climate Database, interpolated onto a 5km grid, and all available hourly rainfall data from stations, as listed in Table 5 and mapped in Figure 6. The total rainfall for each day on each TopNet sub-catchment is found by selecting the grid point nearest the sub-catchment centroid, from the interpolated surface of daily raingauge totals. The TopNet model was used with hourly timesteps. The daily rainfall for each sub-catchment (as estimated above) was disaggregated into 24 onehour totals, using a temporal pattern for that day which is determined by interpolating temporal patterns from all available hourly gauges.

Table 4: Flow recording sites used for simulation modelling

Site name	Site number	Catchment Area (km^2) area	Start of record	End of record	Years of record
Pokaiwhenua at Puketurua	1043419	448	1-Oct-1963	1-Jan-2007	43
Waiotapu at Reporoa	43472	228	24-Feb-1960	1-Jan-2007	47
Tahunaatara at Ohakuri Rd	1043428	210	16-Apr-1964	1-Jan-2007	43
Mangakino at Dillon Rd	1043427	337	16-Apr-1964	1-Jan-2007	43
Waipapa at Ngaroma Rd	43435	137	10-Apr-1964	1-Jan-2007	43
Waipapa at Mulberry Rd	2043441	85.4	7-May-1986	8-Sep-1995	9
Pokaiwhenua at Forest Products Weir	43411	62.1	1-Jan-1960	8-Nov-1999	40
Mangahanene at SH1	1443462	8.75	28-Sep-1972	1-Jan-2007	34
Mokauteure at Forest Rd	2043446	38	10-Jul-1986	1-Aug-1991	5
Pokaiwhenua at Wiltsdown Rd	1843461	19.3	16-May-1988	6-Apr-1993	5
Waiotapu at Campbell Rd	2043493	47.6	10-Dec-1986	11-Jul-2001	15
Orakonui at Ngatamariki	2043497	73.5	28-Sep-1987	3-Mar-1992	4
Otamakokore at Hossack Rd	2143401	40.1	9-Dec-1986	1-Jan-2007	20
Mangatete at Te Weta Rd	2143404	30.6	10-Dec-1986	13-Dec-1994	8
Otumaheke at Spa Hotel	2143412	9.1	10-Dec-1986	30-Jan-2003	16
Mangakara at Hirsts	1043434	22	25-Jun-1969	24-Jan-1994	25
Otutira at Otutaru	1043476	0.045	15-Aug-1966	29-Aug-1980	14
Little Waipa at Puketurua	1043494	94	22-Oct-1965	1-Apr-1969	3
Purukohukohu at Weir	1143407	1.69	9-Mar-1970	2-May-1984	14
Purukohukohu at Puruorakau	1143408	0.372	19-Dec-1968	19-Jan-1987	18
Purukohukohu at Puruki	1143409	0.344	23-Dec-1968	1-Jan-2007	38
Purukohukohu at Purutaka	1143442	0.225	27-Dec-1968	1-Jan-2007	38
Waikato at Reids Farm	1143444	3305	23-Sep-1969	1-Jan-2007	37
Purukohukohu at Puruki-Rua	1443423	0.087	22-Feb-1971	10-Jan-1995	24
Purukohukohu at Puruki-Toru	1443424	0.138	5-Feb-1971	10-Jan-1995	24
Puruwai at Gorge	1443433	0.278	19-May-1972	7-Oct-1994	22
Purukohukohu at Puruki-Tahi	1443463	0.059	12-Dec-1972	10-Jan-1995	22
Te Waro at Puruhou	1543487	0.35	20-Dec-1979	19-Jan-1987	7
Purukohukohu at Purutakaiti	2043418	0.113	19-Dec-1985	14-Feb-1992	6

* Flow data up to the start of 2007 were assembled for use in the modelling study, but measurements continue after this date at some sites.

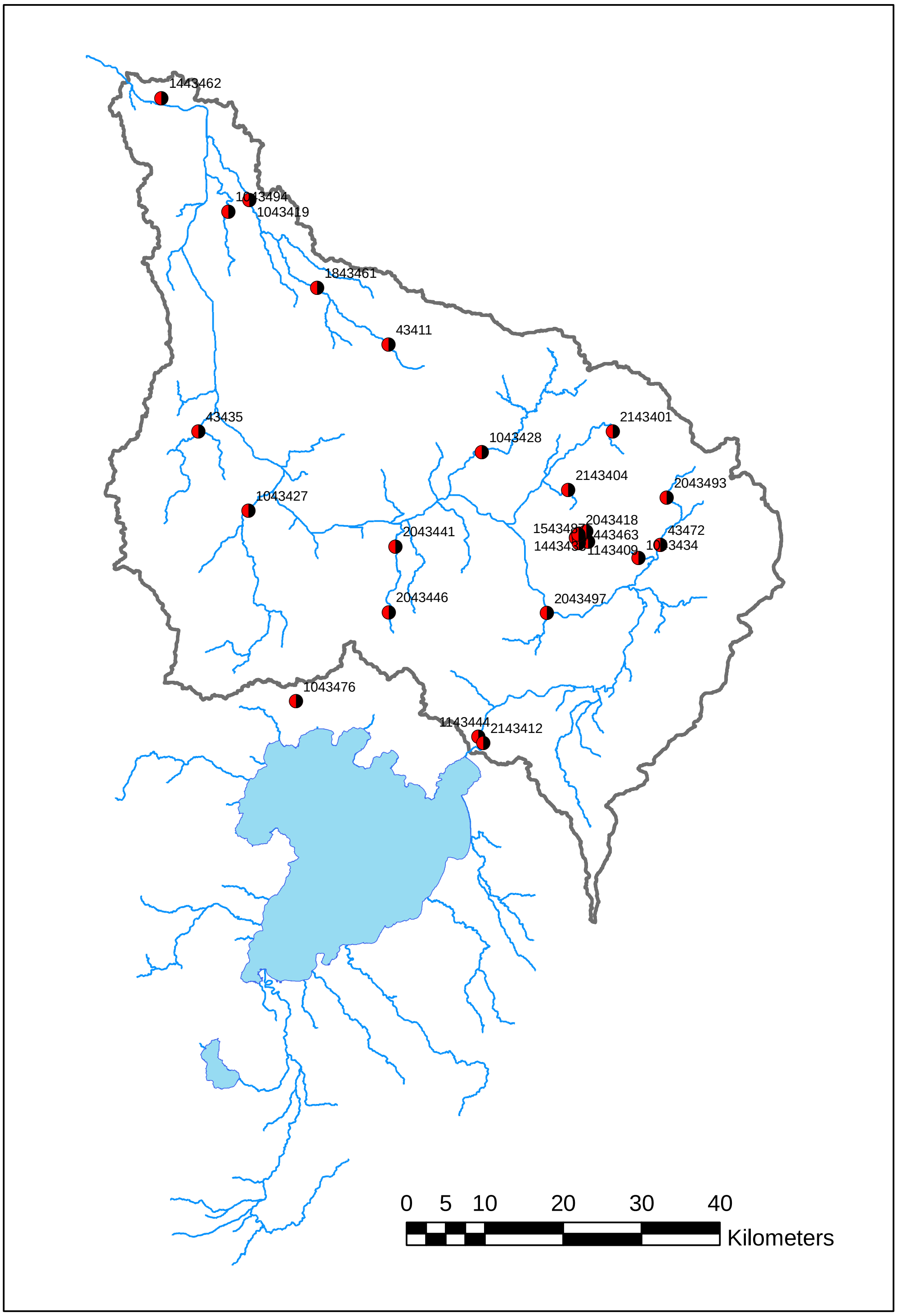


Figure 5: **Locations of flow gauges used in the TopNet model. Labels are site numbers.**

Table 5: Hourly rainfall stations

River	Site name	Site number	Start date	End date *	Years of Record
Waipapa	Goodalls Road	757901	8-Oct-1991	20-Sep-2007	16
Te Puna Stm	Stannett	766002	25-Sep-1990	17-Aug-2007	17
Waimapu	McCarrolls Farm	767101	30-Mar-2006	3-Aug-2007	1
Kopurereroa	Williams Rd	768102	11-Sep-1990	26-Jul-1992	2
Kaituna	Te Matai	768301	26-Jul-1989	25-Jun-2007	18
Mangorewa	Mangorewa	768310	1-Sep-1985	31-Aug-2007	22
Pongakawa	Pongakawa	769402	26-Jun-1996	2-Oct-2007	11
Ohinekoao	Harris Saddle	769705	4-Oct-2001	2-Oct-2007	6
Mangorewa	Kaharoa Link	860205	2-Sep-1985	30-Aug-2007	22
Mangorewa	Kaharoa	860206	1-Sep-1985	1-Jan-2000	14
Lake Rotoiti	Okawa Bay	860305	2-Feb-1980	5-Sep-2007	28
Kaituna	Whakawerawera	861204	1-Jan-1960	28-Aug-2007	48
Roto-A-Tamaheke	Path	861221	24-May-1984	8-Sep-1992	8
Torepatutahi	East Rd	123456	2-May-2000	22-Oct-2002	2
Tamihana	Matamata Aerodrome	757710	1-Aug-2005	1-Aug-2007	2
Waihou	Kaimai Summit	758910	20-Oct-1981	2-Oct-1989	8
Rapurapu	Kinlochs Farm	759914	3-Aug-1988	13-Nov-1992	4
Rapurapu	Kaimai	759916	13-Nov-1992	1-Aug-2007	15
Purere	Whites Rd	850810	2-Feb-1986	1-Jun-1991	5
Kuhatahi	Kuhatahi	850910	18-Jun-1976	30-Sep-1996	20
Kuhatahi	Feierabands Weir	850913	11-Jul-1988	4-Sep-1989	1
Oraka	Pinedale	851812	6-Jul-1988	24-Jan-1990	2
Waipa	Otewa	853410	31-May-1981	1-Aug-2007	26
Puniu	Ngaroma	853510	21-Jun-1982	1-Aug-2007	25
Mangaokewa	Wharekiri Stn	855510	30-Jun-1989	1-Aug-2007	18
Waihaha	Forest Boundary	857710	31-May-1976	21-Sep-1988	12
Waihaha	Farmhouse	857711	21-Sep-1988	25-Apr-1995	7
Waipari	Asteroid Rd	860011	12-Aug-1981	30-Aug-1982	1
Oraka	Muir Rd	861012	29-Jun-1979	5-Sep-1989	10
Mohaka	Te Haroto	961610	16-Dec-1998	20-Sep-2007	9
Ngaruroro	Otutu Bush	962211	2-Mar-1989	19-Sep-2007	19
Esk	Te Pohue No.2	962610	19-Dec-1994	20-Sep-2007	13
Esk	Te Pohue	962711	2-May-1985	8-Nov-1995	11
Esk	Maunganui	962712	16-Apr-1996	18-Sep-2007	11
Ngahere	Ngahere Telemetry	963416	7-Dec-1988	7-Aug-2007	19
Mangatutu	Waihau	963512	20-Dec-1984	22-Aug-2007	23
Esk	Glengarry	963712	26-Feb-1999	20-Sep-2007	9
Whanganui	Te Porere	950511	22-Sep-1962	13-Apr-2004	42
Mangatoetoenui	Tukino	953702	19-Dec-1991	10-Dec-2003	12
Uptha Ck	Science Centre	758312	1-Oct-1980	14-Apr-1982	2
Waitakarurutrib	Scotsmans Valley	758510	13-Aug-1980	16-Feb-1987	7
Mangahanene	Kentucky Farm	759610	18-Sep-1975	5-Aug-1991	16
Pokaiwhenua	New North Rd	862010	29-May-1963	14-Jan-1994	31
Mohaka	Tarawera	960510	12-Aug-1985	5-Jan-1994	8
Mohaka	Te Haroto	961510	31-Mar-1982	10-Oct-1985	4
Ngahere	Ngahere Hut	963410	5-Jan-1973	3-Oct-2007	35
Ngahere	Clearing	963411	22-May-1977	15-Oct-1980	3
Ngahere	Ngahere	963412	26-Aug-1969	16-Jun-1974	5
Esk	Esk Forest	963710	13-Jun-1973	26-Jan-1976	3
Waikato	Ruakura	757336	2-Jul-2001	16-Oct-2007	6
Mangakara	Maungatautari	850636	15-Jun-2001	17-Oct-2007	6
Pokaiwhenua	Puketurua	851736	16-Sep-1991	6-Nov-2007	16

River	Site name	Site number	Start date	End date *	Years of Record
Pokaiwhenua	Pumping Station	852912	29-May-2001	11-Oct-2007	6
Waipapa	Ngaroma Rd	853736	13-Sep-1991	6-Nov-2007	16
Mangakino	Dillon Rd	854736	1-Jan-1991	6-Nov-2007	17
Waipapa	Forest Rd	855912	1-Apr-1998	1-Jun-1999	1
Mokai 1	Forest Rd	855913	1-Apr-1998	1-Jun-1999	1
Waipapa	Paerata Rd	855936	6-Aug-2001	11-Oct-2007	6
Tutaeuaua	Bird Br	856701	13-Oct-2004	10-Oct-2007	3
Tutaeuaua	Wetland	856702	14-Oct-2004	23-Oct-2007	3
Mangakino	Kakaho Rd	856736	20-Jun-2001	11-Oct-2007	6
Otutira	No 5	856810	5-Jan-1971	31-Dec-1975	5
Otutira	Otumaroke	856862	24-May-1972	4-Aug-1980	8
Otaketake	Otake Rd	856910	15-Sep-1973	3-Jun-1980	7
Whareroa	Managers House	858710	26-May-1976	24-Jan-1980	4
Kaituna	Dodds	860116	10-Nov-1975	24-Apr-1978	2
Kaituna	Te Reinga	861114	17-Nov-1975	3-Apr-1978	2
Kaituna	8 Mile	861218	6-Nov-1975	4-Apr-1978	2
Kaituna	Carrs	861313	4-Nov-1975	18-Jan-1978	2
Te Ngae Drain	PRD	861315	15-Dec-1981	6-Aug-1986	5
Pomare	Pukehangi Rd	862212	19-Dec-1981	18-Sep-1986	5
Tahunaatara	Ohakuri Rd	863136	13-Sep-1991	6-Nov-2007	16
Purukohukohu	P4	864201	4-May-1969	23-Oct-2007	38
Mangakara	M1	864210	3-Aug-1964	5-Jan-1994	29
Waiotapu	Reporoa	864336	13-Sep-1991	6-Nov-2007	16
Whirinaki	Galatea	865736	13-Sep-1991	5-Nov-2007	16
Waikato	Wairakei	866101	1-Jan-1986	1-Jul-1988	2
Waikato	Reids Farm	867136	16-Sep-1991	6-Nov-2007	16
Rangitaiki	Kokomoka	868410	8-Aug-1977	4-Apr-1979	2
Waitahanui	Collins Farm	869210	9-Mar-1976	1-Jun-1979	3
Kuratau	Space Station	858701	1-Jan-1994	1-Oct-2007	14
Whanganui	Piriaka	859304	11-Dec-2001	1-Oct-2007	6
Waimarino	Kepa Rd	859804	20-Jan-1994	1-Oct-2007	14
Whanganui	Te Porere Redoubt	950512	30-Jun-2004	1-Oct-2007	3
Poutu	Poutu Dam	950701	14-Nov-2001	1-Jan-2004	2
Rotoaira		950702	25-May-2004	1-Oct-2007	3
Tongariro	Rangipo Dam	950808	15-Nov-2001	15-Jan-2004	2
Whanganui	Okupata	951511	1-Nov-1966	1-Feb-1990	23
Whakapapanui	Whakapapanui	951514	15-Nov-2001	1-Oct-2007	6
Tongariro	Ruatahuna	951903	5-Jul-2001	1-Oct-2007	6
Tongariro	Mangatoetoe	952710	14-Dec-1987	1-Oct-2007	20
Tongariro	Karikaringa	952801	5-Jul-2001	8-Jan-2007	6
Tongariro	Karikaringa No 2	952802	18-Jul-2006	1-Oct-2007	1
Mangatoetoenui	Tukino	953703	4-Dec-2001	1-Oct-2007	6
Moawhango	Moawhango Lake	954703	15-Nov-2001	1-Oct-2007	6
Tauranga-Taupo	Kiko Rd	960010	26-Jul-2001	1-Oct-2007	6
Makotuku	F Trig	953510	14-Nov-1968	25-Oct-2007	39
Makotuku	Gauging Site	953511	22-Apr-1994	12-Oct-2006	12
Mangaio	Mangaio Central	953711	24-Jun-1971	14-Jan-1976	5
Mangaio	Burma Rd	953712	1-Nov-1967	11-Sep-1979	12
Waitangi	Gravel Pit	954611	1-Sep-1967	12-Jan-1994	26
Mangaio	Gauging Site	954712	2-Mar-1973	7-Jan-1976	3

* Hourly rainfall data up to 2007 was assembled for use in the modelling study, but measurements continue after the end date at some sites.

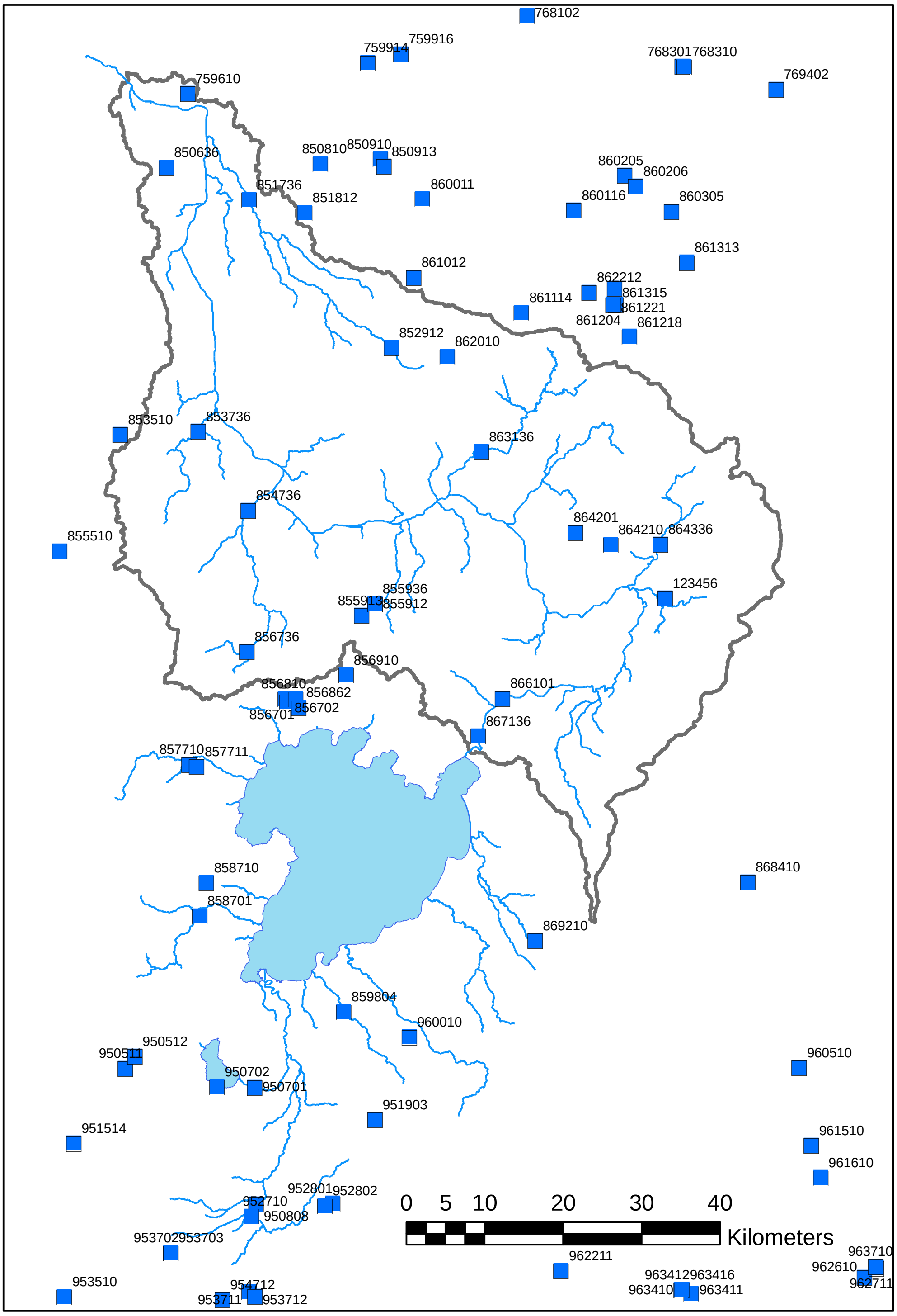


Figure 6: **Locations of hourly raingauges corresponding to Table 5. Labels are site numbers.**

4. Model calibration

4.1. Strategy

The calibration process is complex because the objectives for modelling are multi-faceted. It is desirable to produce model simulations which:

1. Are a reasonable facsimile of historical flood hydrographs at both the local scale (i.e. ~10 km^2) and the scale at which tributaries discharge into the Waikato (i.e., up to 1000 km^2)

2. Use model runoff generation mechanisms which are consistent with small-scale field experiments

3. Reproduce observed significant differences in flood hydrology between pasture and forest land cover (these observations are for catchments less than 1 km^2)

A two-step strategy was attempted to overcome the large range of spatial scales. A high-resolution simulation model of the Mangakara catchment, containing the Purukohukohu catchment, was built first (area shown in Figure 3). The intention was to verify that the model could reproduce both the observations at scales of a few hectares at Purukohukohu, and the Mangakara tributary.

This model proved too difficult to calibrate, given the constraints on which runoff generation mechanisms were known to take place. No set of parameters was found which matched the known field data, and also produced the observed flood hydrographs at the various flow measurement sites within the Mangakara catchment. This is perhaps a disappointing result, but reflects the current stage of development of catchment models. Some calibration directly to hydrographs, without full regard for the experimental data which is generally at a different spatial scale, remains an essential element of practical spatially distributed simulation modelling in hydrology. With the failure of the original two-step strategy, the model is now only calibrated at the scale of the tributary sub-catchments (Pokaiwhenua Stream at Puketurua, Waiotapu Stream at Reporoa, Tahunaatara Stream at Ohakuri Rd, Mangakino Stream at Dillon Rd, Waipapa River at Ngaroma Rd).

4.2. Overview of TopNet parameter estimation

The parameters of the TopNet model are listed in Table 1 and Table 2. Some of these parameters are important in describing soil water processes, but are difficult to estimate from soils data – their estimation is described in section **Error! Reference**

source not found.. Other parameters are directly related to land use change, and so are important in the context of this study – methods to estimate these parameters are described in section **Error! Reference source not found.**.

4.3. Assignment of parameters controlled by soil properties

Table 3 shows that catchment response to rainfall varies significantly within the middle Waikato. This variation is understood to be controlled by soil properties which are quantified through TopNet model parameters that require calibration. This calibration step can lead to arbitrary outcomes (that is, model parameters which provide good reproduction of current flows, but are not useful for future land use change scenarios) if the modeller does not apply constraints to the calibration process. The model can be constrained by setting physically reasonable parameter values, and by considering whether the runoff generation mechanisms it uses are reasonable. In this case, the key constraint was based on a review of the possible dominant reasons behind the patterns of runoff response demonstrated in Table 3 (but including other flow recording sites in the catchment where similar information is available). The factors which affect responsiveness to rainfall in this region are complex and only partially understood. Given the small number of catchments, relative to the number of potential explanatory factors, it was not considered feasible to find more than one dominant controlling factor, nor to use a multivariate statistical approach, because the risk of finding coincidental correlations would be too high.

A search of a wide range of plausible factors revealed that two soil properties (macroporosity and rooting depth) in the Fundamental Soils Legend (developed by Landcare Research) show adequate and physically-reasonable correlation with runoff response, though the explanation is incomplete. After discussion with members of the Technical Expert Panel (suggestion by Ian Jowett to consider soil types in Mangahanene Stream and Waipapa Stream), a further soil characteristic (fraction of catchment with yellow-brown pumice (YBP) or podzol (POD) soils) was identified as potentially useful.

These soils data are summarised in Table 6 for the gauged catchments referred to previously. The macroporosity values shown here are those mapped in the Fundamental Soils Legend of the Land Resources Inventory, for the top 0.6m of soil (known as MPOR_S_MID); macroporosity data for deeper levels in this region are not in the soils database. The soil depths reported above are the midpoint of the Potential Rooting Depth (PRD_MID) field. The macroporosity values reported here are at variance with those shown in a recent draft report on flood frequency (Mulholland 2007, draft), e.g. the value for Waipapa River at Ngaroma Rd is given by Mulholland as 15.05, compared with 12.2 in Table 6).

Table 6: Mapped soil characteristics showing some association with runoff response.

Catchment	Mean Macroporosity (%)	Fraction of Catchment with mapped macroporosity > 0.20	Mean Soil Depth (m)	Fraction of Catchment with mapped soils >1.2m deep	Fraction of Catchment with YBP or POD soils
Pokaiwhenua Stream at Puketurua	15.8	0.52	1.31	0.89	0.94
Waiotapu Stream at Reporoa	12.8	0.24	0.93	0.45	0.85
Tahunaatara Stream at Ohakuri Rd	13.3	0.41	1.20	0.64	0.66
Mangakino Stream at Dillon Rd	11.9	0.03	1.22	0.81	0.50
Waipapa River at Ngaroma Rd	12.2	0.09	1.20	0.76	0.77
Waipapa Stream at Mulberry Rd	11.4	0.00	1.22	0.79	0.46
Pokaiwhenua at Forest Products	14.3	0.50	1.21	0.66	0.88
Mangahanene Stream at SH1	20.0	1.00	1.20	0.52	0.00

4.3.1. Macroporosity

The correlation (or lack thereof) between macroporosity and (lack of) flood responsiveness (divisor, *b*) is shown in Figure 7. The ellipse added to the figure selectively focuses attention on a positive correlation between the divisor *b* and the fraction of the catchment area with high macroporosity (MPOR_S_CLASS=1). Higher values of *b* indicate less responsive catchments. The use of an area fraction, rather than the mean value, allows for the possibility that it is the presence or absence of extreme values of macroporosity which influences hydrological responsiveness. As noted by the Technical Expert Panel, one could also justify a negative correlation between macroporosity and flood responsiveness by instead selectively focussing on a different subset of catchments in the same figure.

The more damped responses (e.g., Pokaiwhenua) tend to come from catchments with a prevalence of high macroporosity in the top 0.6 m of the soil (the variable MPOR_S of Newsome et al (2000)). Macroporosity measures the presence of large pore spaces in the soil. These larger spaces can store and transmit water more water per unit volume of soil than smaller pores. The proposed rationale for this association is that where high macroporosity is more prevalent, more water can be stored in the soil for a given rainfall, and thus less runoff would be produced.

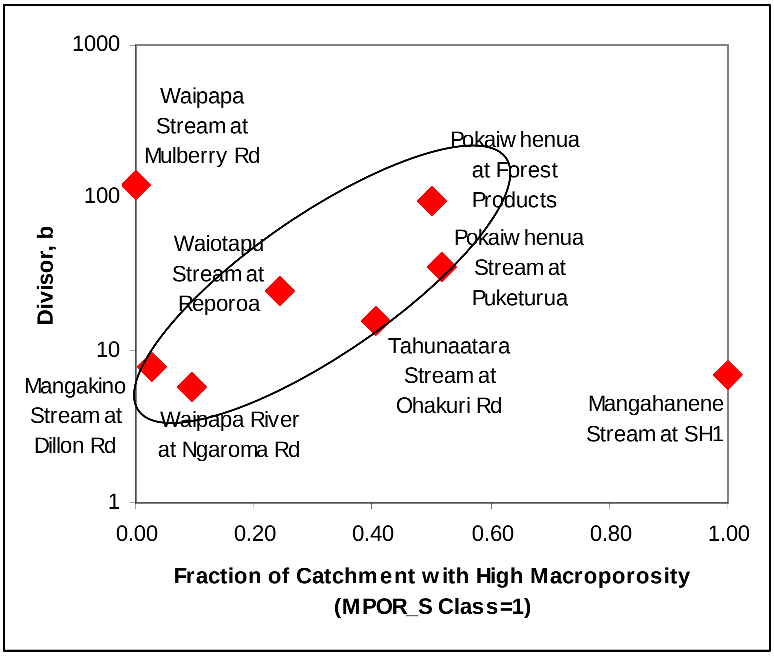


Figure 7: **Association of Jowett's divisor b (used as a measure of catchment responsiveness) with values of macroporosity. High values of b indicate less responsive catchments. See text for discussion of outliers.**

The damped responses also tend to come from catchments with deeper soils, but the range in soils depths is low, indicating that perhaps the steeper parts of the catchment are unsampled. A catchment with deeper soil would be able to store more water from a given rain event, and thus would be expected to produce less subsurface storm runoff for a given rain event. In a deeper soil, the likelihood of shallow water tables intersecting the ground surface is lower, and thus one might expect a smaller proportion of saturated areas in such catchments, and this less saturation excess runoff.

At this stage the choice of which soil variable to favour remains arbitrary, since the spatial patterns of the two are similar, either one would provide similar information to guide calibration. Two catchments which do not display this correlation are Mangahanene at SH1 and Waipapa Stream at Mulberry Road. Both were treated by Jowett (1999) as special cases, so it is not surprising that they also feature here. Mangahanene at SH1 is more responsive than the soils data suggest, and according to Jowett (1999) this responsiveness is due to steep slopes. Waipapa Stream at Mulberry Road (as opposed to Waipapa River) is less responsive than soils data would suggest, and Jowett (1999) ascribes this to a variety of factors including low slope, poorly defined drainage network, and potentially deeper soils (though not according to the soils database).

By November 2008, this association between macroporosity and flood responsiveness was NOT in use, but the discussion above is temporarily retained as a record of prior investigations.

4.3.2. Genetic soil group

Analysis of the genetic soil group field of the Fundamental Soils Legend of the Land Resource Inventory (Newsome et al. 2000) indicates that 94% of the middle Waikato (Taupo to Karapiro) is either YBP (yellow-brown pumice soil, 70%), YBL (yellow-brown loam, 20%) or POD (podzol 4%). No other class of NZGSOIGRP comprises more than 1.5% of the middle Waikato. The podzol soils are a small fraction of the study region, but comprise 26% of one of the larger gauged catchments, Mangakino Stream at Dillon Rd. The fraction of each of the above gauged catchments which is in YBP or POD is also given in Table 6.

A comparative analysis of the mapped water holding characteristics of YBP, YBL and POD is given in Table 7. The YBP and POD soils reportedly have slightly higher average values of three soil properties: Profile Available Water (PAW), Profile Readily Available Water (PRAW), and Macroporosity in the upper 0.6m, relative to the YBL soils. Care should be taken in interpreting these data because it is not certain that the underlying data are representative of the region (in particular it is possible that hill soils were under-sampled). In the absence of confounding factors, the YBL and POD soils which are able to store more water might be expected to have a more damped response to a rainfall event of a given size, since storm rainfall can be stored instead of being transmitted as subsurface stormflow. In addition, the soils with more storage capacity might be expected to have deeper water tables (again assuming no confounding factors). In places where the runoff generating mechanism is rain falling on saturated soil (saturation excess runoff), the lower water tables would suggest smaller saturated areas, and thus smaller areas contributing this kind of rapid runoff. However, the relative significance of saturation excess runoff in the catchment is unknown.

The fraction of the catchment in YBP/POD soils is a more reliable predictor of hydrological responsiveness than any of these three quantitative measures, for the admittedly small sample of catchments available. Compare, for example, Figure 8, which relates the prevalence of YBP and POD soils to Jowett's divisor b, with Figure 7, which relates the prevalence of high macroporosity soils to b. Catchments in this dataset with a large proportion of the YBP/POD soils are generally less responsive.

These results provide some corroboration to the above interpretation of Table 7 that YBP and POD soils are less responsive to storm rainfall.

Table 7: **Water holding characteristics of three soil groups (average values over the middle Waikato catchment). Detailed definitions of the four water hjolding characteristics (PRD, PAW, PRAW and MPOR_S) are given in Newsome et al. (2000).**

NZGSOIGRP	Potential Rooting Depth, PRD (m)	Profile Available Water, PAW (mm)	Profile Readily Available Water, PRAW (mm)	Macroporosity in upper 0.6m, MPOR_S (%)
YBP	1.2	201	84	13
YBL	1.2	192	71	11
POD	1.3	259	87	17

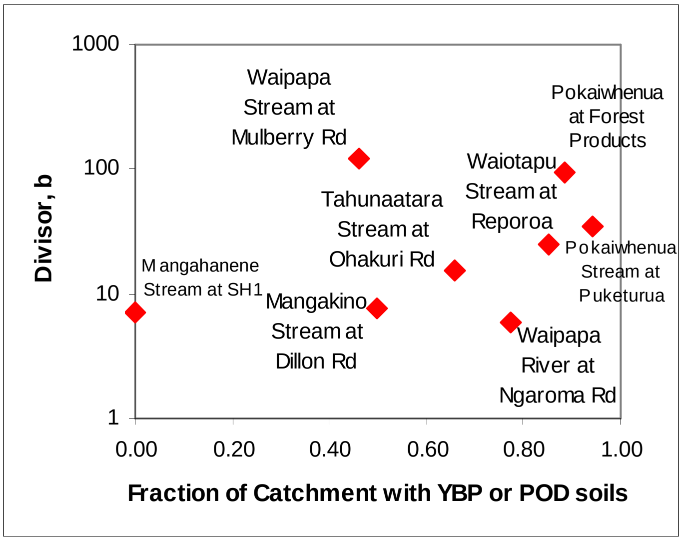


Figure 8: **Association of Jowett's divisor b (used as a measure of catchment responsiveness) with fraction of catchment containing YBP or POD soils. High values of b indicate less responsive catchments. See text for discussion of outlier.**

None of this explains the unresponsive hydrology of Waipapa Stream at Mulberry Road, for which only the rationalisation of Jowett is available (low slope, poorly defined drainage network, and potentially deeper soils). Note that the Waipapa Stream data are consistent with the short series of flow data from its Mokautere sub-catchment, and so there is independent support for the Waipapa Stream data. The nearby Mangakino catchment has a similar mix of soil groups to those in the Waipapa Stream catchment, but the Mangakino is much more responsive to rainfall. The slopes reported in the Land Resource Inventory within the Waipapa Stream at Mulberry catchment (about 29% in classes A, B, or C, i.e. flat, undulating or rolling, up to 15 degrees) are lower than the adjacent Mangakino catchment (17% in classes A, B, or C). This difference is perhaps not large enough to explain the apparent difference in hydrological response – both catchments do have an appreciable area which is mapped as relatively steep. Thus Waipapa Stream catchment remains an anomaly, and any future water management investigations for this catchment would be aided by studies of the hydrological processes there.

The absence of YBP and POD soils from Mangahenene at SH1 does provide a possible explanation of the highly responsive hydrology of that catchment. Although that responsiveness has previously been ascribed to the steepness of the catchment (Jowett 1999), and more recently to the land use (Mulholland, memo to TEP 20 June 2008), As stated in the beginning of this section, the understanding of the factors affecting catchment responsiveness is inconclusive. The purpose here is to define TopNet soil model parameters. We adopt soil group as an explanation, because it also explains responsiveness of several other middle Waikato catchments.

4.4. Assignment of parameters controlled by land cover

The three most important 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. Soil properties were found to have only a secondary influence on infiltration rate in this study.

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 Environment Waikato (EW) 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. However, an adequate calibration was obtained without further adjustement. Since the EW 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 9), and are listed in Table 8.

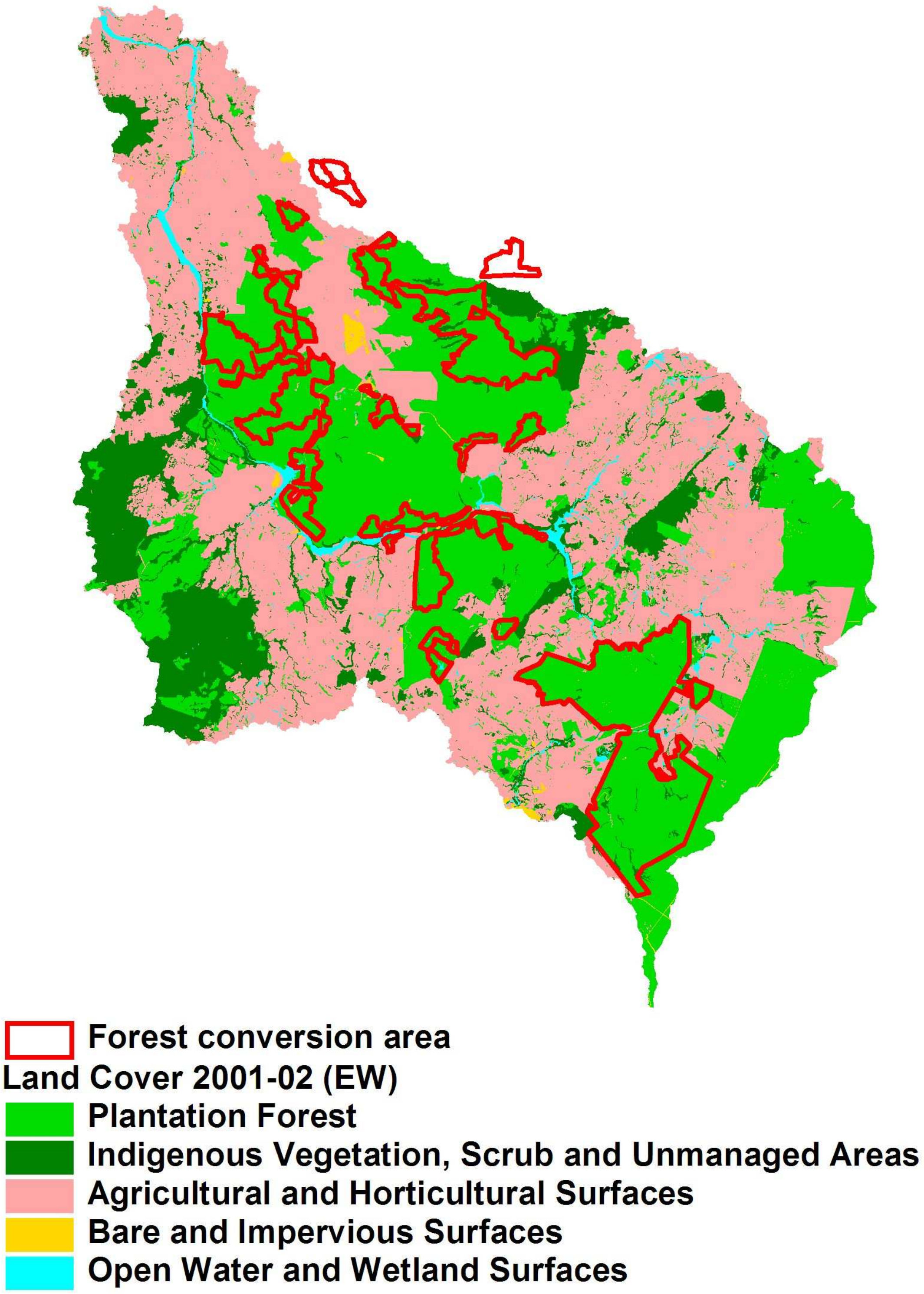


Figure 9: **Current land cover**

Table 8: 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

4.5. Model calibration process

An adequate model calibration was achieved, after considerable exploration of the data.

The key soil-controlled parameters to estimate for the TopNet model in this catchment were saturated hydraulic conductivity at the soil surface, effective depth of soil for subsurface flow, and lateral saturated hydraulic conductivity.

The calibration event was the July 1998 flood. A five-month period (1-May to 1-September 1998) was used, because the simulation model is a continuous model, not an event-based model. It therefore needs time to establish its own initial conditions for the flood: this is especially important in slowly-responding catchments. The long calibration period also gives the opportunity to check the model's representation of responses to a wide variety of events. If it performs well in many events, this increases the chance that it will perform adequately under changed conditions. Performance of the model was also calculated as the total runoff in a 3-day period around the flood peak. The performance of the model in reproducing the 3-day total runoff difference between Taupo Outflow and Karapiro was used as the primary calibration criterion, and the performance of the model on the Pokaiwhenua at Puketerua catchment was used as a secondary criterion. The Karapiro-Taupo runoff is a quantity of direct interest to hydraulic modelling, so it is worth checking on its simulation. The Pokaiwhenua catchment is the major gauged catchment which will be most affected by land use conversion, so its simulation is also of interest. As a result there are still significant discrepancies for many of the gauged tributary catchments.

The calibration process was manual, no automatic, because consideration of the (as yet poorly understood) runoff generation processes was required, in order to get a reliable model for prediction of change.

The effective depth of soil for subsurface flow (TOPMODF parameter) was assumed to be correlated with the fraction of each sub-catchment which had YBP or POD soils. Following the guidance of Figure 8, if the fraction of the catchment with YBP or POD soils was less than 80% then a TOPMODF value of 5 m^{-1} was assigned, otherwise a value of 0.05 m^{-1} was assigned (Figure 10). The exact nature of the relationship between these two model parameters and macroporosity were subject to calibration. The relationship preserved the relationship described above, i.e. higher macroporosity soils were given parameter values indicating less responsiveness. For the TopNet model, responsiveness is lower if the effective depth for subsurface flow is larger, and also if the lateral saturated hydraulic conductivity is lower.

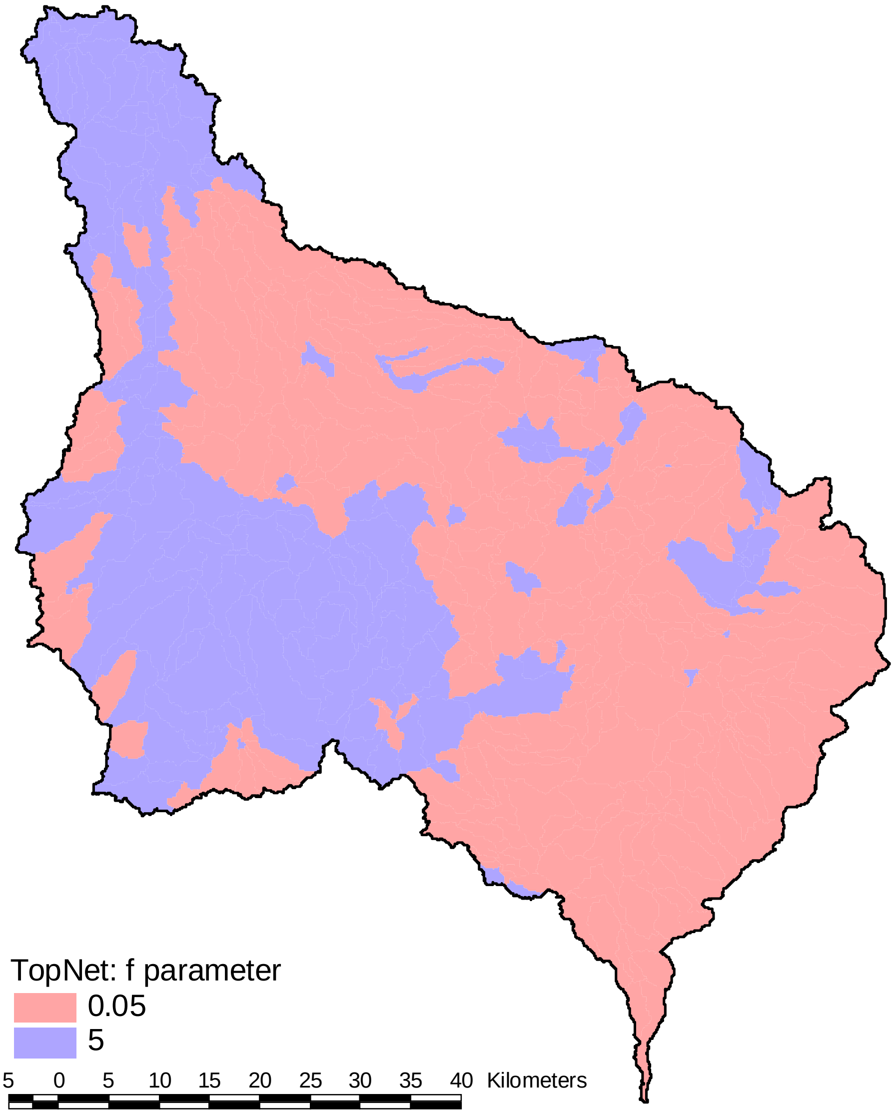


Figure 10: Spatial distribution of effective depth (m^{-1}) of soil for subsurface flow (TopNet TOPMODF parameter) as applied in the simulation model. The blue areas are predicted by TopNet to be more responsive (for flooding) then the pink areas.

This calibration attempts to capture poorly understood subsurface processes and it must be acknowledged that the physical basis of the correlation is not understood. However, since these processes control subsurface dynamics, which are not physically altered by the envisaged land use changes, it is plausible to expect these empirical relationships to be stable. Clearly the water inputs to the subsurface flow system will change with land use change.

The saturated hydraulic conductivity at the surface (HYDCON0) was first estimated using the data mapped by an Environment Waikato study (Taylor et al. 2009). However, the rainfall intensities used to force the TopNet model were far less than the saturated conductivities. All these mapped conductivity values were reduced by a calibration factor, in order to produce some infiltration excess runoff. However, the modelled runoff was much more sensitive to changes in TOPMODF than to physically reasonable changes in HYDCON0. The calibrated model reported here scales all mapped conductivity values by a factor 0.05.

The lateral saturated hydraulic conductivity was assumed to be the same as the saturated conductivity of forest on the corresponding soil type, mapped by an Environment Waikato study (Taylor et al. 2009). A low lateral conductivity means that the water table is forced closer to the surface, and saturated areas are larger, so that more surface runoff is produced by the saturation excess mechanism.

4.6. Model calibration results

Model calibration was carried out in two steps:

1. Calibration was done on July 1998 event.

2. The calibrate model was run for 1965-2005 using observed rainfalls to produce runoff and tested against observed data (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 Figures 11 and 12, 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 following figures show the model calibration hydrographs for the July 1998 flood. Figure 13 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.

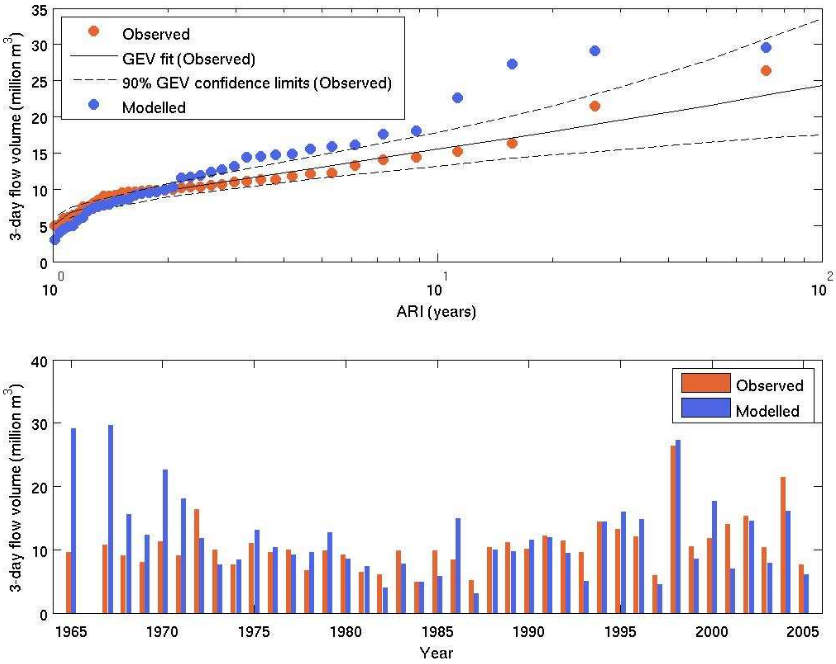


Figure 11: **Modelled and observed annual maximum 3-day floods for Mangakino at Dillon Road. Upper panel: Annual series; lower panel: Flood frequency analysis - analysis of observations by SKM (Thornburrow & Mulholland 2009).**

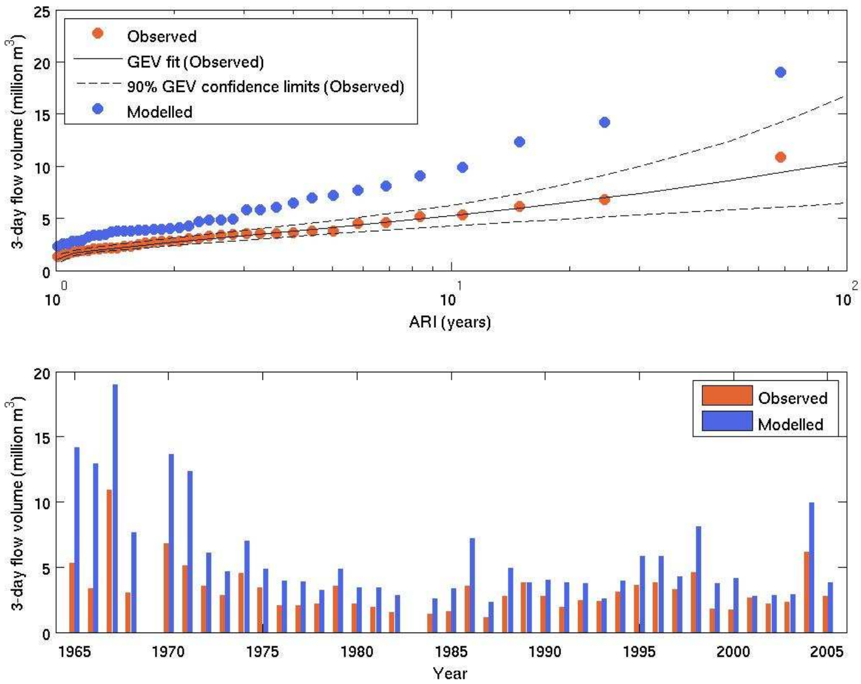


Figure 12: **Modelled and observed annual maximum 3-day floods for Waiotapu at Reporoa. Upper panel: Annual series; lower panel: Flood frequency analysis - analysis of observations by SKM (Thornburrow & Mulholland 2009).**

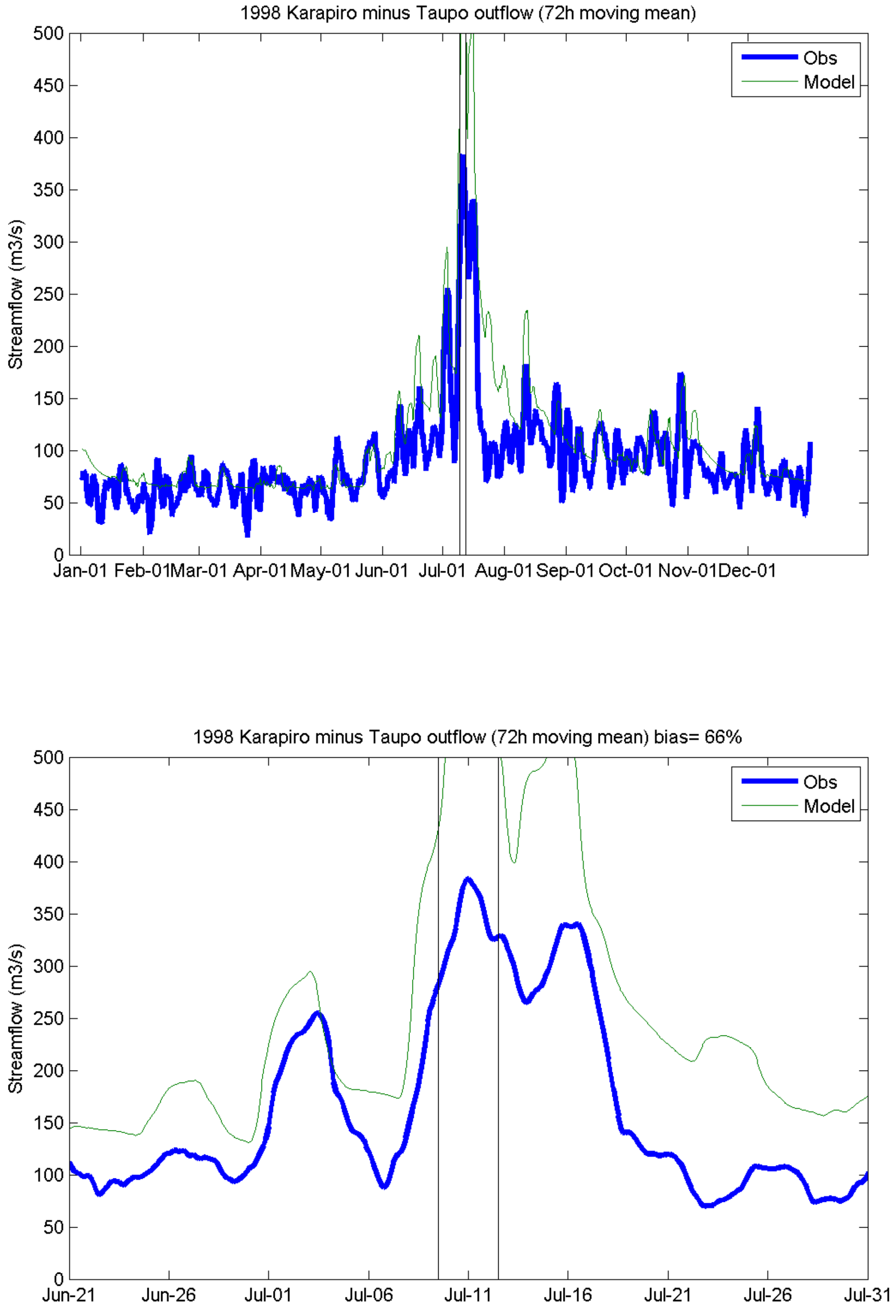


Figure 13: **TopNet validation plot for 1998 flood, for the difference between Karapiro and Taupo outflows. Top panel shows observed and modelled 72-h moving mean flows for entire year; Bottom panel shows detail at time of flood.**

The following figures (Figure 14 to Figure 18) 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).

The lower panel shows which runoff generation mechanisms were operating at one sub-catchment within each monitored catchment shown. There is no guarantee that the sub-catchment is representative. In the legend, drainage (in grey) refers to the modelled flow of water from the root zone to the shallow saturated zone. SSF refers to subsurface flow (in yellow), SSF+SATXS refers to the sum of subsurface and saturation excess runoff (in green), and SSF+SATXS+INFXS refers to the sum of subsurface, saturation excess runoff and infiltration excess runoff (in blue). If no blue is visible, there was no infiltration excess. If no green is visible, there was no saturation excess runoff. These terms are also shown in the same colours on the flow diagram in Figure 2.

Further assessments of model performance are made in a separate report (Jowett 2009), looking at event rainfall-runoff relationships for tributary streams, predictions by other models of inflow volumes into dam catchments, and total inflows between Taupo and Karapiro: those analyses are not repeated here. Jowett (2009, p1) summarizes his results as follows:

> *"The TOPNET (NIWA) model was not as strongly influenced by temporal pattern and storm intensity as the HEC/HMS model. The TOPNET model predicted tributary catchments responses well in some tributary catchments, but tended to under-predict in two. However, the predicted total inflows agreed with inflows calculated by subtracting Taupo from Karapiro discharge and with other model estimates."*

5. Modelling change in land use on simulated floods

The areas outlined in red in Figure 19 are projected to change from forest to dairy pasture. The model developed in this report will be used to compare the flood regimes before and after that change, by running the model with and without that change.

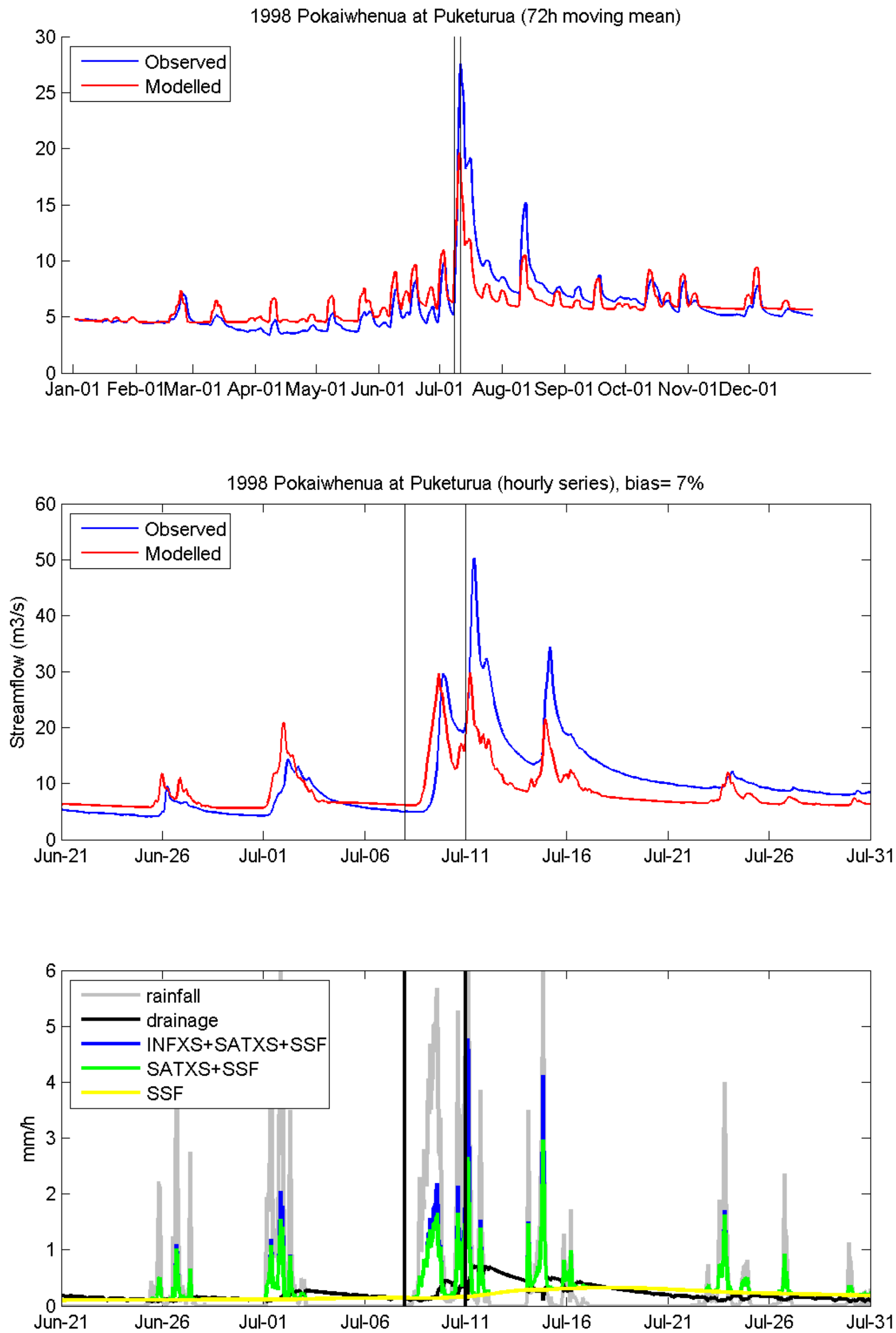


Figure 14: **TopNet validation plot for 1998 flood, Pokaiwhenua at Puketurua. Top panel shows observed and modelled 72-h moving mean flows; Middle panel shows observed and modelled hourly flows; Bottom panel shows which runoff generation mechanisms were operating at one sub-catchment within each monitored catchment shown.**

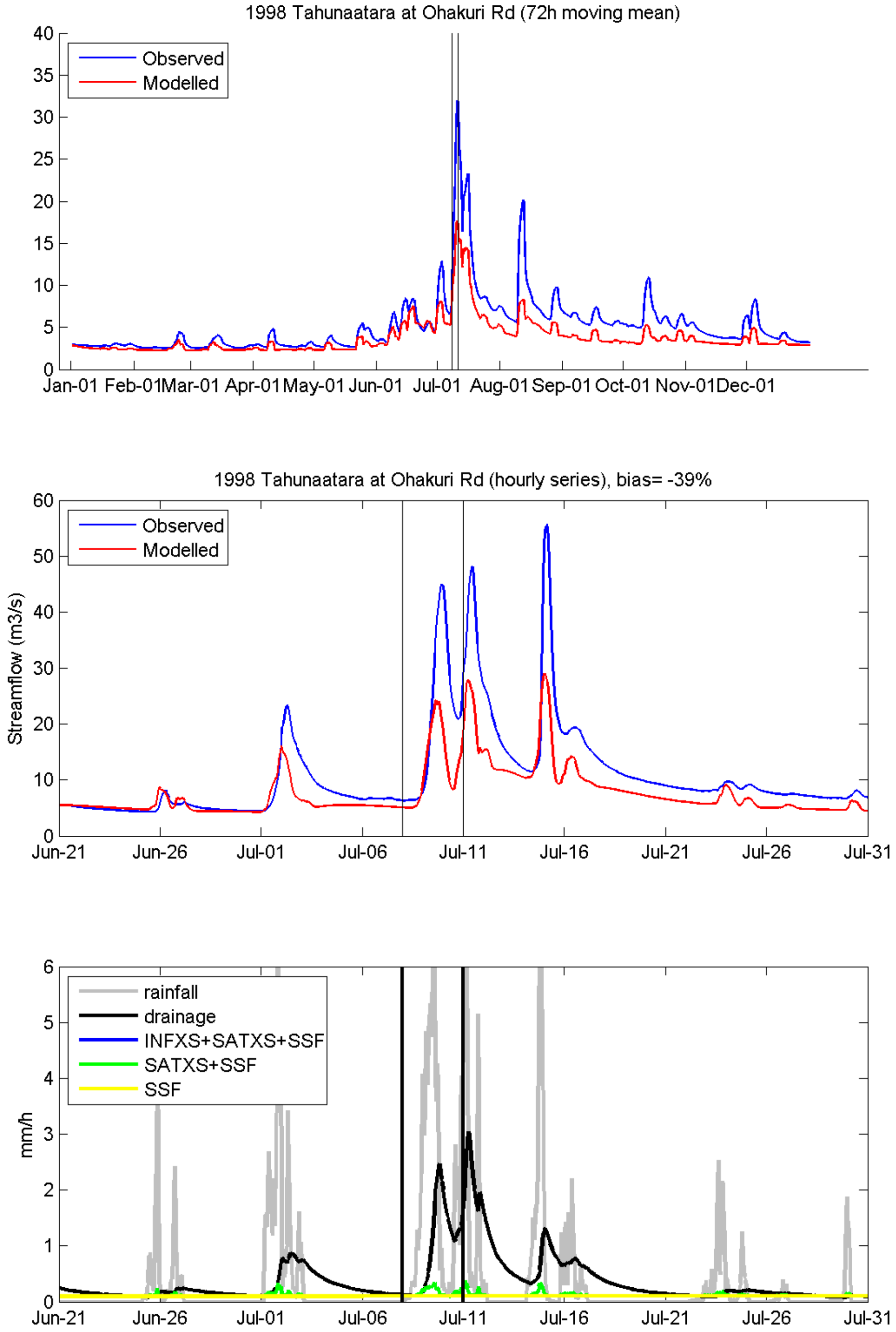


Figure 15: **TopNet validation plot for 1998 flood, Tahunaatara at Ohakuri Road. Top panel shows observed and modelled 72-h moving mean flows; Middle panel shows observed and modelled hourly flows; Bottom panel shows which runoff generation mechanisms were operating at one sub-catchment within each monitored catchment shown.**

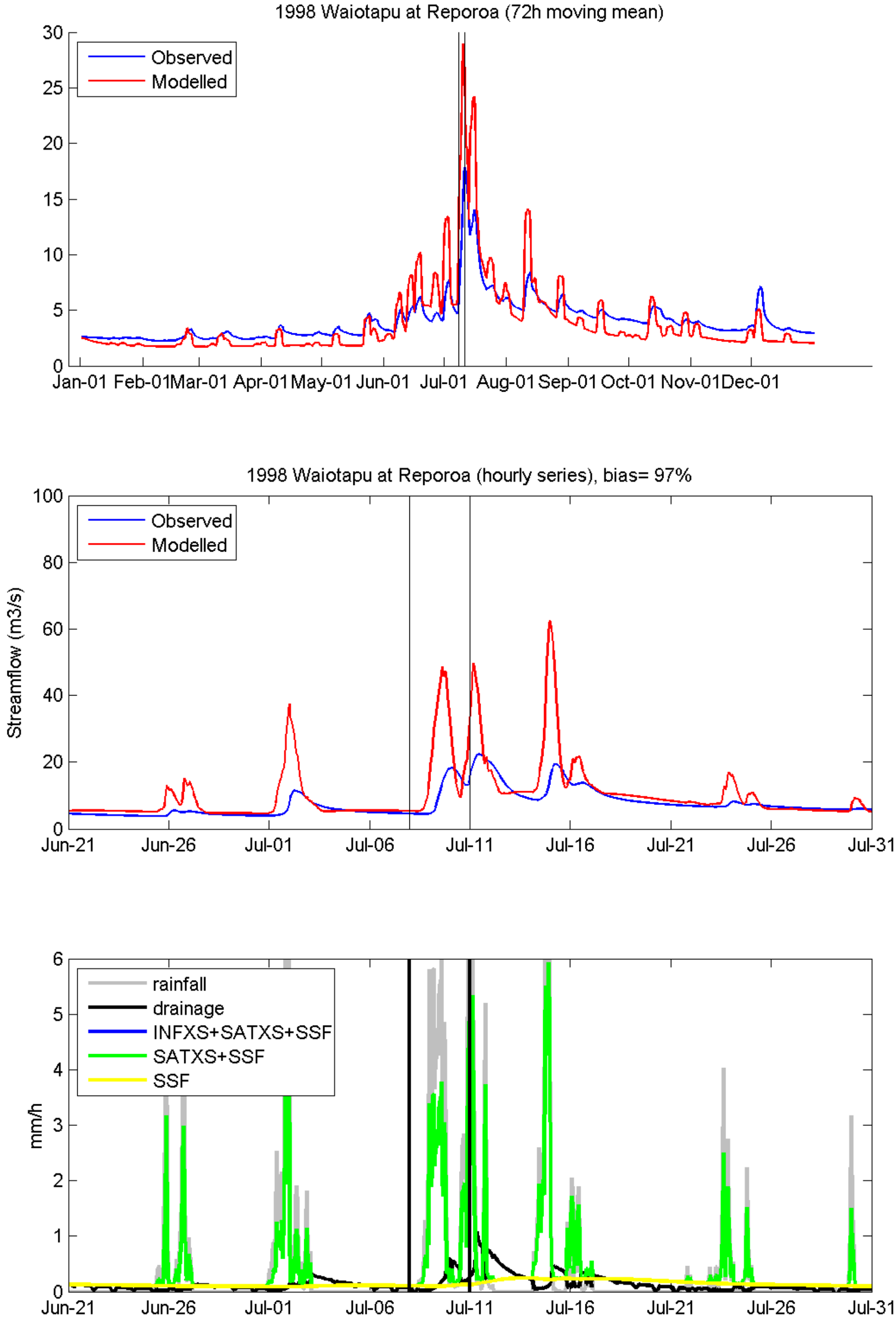


Figure 16: **TopNet validation plot for 1998 flood, Waiotapu at Reporoa. Top panel shows observed and modelled 72-h moving mean flows; Middle panel shows observed and modelled hourly flows; Bottom panel shows which runoff generation mechanisms were operating at one sub-catchment within each monitored catchment shown.**

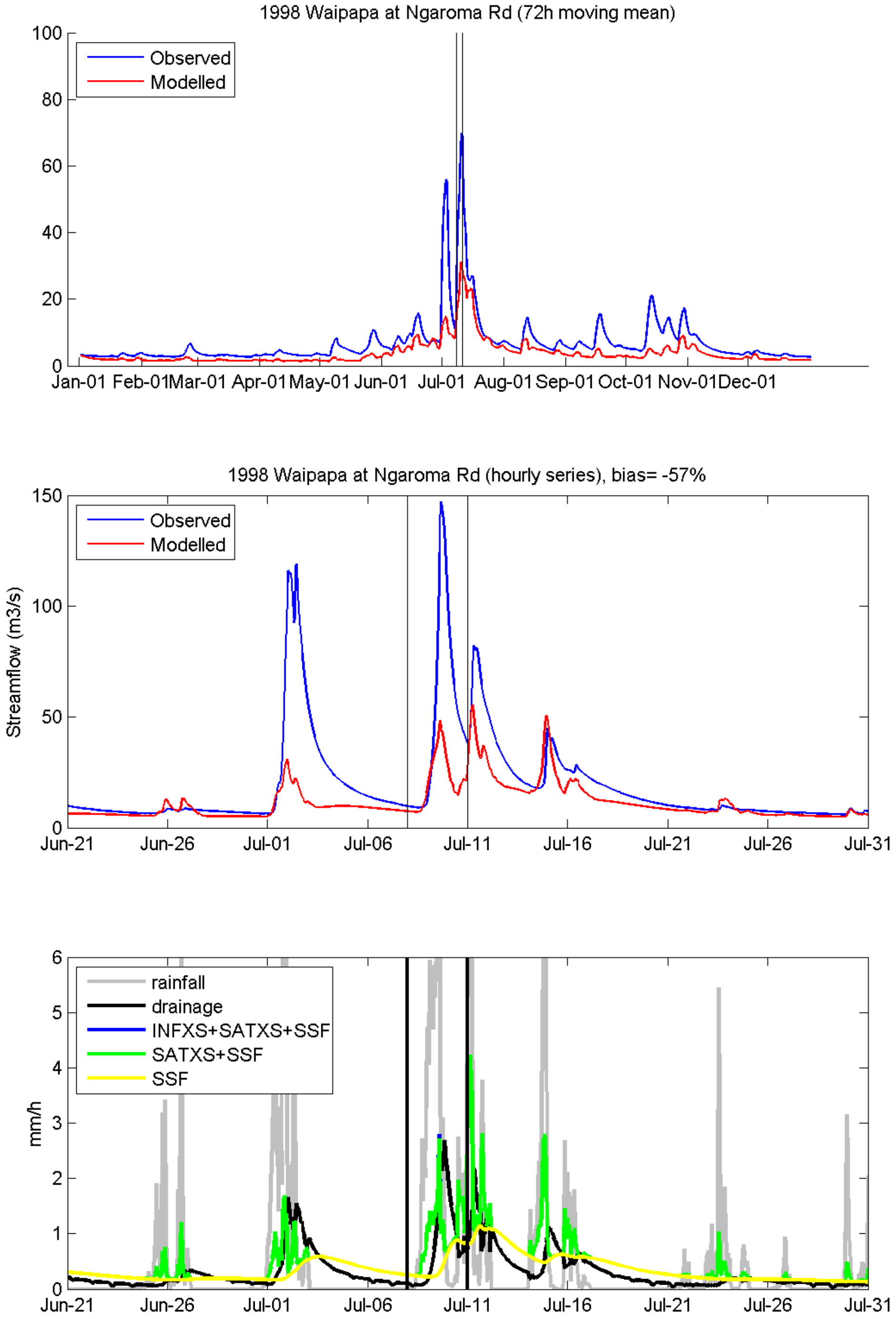


Figure 17: **TopNet validation plot for 1998 flood, Waipapa at Ngaroma Road. Top panel shows observed and modelled 72-h moving mean flows; Middle panel shows observed and modelled hourly flows; Bottom panel shows which runoff generation mechanisms were operating at one sub-catchment within each monitored catchment shown.**

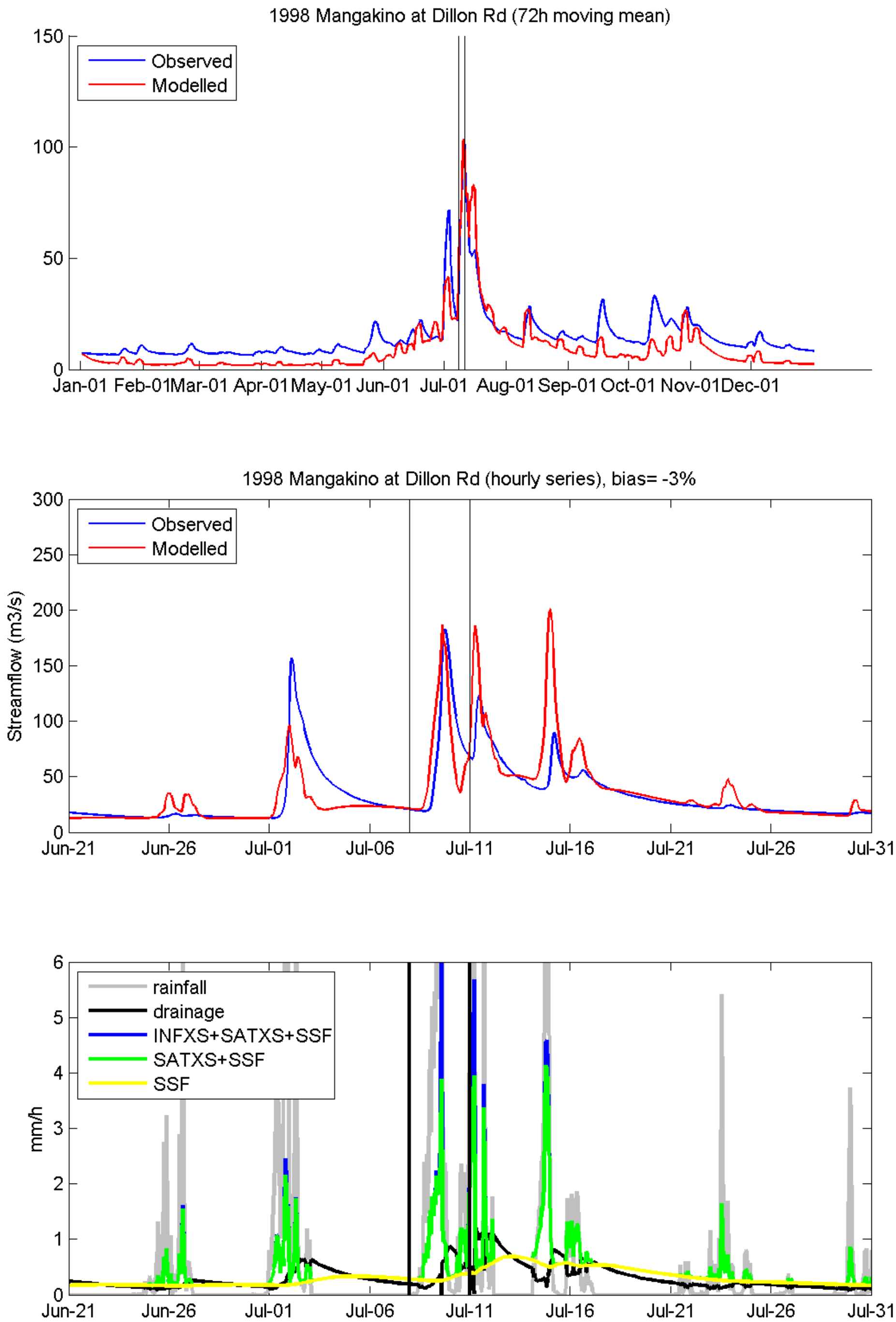


Figure 18: **TopNet validation plot for 1998 flood, Mangakino at Dillon Road. Top panel shows observed and modelled 72-h moving mean flows; Middle panel shows observed and modelled hourly flows; Bottom panel shows which runoff generation mechanisms were operating at one sub-catchment within each monitored catchment shown.**

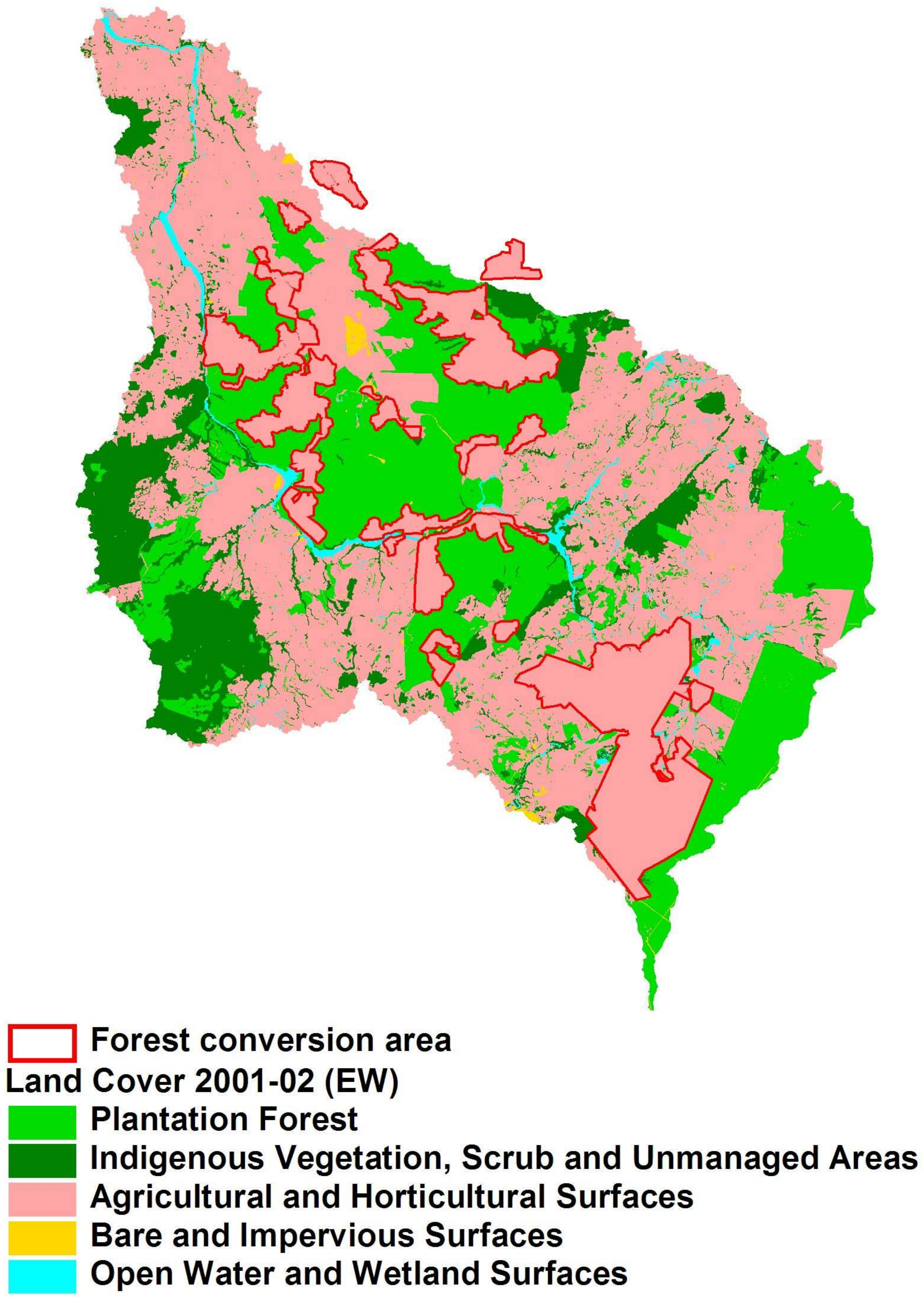


Figure 19: **Assumed future land cover after forest removal is complete**

The most obvious hydrological change due to land use conversion is expected to be in the infiltration characteristics of the soils. The saturated hydraulic conductivity at the ground surface is the model parameter which is altered, to make a prediction of the impact of forest conversion to dairy pasture. A map of hydraulic conductivity was prepared for the current land cover (see Section **Error! Reference source not found.**), and for the land cover after the projected forest conversion is completed (by changing the hydraulic conductivity within the red outlines in Figure 19 to the values indicated by Taylor et al (2009) 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. Each modelled subcatchment has a different value of hydraulic conductivity, obtained by overlaying the subcatchment boundaries on a map of hydraulic conductivity, and assigning the average value. The hydraulic conductivity value for a model sub-catchment is found by taking the average of all conductivity values in the catchment.

The change from forest to dairy will also change the 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 ran events is that pasture soils are somewhat wetter than forest soils, other things 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 8.

5.1. Synthetic rainfall events

To assess the potential impact of land use change, the flood responses of 6 synthetic storm events of 3-day duration and various magnitudes are simulated using the model presented above, via two case studies. The 3-day duration was chosen as typical of severe flooding events in the lower Waikato. The 6 synthetic storms represent rainfall events with return periods of approximately 5, 10, 20, 50, 100 and 500 years. The expected total 72-hour rainfall depths for these 6 return periods were estimated using the HIRDS system (Thompson 2002) for regular grid points over the entire catchment. These estimated total rainfall depths were distributed in time in two case studies according to two storm profiles (July 1998 an February 1958, Figure 20) and scaled for each case using estimates of areal reduction factors (ARF).

HIRDS 72-hour rainfalls for the 6 return periods are shown in Figures 21, 22, and 23, and summarised in Table 9. For a 3-day total over a 4500 km2 catchment, an areal reduction factor was estimated as 0.88 (Figure 1 of Tomlinson and Thompson (1980)). The reduction factors adopted in this study are somewhat smaller. Discussions of ARF in Tomlinson (1978) indicate that severe rainstorms are extremely variable in their depth-area characteristics, and so Tomlinson and Thompson (1980) recommend that ARF should be used with caution, especially when dealing with rainfalls of long return period.

Table 9: Catchment mean rainfall information over middle Waikato

Return Period (y)	5	10	20	50	100	500
HIRDS 72-h Rainfall (mm)	129	148	169	202	233	302
July 1998 pattern	83	96	109	130	150	191
February 1958 pattern	97	111	127	152	175	227

In the first case study, the rainfall was distributed in space and time according to the July 1998 rainfall event. The initial conditions used to simulate each synthetic storm were the modelled conditions as at the start of the July 1998 event. We estimate that the July 8-11 storm had return period for 4500 sq km catchment mean 72-h rainfall of between 10 and 25 years. Henderson and Thompson (2000) report the 72-h Taupo-Karapiro tributary runoff for the July 1998 event (3 days starting 1998-07-10) as having a return period of 26 years. We do not expect a precise match between rainfall and runoff return periods, because event runoff is also dependent on other factors (e.g. antecendent conditions, choice of baseflow separation method). The largest 9am-to-9am 3-day catchment mean rainfall recorded over the middle Waikato in July 1998 was 134 mm from 9am 8 July to 9am 11 July. The largest 3-day total for any start time is known at gauges, but not for the catchment as a whole. An upper bound is the largest 4-day catchment mean rain in July 1998, which was 157 mm from 9am 8 July to 9am 12 July. We adopted 145 mm as an estimate. Table 9 gives the resulting scaling factors needed to convert the 8-11 July 1998 rainfalls to rainfall events of the various return periods. Neither the precise choice of the ARF nor the July 1998 rainfall total are critical choices – their purpose is to create rainfall events of appropriate magnitudes for evaluation of a land use scenario. They are not intended for design flood estimation.

In the second case study, the storm totals at each point in the catchment were assumed to be given by the HIRDS 3-day totals, multiplied by an areal reduction factor (see below). The catchment average storm profile from a February 1958 rainfall event (Figure 20) was assumed to be spatially uniform, i.e. it was assumed that the storm had the same temporal profile (Figure 20) all over the catchment. For a 3-day total over a 4500 km^2 catchment, 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 (Table 9). The initial conditions used to simulate each synthetic storm were the modelled conditions at 23rd of February 2004, to reflect wet initial conditions.

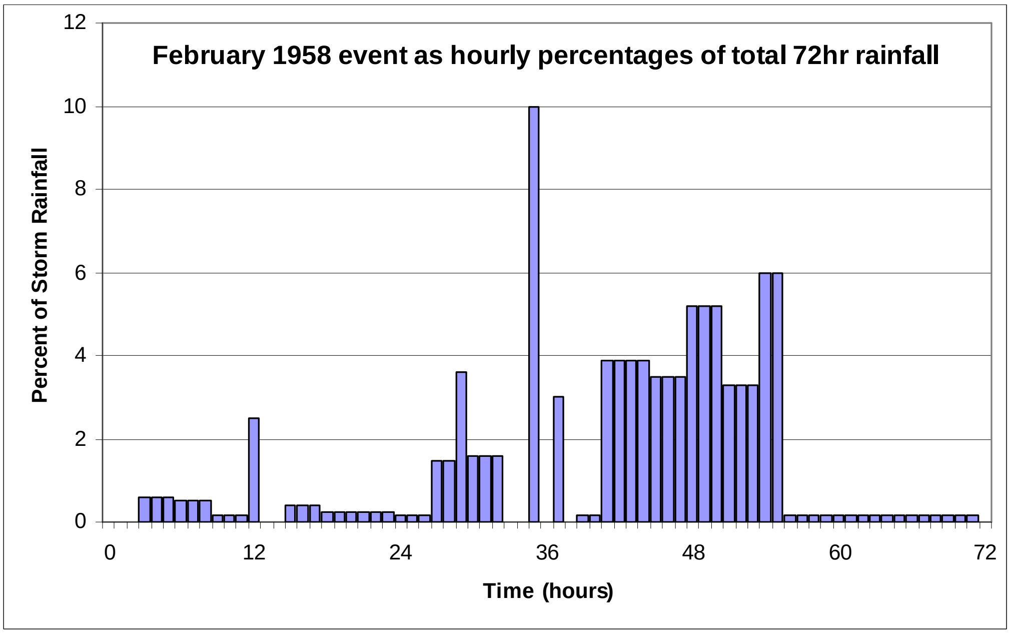
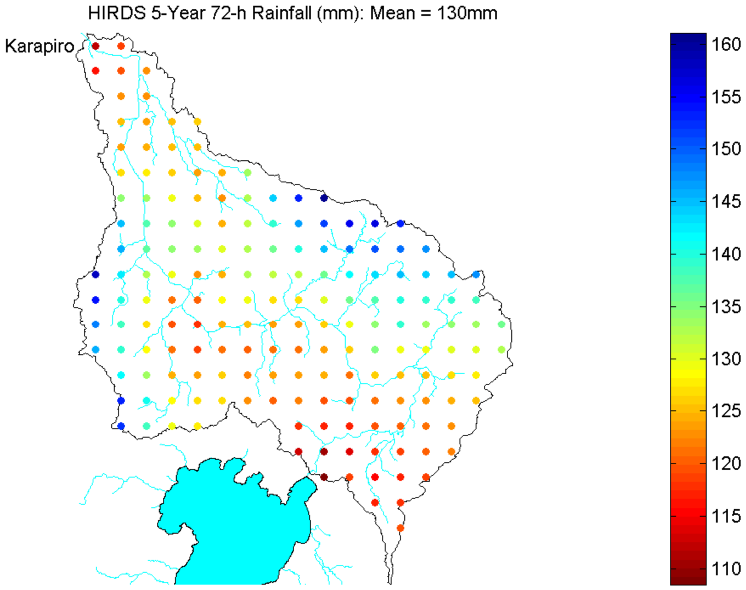


Figure 20: **Storm rainfall profile for the February 1958 as applied to model land use change impacts.**

The 6 synthetic rain events in each case study were each used to drive the TopNet model, under both the current and the future land use scenarios. Flows were aggregated to the dam tributary catchments by the stream routing algorithm of TopNet. The flows to each of the dam catchments (Table 10) are provided as hourly time series for use in the Waikato River flood routing model.

Table 10: **Reach identifiers for Waikato River locations in the River Environment Classification digital river network, used to extract modelled river flow information from TopNet model.**

name	NZREACH
Taupo	3043367
Ohakuri	3034685
Atiamuri	3034459
Whakamaru	3034469
Maraetai	3032974
Waipapa	3030179
Arapuni	3024654
Karapiro	3020360



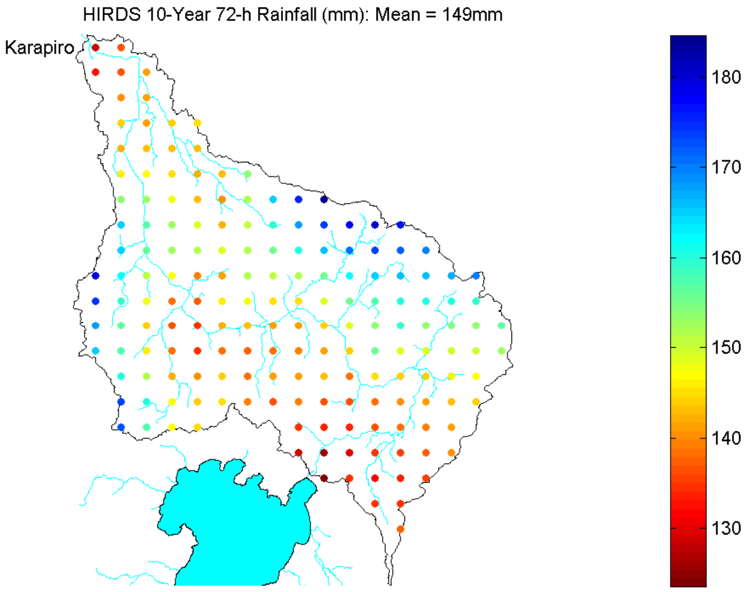
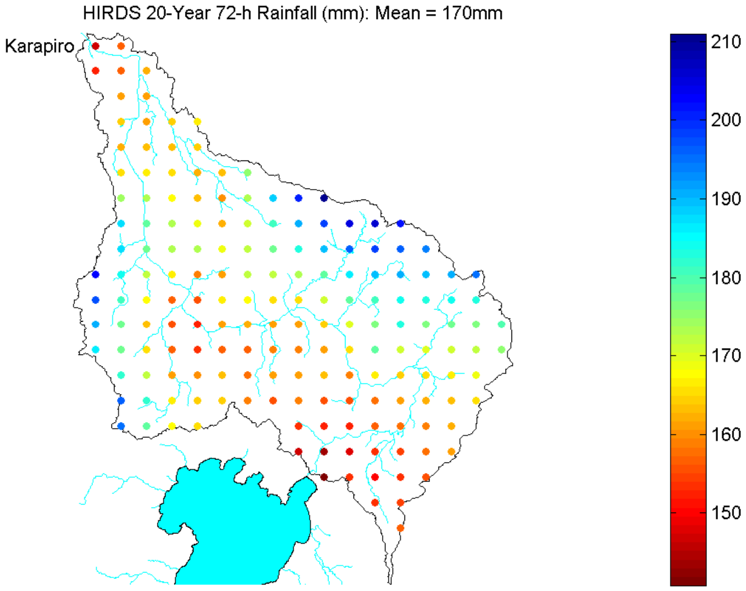


Figure 21: HIRDS 5- and 10-year 72-h rainfalls over the middle Waikato



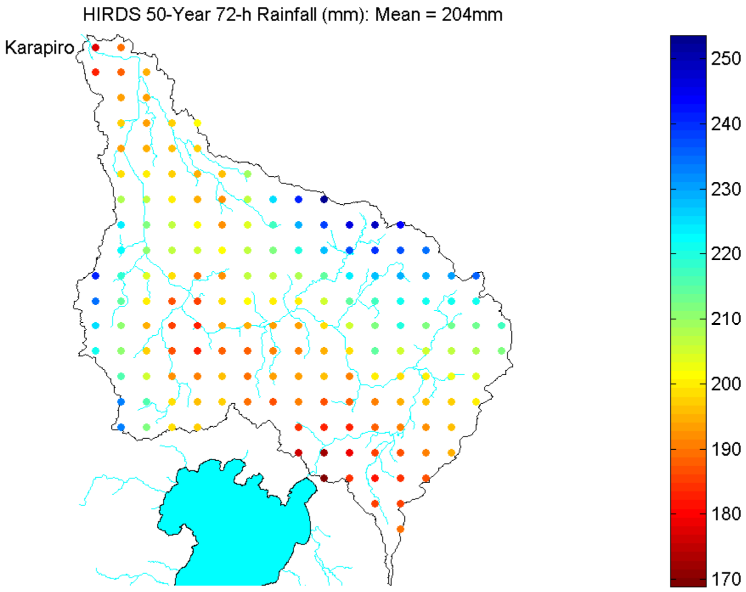
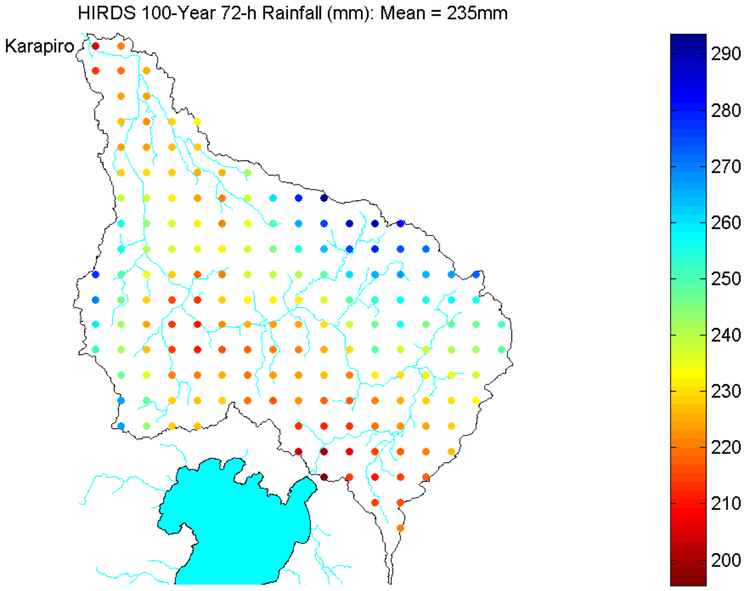


Figure 22: HIRDS 20- and 50-year 72-h rainfalls over the middle Waikato



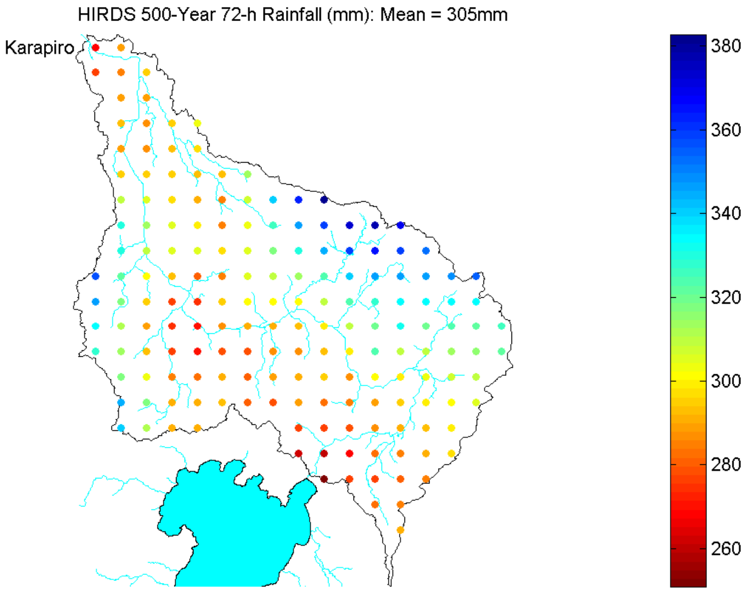


Figure 23: HIRDS 100- and 500-year 72-h rainfalls over the middle Waikato

5.2. Tributary flood simulations for the July 1998 synthetic rainfall

Figure 24 shows the simulated hyetographs and hydrographs for the 7 dam catchments for the current and converted cases for the 100-year return period event. Four of the catchments show no appreciable change in the hydrographs due to land use conversion.

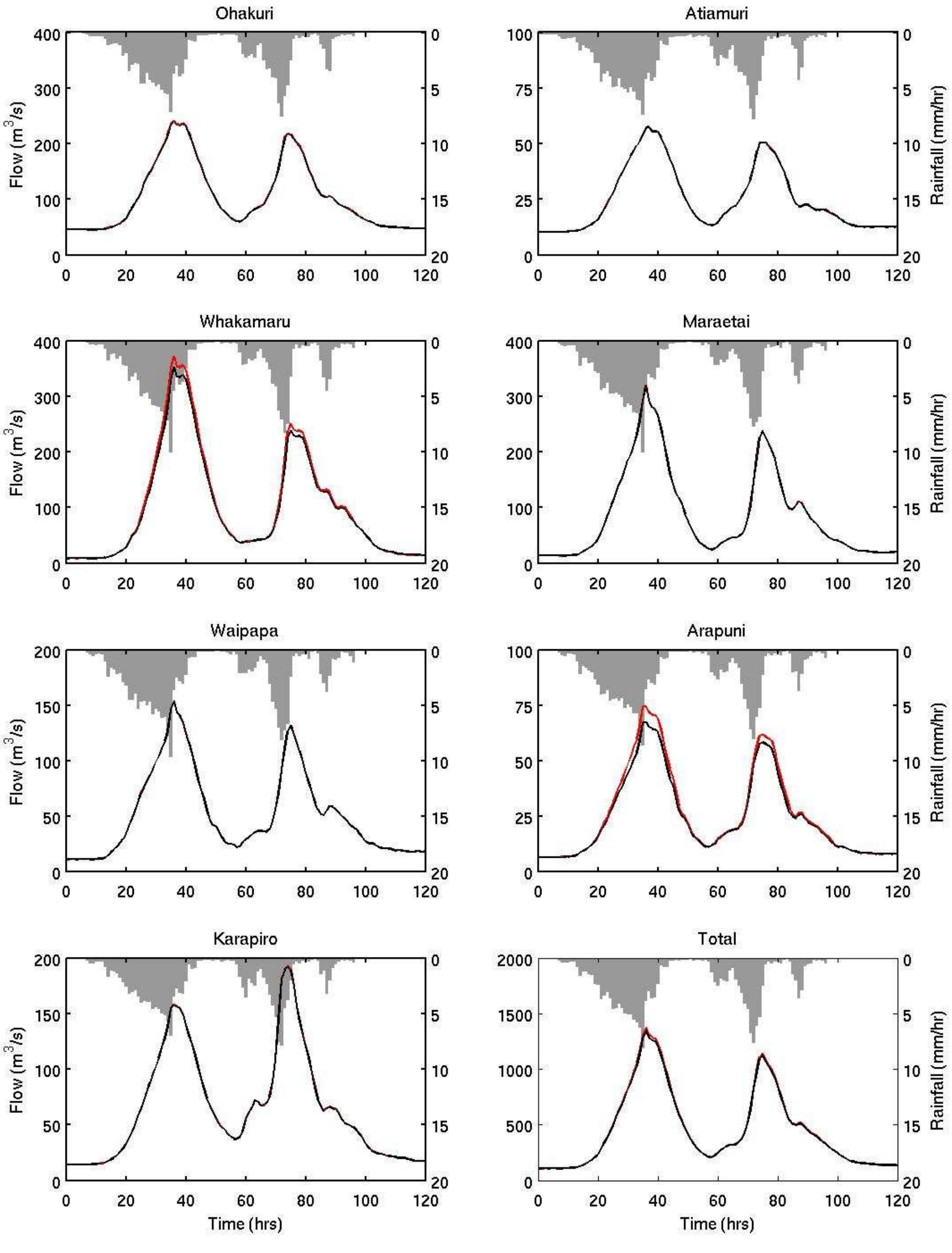


Figure 24: Simulated hydrographs for each of the dam catchments as simulated by TopNet for the 100-year rainfall event under current (black lines) and converted (red lines) land use scenarios.

Figure 25 displays the model results as hydrographs of total outflow from the study area for the 6 synthetic events and the current and converted scenarios.

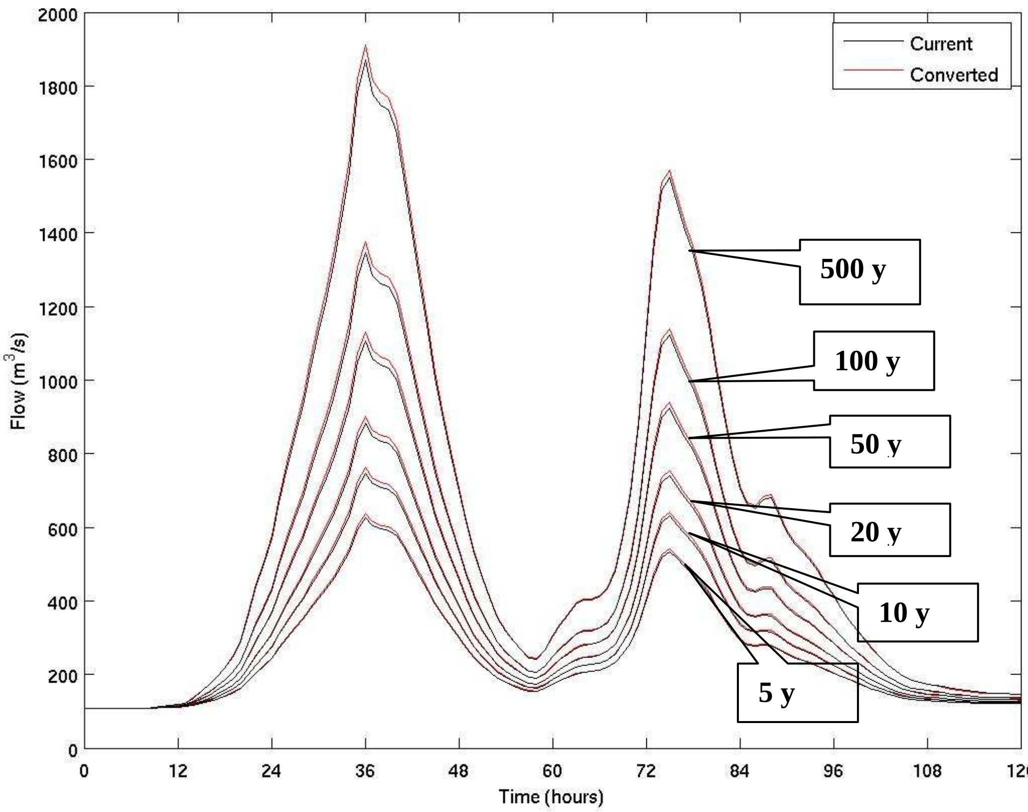


Figure 25: Simulated Taupo-Karapiro inflow hydrographs for the 6 synthetic rainfall events under current (black) and converted (red) land use scenarios.

The greatest absolute changes in flow are at peak flow and the largest percentage increases are correlated with the absolute flow and occur at the hydrograph peak (Figure 26).

Figure 27 shows the changes in hydrograph peak for different return periods and the different catchments as well as the total Taupo-Karapiro inflows ('combined'). This indicates again that only three dam catchments, Ohakuri, Whakamaru, and Arapuni, show a modelled detectable response to land use conversion, in terms of their hydrograph changes and contribute to the changes in the study area hydrograph. Note that relative changes show a maximum at 50/100 year return intervals for two catchments. This indicates that storms of this magnitude will essentially saturate the soil regardless of land cover. Thus while more intense storms will continue to produce higher flood flows, the relative increase in flows diminishes.

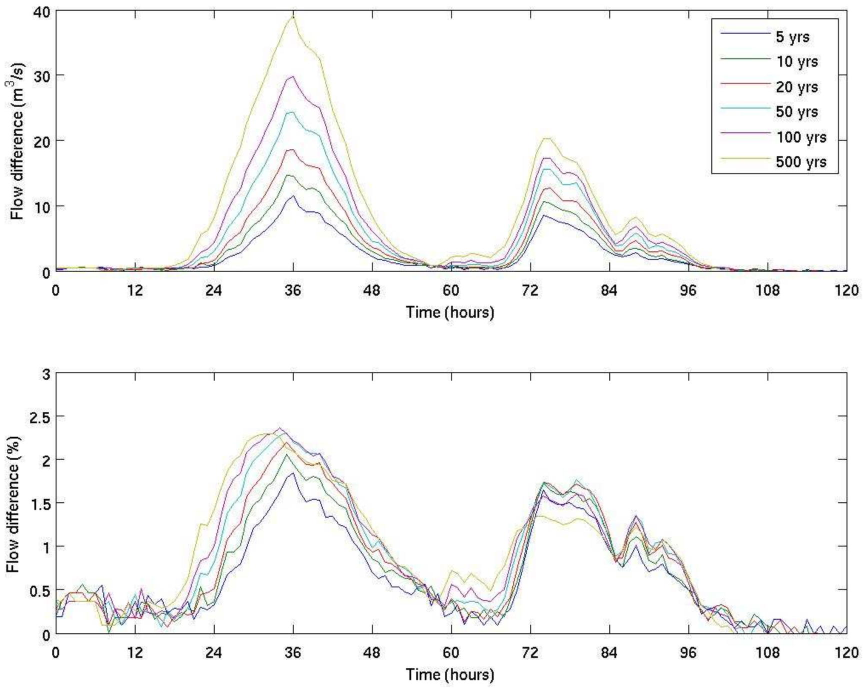


Figure 26: Difference in simulated Taupo-Karapiro inflow due to land use change for the 6 storm scenarios. Differences are expressed as changes in m^3/s (top graph) and percent (bottom graph) relative to the current land use scenario.

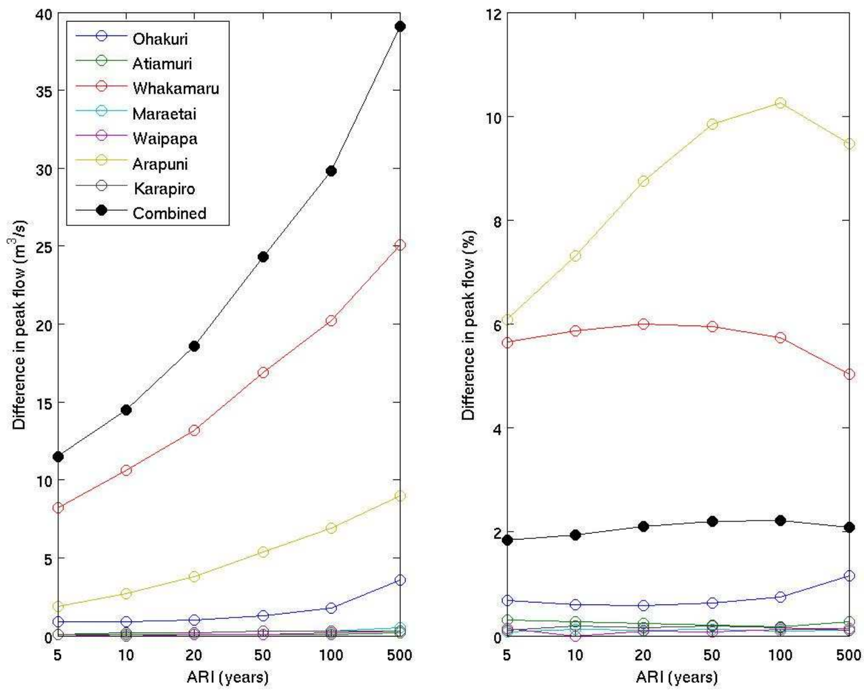


Figure 27: Peak flow differences in m^3/s (left) and percent (right) for the converted scenarios compared to current land use hydrographs. Results are displayed for different return intervals and the dam catchments as well as the outlet.

Table 11 summarizes hydrograph peaks and the changes for all catchments, return intervals and the current and converted scenarios, highlighting catchments and return intervals at which appreciable increases are predicted.

Table 11: Simulated hydrograph peaks for current (first panel) and converted (second panel) scenarios, for the different return intervals, and catchments. Third and fourth panel show peak hydrograph changes in m3/s and percentage.

Return Interval	Ohakuri	Atiamuri	Whakamaru	Maraetai	Waipapa	Arapuni	Karapiro	Taupo-Karapiro
	PeakCurrent [m^3/s]							
5	132	33	145	135	75	31	88	625
10	151	37	181	166	87	37	105	747
20	171	42	220	200	102	43	125	884
50	205	50	284	258	127	55	157	1107
100	240	58	352	320	154	67	193	1347
500	314	75	498	456	216	95	269	1871
	PeakConvert [m^3/s]							
5	133	33	153	135	75	33	88	637
10	151	37	191	166	87	40	105	762
20	172	42	233	201	102	47	125	902
50	206	50	301	258	127	60	158	1131
100	242	58	372	320	154	74	193	1377
500	317	76	523	456	216	104	269	1910
	PeakDiffAbs [m^3/s]							
5	1	0	8	0	0	2	0	12
10	1	0	11	0	0	3	0	15
20	1	0	13	0	0	4	0	19
50	1	0	17	0	0	5	0	24
100	2	0	20	0	0	7	0	30
500	4	0	25	1	0	9	0	39
	PeakDiffPerc [%]							
5	1	0	6	0	0	6	0	2
10	1	0	6	0	0	7	0	2
20	1	0	6	0	0	9	0	2
50	1	0	6	0	0	10	0	2
100	1	0	6	0	0	10	0	2
500	1	0	5	0	0	9	0	2

To gain a preliminary indication of the impact of land conversion impacts on Waikato River floods for the different return periods, we computed the peak 72-hr moving average flows. These were compared for the different catchments and for the different return intervals (Figure 28, Table 14).

The model outputs indicate the impact of land use conversion on 72hr Taupo-Karapiro flood volumes would be a 1% increase when using the 5-10 year rainfall test events, and a 2% increase when using the 100-500 year rainfall test events. The modelled increase in flood volume is associated mainly with the Whakamaru, Arapuni and Ohakuri dam catchments.

5.3. Tributary flood simulations for the February 1958 synthetic rainfall

Figure 29 shows the simulated heyetographs and hydrographs for the 7 dam catchments for the current and converted cases for the 100-year return period event. Again, four of the catchments show no appreciable change in the hydrographs due to land use conversion.

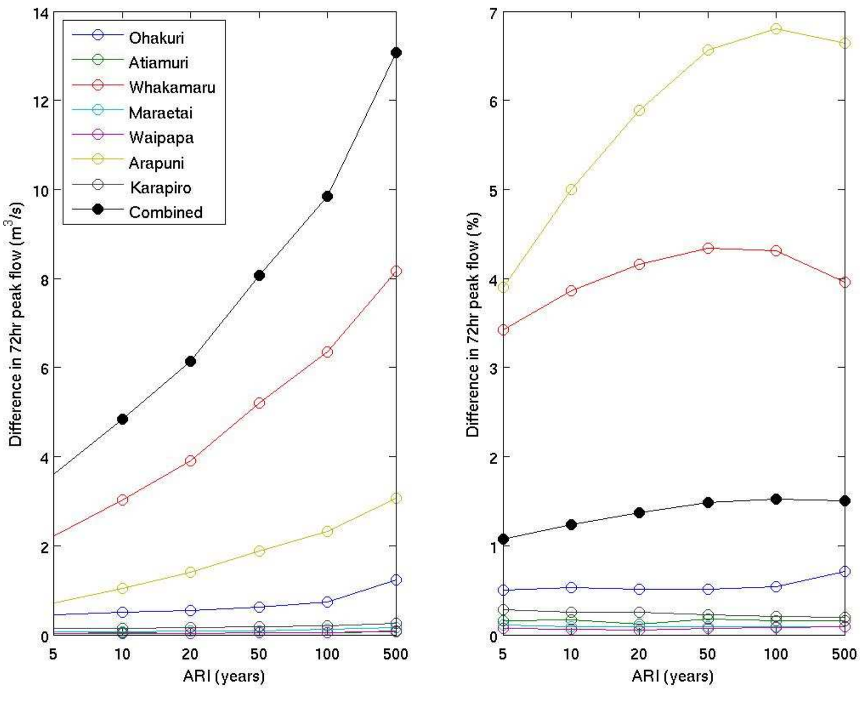


Figure 28: Peak 72-average flow differences in m^3/s (left) and percent (right) for the converted scenarios compared to current land use hydrographs. Results are displayed for different return intervals and the dam catchments as well as the total inflow.

Table 12: Peak 72-average flows for current (first panel) and converted (second panel) scenarios, for the different return intervals, and catchments. Third and fourth panel show changes in m3/s and percentage.

Return Interval	Ohakuri	Atiamuri	Whakamaru	Maraetai	Waipapa	Arapuni	Karapiro	Taupo-Karapiro
	72hr-Current [m3/s]							
5	88	21	65	60	38	18	48	338
10	96	23	79	72	44	21	56	390
20	106	25	94	84	50	24	64	447
50	122	29	120	106	60	29	78	543
100	138	33	147	129	72	34	93	645
500	173	42	206	180	97	46	128	869
	72hr-Convert [m3/s]							
5	88	21	67	60	38	19	48	342
10	97	23	82	72	44	22	56	394
20	107	25	98	84	50	25	64	454
50	122	29	125	106	60	31	78	551
100	139	33	154	129	72	36	93	655
500	174	42	215	180	98	49	126	882
	DiffAbs [m3/s]							
5	0	0	2	0	0	1	0	4
10	1	0	3	0	0	1	0	5
20	1	0	4	0	0	1	0	6
50	1	0	5	0	0	2	0	8
100	1	0	6	0	0	2	0	10
500	1	0	8	0	0	3	0	13
	DiffPerc [%]							
5	1	0	3	0	0	4	0	1
10	1	0	4	0	0	5	0	1
20	1	0	4	0	0	6	0	1
50	1	0	4	0	0	7	0	1
100	1	0	4	0	0	7	0	2
500	1	0	4	0	0	7	0	2

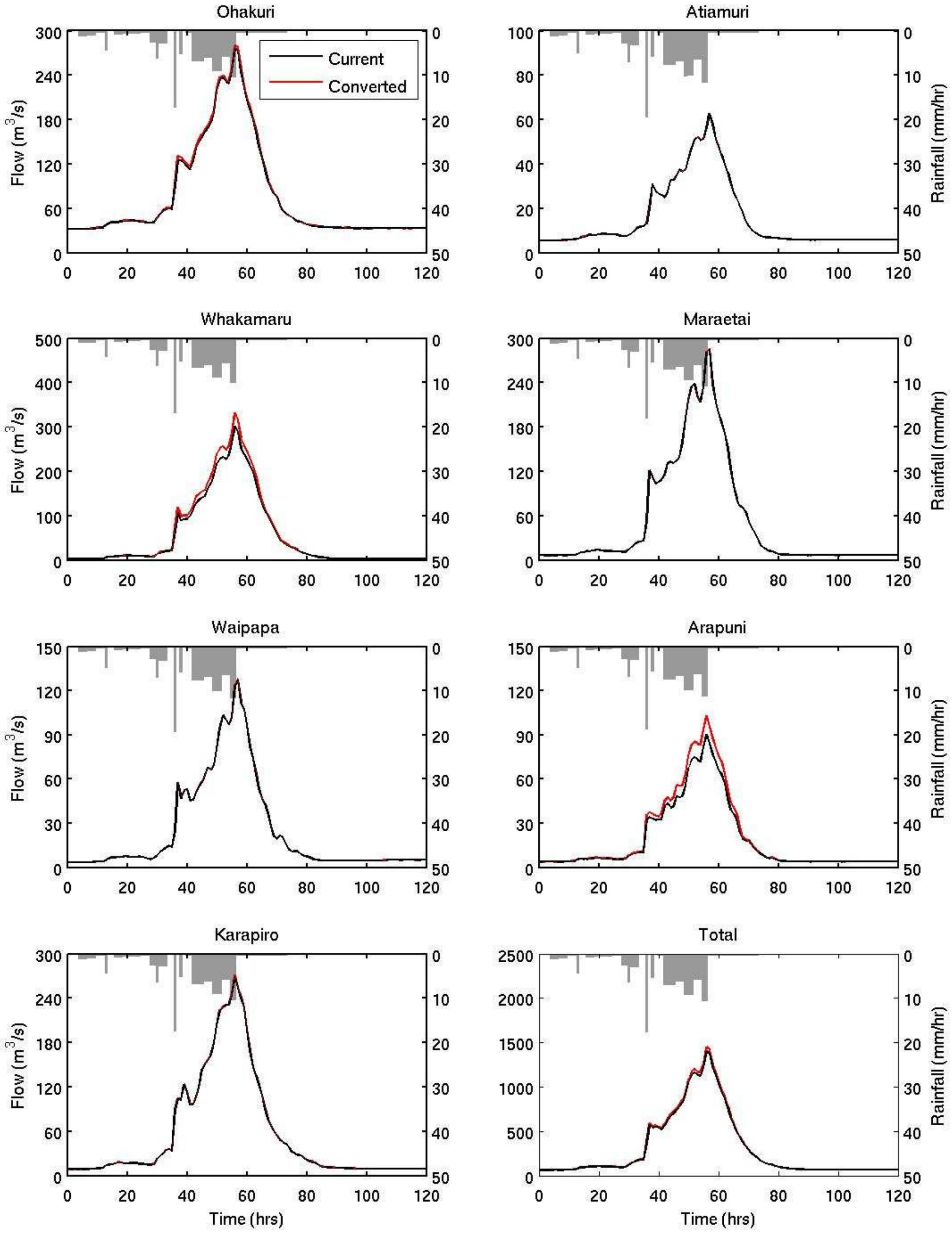


Figure 29: **Simulated hydrographs for each of the dam catchments as simulated by TopNet for the 100-year rainfall event under current (black lines) and converted (red lines) land use scenarios.**

Figure 30 displays the model results as hydrographs of total outflow from the study area for the 6 synthetic events and the current and converted scenarios.

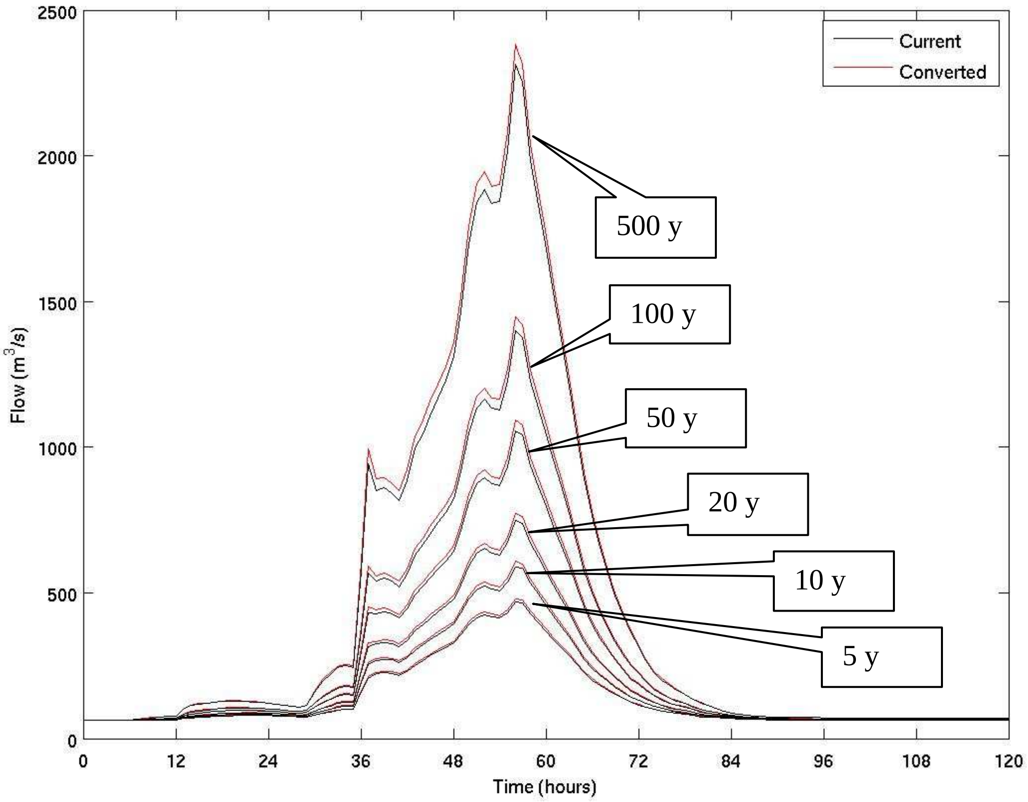


Figure 30: Simulated Taupo-Karapiro inflow hydrographs for the 6 synthetic rainfall events under current (black) and converted (red) land use scenarios.

The greatest absolute changes in flow are at peak flow (Figure 31), and the largest percentage increases occur on the rising limb of the hydrograph.

Figure 32 shows the changes in hydrograph peak for different return periods and the different catchments as well as the total Taupo-Karapiro inflows (‘combined’). This indicates again that only three dam catchments, Ohakuri, Whakamaru, and Arapuni, show a modelled detectable response to land use conversion, in terms of their hydrograph changes and contribute to the changes in the study area hydrograph. Same ‘peak change’ behaviour at 50/100 years return intervals is observed for the Arapanui and Whakamaru catchments.

Table 13 summarizes hydrograph peaks and the changes for all catchments, return intervals and the current and converted scenarios, highlighting catchments and return intervals at which detectable increases are predicted.

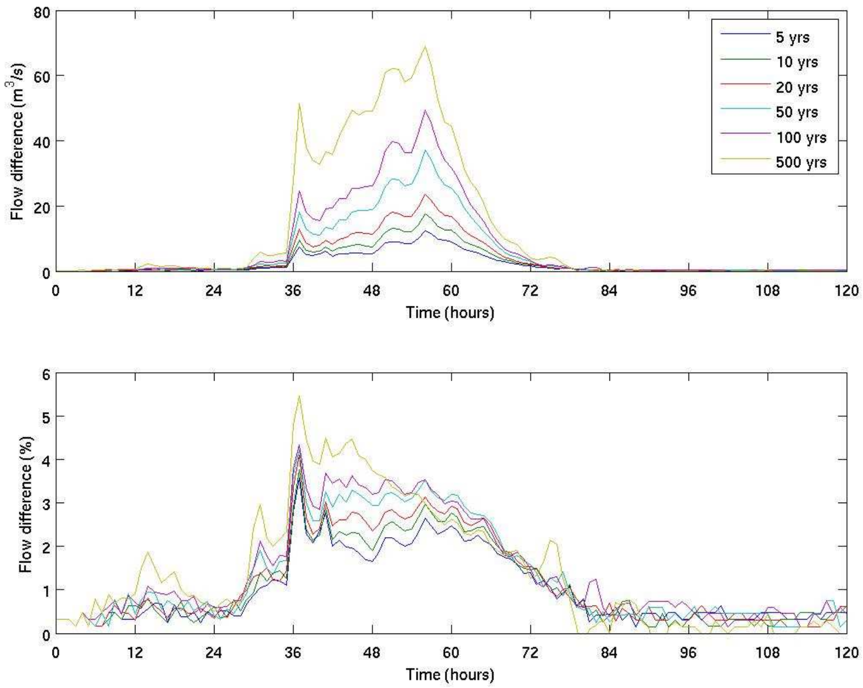


Figure 31: Difference in simulated Taupo-Karapiro inflow due to land use change for the 6 storm scenarios. Differences are expressed as changes in m^3/s (top graph) and percent (bottom graph) relative to the current land use scenario.

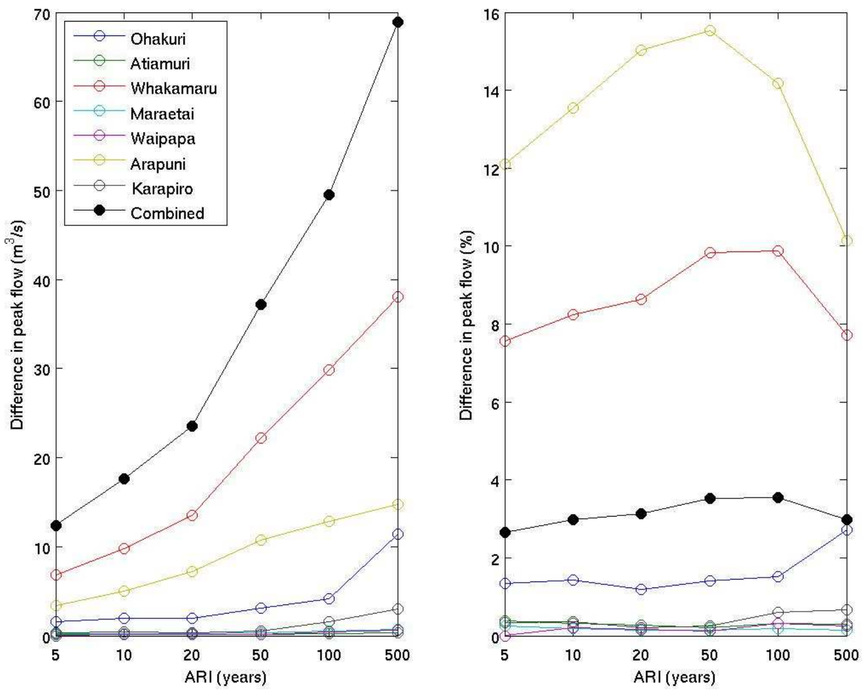


Figure 32: Peak flow differences in m^3/s (left) and percent (right) for the converted scenarios compared to current land use hydrographs. Results are displayed for different return intervals and the dam catchments as well as the outlet.

Table 13: Simulated hydrograph peaks for current (first panel) and converted (second panel) scenarios, for the different return intervals, and catchments. Third and fourth panel show peak hydrograph changes in m3/s and percentage.

Return Intervals	Ohakuri	Atiamuri	Whakamaru	Maraetai	Waipapa	Arapuni	Karapiro	Taupo-Karapiro
	PeakCurrent [m3s-1]							
5	119	26	90	83	37	28	90	468
10	140	31	119	109	46	37	114	590
20	169	38	156	142	60	48	145	748
50	220	49	226	209	90	69	205	1056
100	276	63	302	285	128	90	270	1399
500	418	104	494	478	238	146	444	2313
	PeakConvert [m3s-1]							
5	121	26	97	83	37	32	90	481
10	142	31	129	109	46	42	114	607
20	170	38	170	142	60	55	146	771
50	223	49	248	209	90	80	205	1093
100	280	63	331	286	128	103	271	1449
500	430	104	532	479	238	161	447	2382
	PeakDiffAbs [m3s-1]							
5	2	0	7	0	0	3	0	12
10	2	0	10	0	0	5	0	18
20	2	0	14	0	0	7	0	23
50	3	0	22	0	0	11	1	37
100	4	0	30	1	0	13	2	50
500	11	0	38	1	1	15	3	69
	PeakDiffPerc [%]							
5	1	0	8	0	0	12	0	3
10	1	0	8	0	0	14	0	3
20	1	0	9	0	0	15	0	3
50	1	0	10	0	0	16	0	4
100	2	0	10	0	0	14	1	4
500	3	0	8	0	0	10	1	3

To gain a preliminary indication of the impact of land conversion impacts on Waikato River floods for the different return periods, we computed the peak 72-hr moving average flows. These were compared for the different catchments and for the different return intervals (Figure 33, Table 14).

5.4. Influence of soil depth on simulation results

Our estimates of soil depths are based on the land resource inventory national databases. The values are regional estimates and can show large spatial variability. Moreover, it is expected that soil rooting depths and water holding capacities change with land–use. We carried out a test to observe the influence of that parameter on our modelling results by changing the soil capacity parameter in TopNet uniformly across the catchment. The simulations show results consistent with our baseline simulations. If the soil capacity is reduced (which would be expected in a forest-to-pasture conversion as rooting depth declines, Figure 34), the Arapanui and Whakamaru catchments reach saturation even under annual events and hence land-use change impacts on flooding are less pronounced for the higher return periods (compare Figure 33). The overall whole-catchment figures for land-use impacts on flooding do not change significantly.

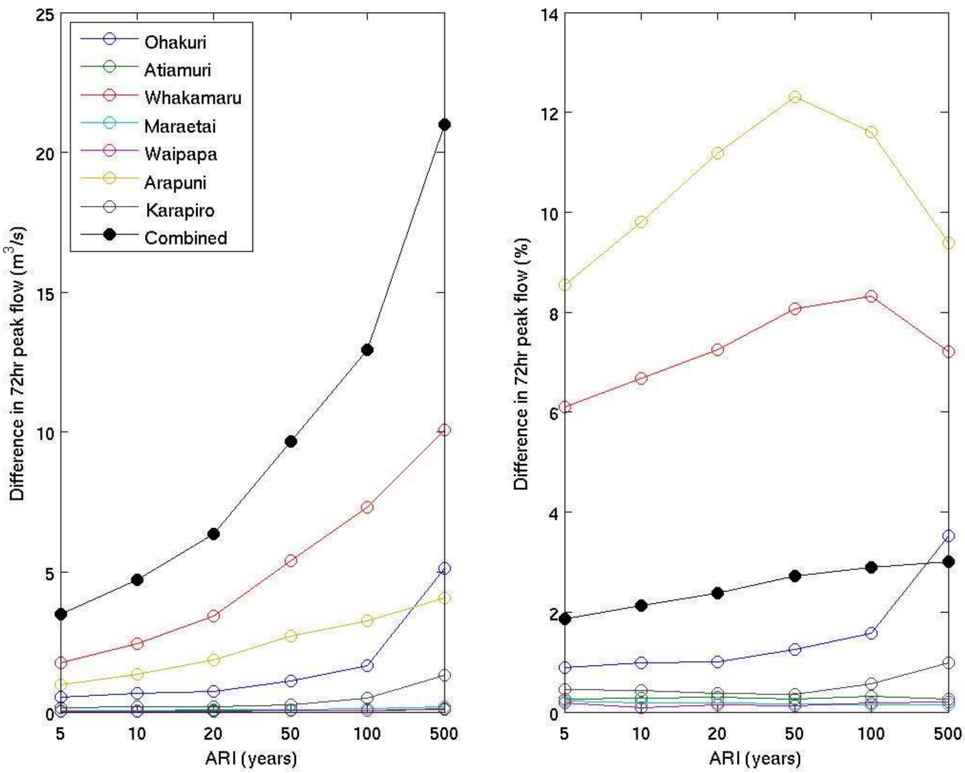


Figure 33: **Peak 72-average flow differences in m^3/s (left) and percent (right) for the converted scenarios compared to current land use hydrographs. Results are displayed for different return intervals and the dam catchments as well as the total inflow.**

Table 14: Peak 72-average flows for current (first panel) and converted (second panel) scenarios, for the different return intervals, and catchments. Third and fourth panel show changes in m3/s and percentage. Light shade indicate catchments with a detectable change, dark shades return intervals at which the three catchments show detectable changes in hydrograph.

	Ohakuri	Atiamuri	Whakamaru	Maraetai	Waipapa	Arapuni	Karapiro	Taupo-Karapiro
	72hr-Current [m3/s]							
5	59	12	29	29	14	11	34	188
10	66	13	37	36	17	14	42	223
20	74	15	47	45	20	17	51	268
50	89	18	67	63	28	22	68	354
100	104	21	88	83	38	28	86	448
500	145	32	140	134	65	44	135	696
	72hr-Convert [m3/s]							
5	60	12	30	29	14	12	35	192
10	66	13	39	36	17	15	42	228
20	75	15	51	45	21	18	51	275
50	90	18	72	63	28	25	68	364
100	106	22	95	83	38	31	86	461
500	151	32	150	134	66	48	136	717
	DiffAbs [m3/s]							
5	1	0	2	0	0	1	0	4
10	1	0	2	0	0	1	0	5
20	1	0	3	0	0	2	0	6
50	1	0	5	0	0	3	0	10
100	2	0	7	0	0	3	0	13
500	5	0	10	0	0	4	1	21
	DiffPerc [%]							
5	1	0	6	0	0	9	0	2
10	1	0	7	0	0	10	0	2
20	1	0	7	0	0	11	0	2
50	1	0	8	0	0	12	0	3
100	2	0	8	0	0	12	1	3
500	4	0	7	0	0	9	1	3

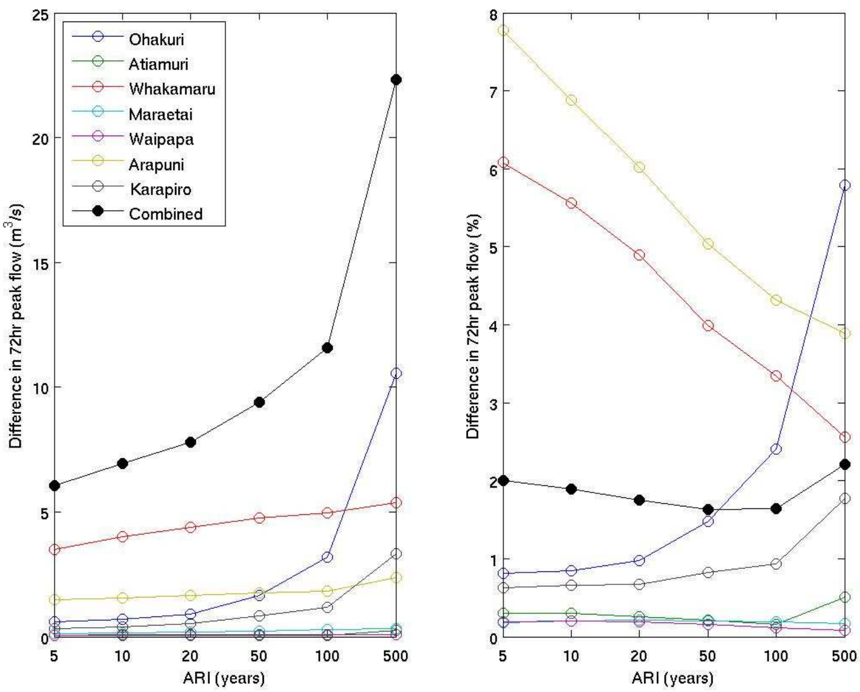


Figure 34: Simulated changes in 72-hour peak flows, assuming only half the capacity of the soil for the whole catchment (compare to Figure 33).

The model outputs indicate the impact of land use conversion on 72hr Taupo-Karapiro flood volumes would be a 2% increase when using the 5-10 year rainfall test events, and a 3% increase when using the 100-500 year rainfall test events. The modelled increase in flood volumes were again associated mainly with the Whakamaru, Arapuni and Ohakuri dam catchments.

5.5. Local flooding

A preliminary assessment of impacts on local flooding can be made using the TopNet results from the test events used above, looking at the modelled results from smaller catchments. TopNet simulates the dam catchments by computing runoff from several hundred subcatchments, and routing them to the main stem of the Waikato. By examining the modelled outflows at locations within the dam catchments, an estimated increase in flood peak can be obtained. It is important to note that this test event may not be ideal for studying smaller catchments – further discussion of appropriate test events might be needed.

The model results for the effect of land use change on flood peaks the 10-year and 100-year test events are shown in Figure 35 and Figure 36, and summarised in Table 15.

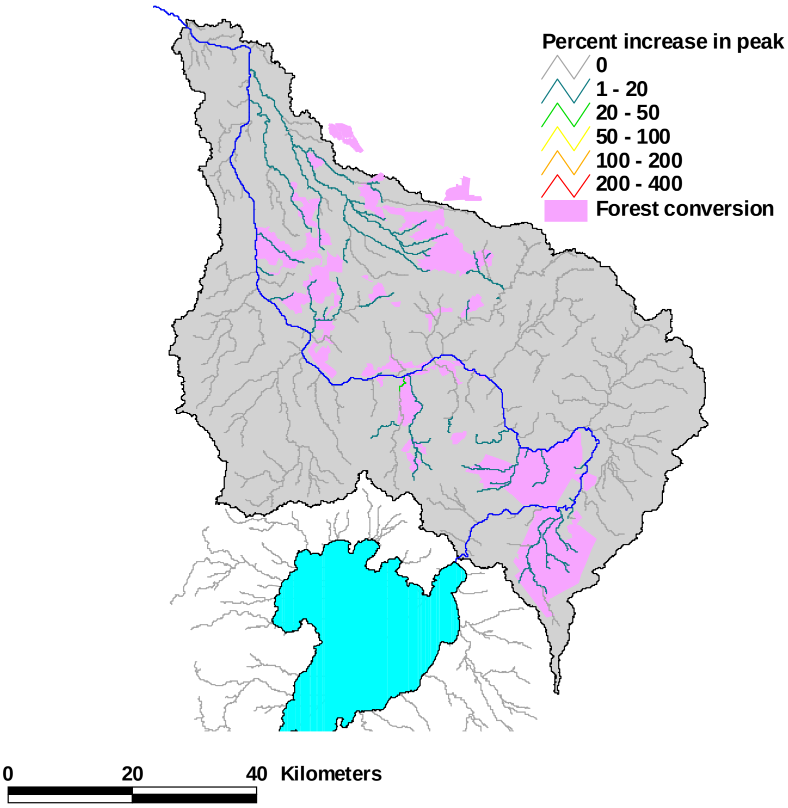


Figure 35: Percentage increase in peak flow for 10 year test rainfall event.

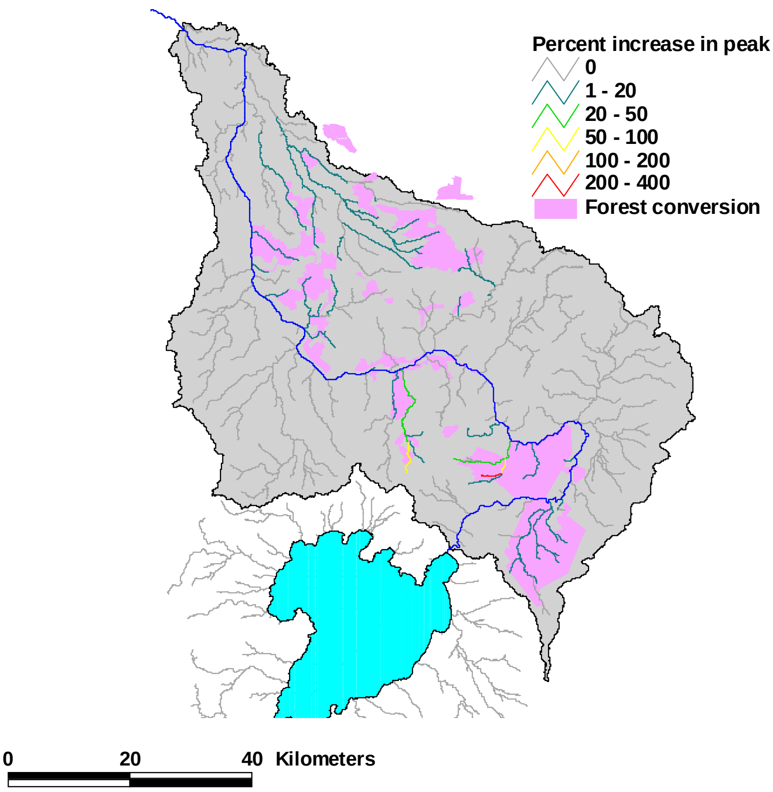


Figure 36: Percentage increase in peak flow for 100 year test rainfall event.

Table 15: Summary of local effects of land use change on flood peaks using the 10-year and 100-year test events

Location	Effect with 10-year test event	Effect with 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

6. Conclusions

The present modelling study suggests that conversion from forest to pasture as proposed would have detectable effects on flood peaks within the Waikato catchment, but only where there is significant conversion, and particularly where loam and other less-permeable soils are also significant. The two most sensitive sub-catchments, Whakamaru and Arapuni, produce peak flows that are about 10-15% greater following conversion; the exact value depends, to a lesser extent, on the magnitude of the storm. Furthermore, it is the rising limb of the flood hydrograph that shows greatest sensitivity to land use change. These effects are dampened, though still detectable, when integrated over the larger catchment. Total flood inflow volumes to the Taupo-Karapiro catchment were predicted to increase by up to 3% as a consequence of land use change. Local-scale flood peaks within the tributary catchments were predicted to increase by up to 5% for small rain events, and by 5-100% for large rain events.

The consistency of the results between the two case studies (1998 and 1958) implies a degree of robustness of the results to differences in climatic drivers. However, these results must be interpreted within the context of the prescribed model. This includes the various simplifications and approximations, as embodied by the model's hydrological representativeness and parameter values, be they land cover attributes or calibrated parameters.

An adequate model calibration has been achieved using the TopNet model for the middle Waikato catchment. Undoubtedly better calibrations can be achieved by allowing more parameters to vary, and fitting individually to each flow record. However, that would not address the point of the study, which is mainly to make predictions about changes in flow for unmonitored tributary catchments under a change in land use. This calibration attempts to strike an appropriate balance between the competing needs for accurate simulations to raise confidence that the model is meaningful, and for parameter values which have not been distorted by the calibration process, so that one can have confidence that untested aspects of the model (e.g. its behaviour in the future) will be acceptably reliable. Ultimately this balance is a judgement which must be made by the Technical Expert Panel as a group, and it is premature to make a final assessment at this point in the process, without receiving review comment from the panel.

The results presented above will need to be compared with the results of the second modelling task, and any significant differences reconciled by the Technical Expert Panel.

One cannot conclude at this stage whether the impacts on Waikato River flows are significant or not. This depends on routing the response of the monitored and unmonitored catchments through the river system, which will be carried out in a separate task of this project.

7. References

Bandaragoda, C.; Tarboton, D.G.; Woods, R.A. (2004). Application of TOPNET in the Distributed Model Intercomparison Project. *Journal of Hydrology 298(1-4)*: 178–201.

Clark, M.P.; Woods, R.A.; Zheng, X.; Ibbitt, R.P.; Slater, A.G.; Rupp, D.E.; Schmidt, J.; Uddstrom, M.J. (2008). Hydrological data assimilation with the Ensemble Kalman Filter: use of streamflow observations to update states in a distributed hydrological model. *Advances in Water Resources 31*: 1309-1324.

Henderson, R.D.; Thompson, S.M. (2000). Waikato tributary floods of July 1998. *NIWA Client Report No. CHC00/54*. 29 p.

Henderson, R.D.; Woods, R.A.; Tait, A.B. (2007). Surface water components of New Zealand's National Water Accounts, 1995-2005. *NIWA Client Report No.* 42 p.

Ibbitt, R.P.; Henderson, R.D.; Copeland, J.; Wratt, D.S. (2001). Simulating mountain runoff with meso-scale weather model rainfall estimates: a New Zealand experience. *Journal of Hydrology 239*: 19-32.

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. (2009). Review of Waikato Flood Modelling with Land Use Change. *Client Report No. IJC907*. 17 p.

Mulholland, M. (2007, draft). Effect of Pine Pasture Conversions in the Upper Waikato River Catchment on Flood Hydrology - Draft. *No. Environment Waikato Technical Report*. 30 p.

MWD (1972). Waikato River Power Development Flood Hydrology and Flood Routing. *Power Design Office, Investigations Section No.* p.

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.

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.

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

Thornburrow, B.; Mulholland, M. (2009). Impact of Land Use Change on Floods in the Upper Waikato. Phase 2: model calibration and flood hydrograph generation. *Client Report No. AE03513.2*. 66 p.

Woods, R.A.; Tait, A.B.; Mullan, A.B.; Hendrikx, J.; Diettrich, J. (2008). Projected climate and river flow for the Rangitata catchment for 2040. *NIWA Client Report No. CHC2008-097*. 36 p.

Appendix 1: Middle Waikato model validation

The following figures (Figures A1.1 – A1.5) show the model calibrations for the flood of August 1990. There is one page per flow recorder. Each flood is shown twice on the same page: once showing a 1-year simulation window (with data as 72-h moving mean), and once showing a close-up of the 3-day flood event. 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).

The lower panel shows which runoff generation mechanisms were operating at one sub-catchment within each monitored catchment shown. There is no guarantee that the sub-catchment is representative. In the legend, drainage (in grey) refers to the modelled flow of water from the root zone to the shallow saturated zone. SSF refers to subsurface flow (in yellow), SSF+SATXS refers to the sum of subsurface and saturation excess runoff (in green), and SSF+SATXS+INFXS refers to the sum of subsurface, saturation excess runoff and infiltration excess runoff (in blue). If no blue is visible, there was no infiltration excess. If no green is visible, there was no saturation excess runoff. These terms are also shown in the same colours on the flow diagram in Figure 2

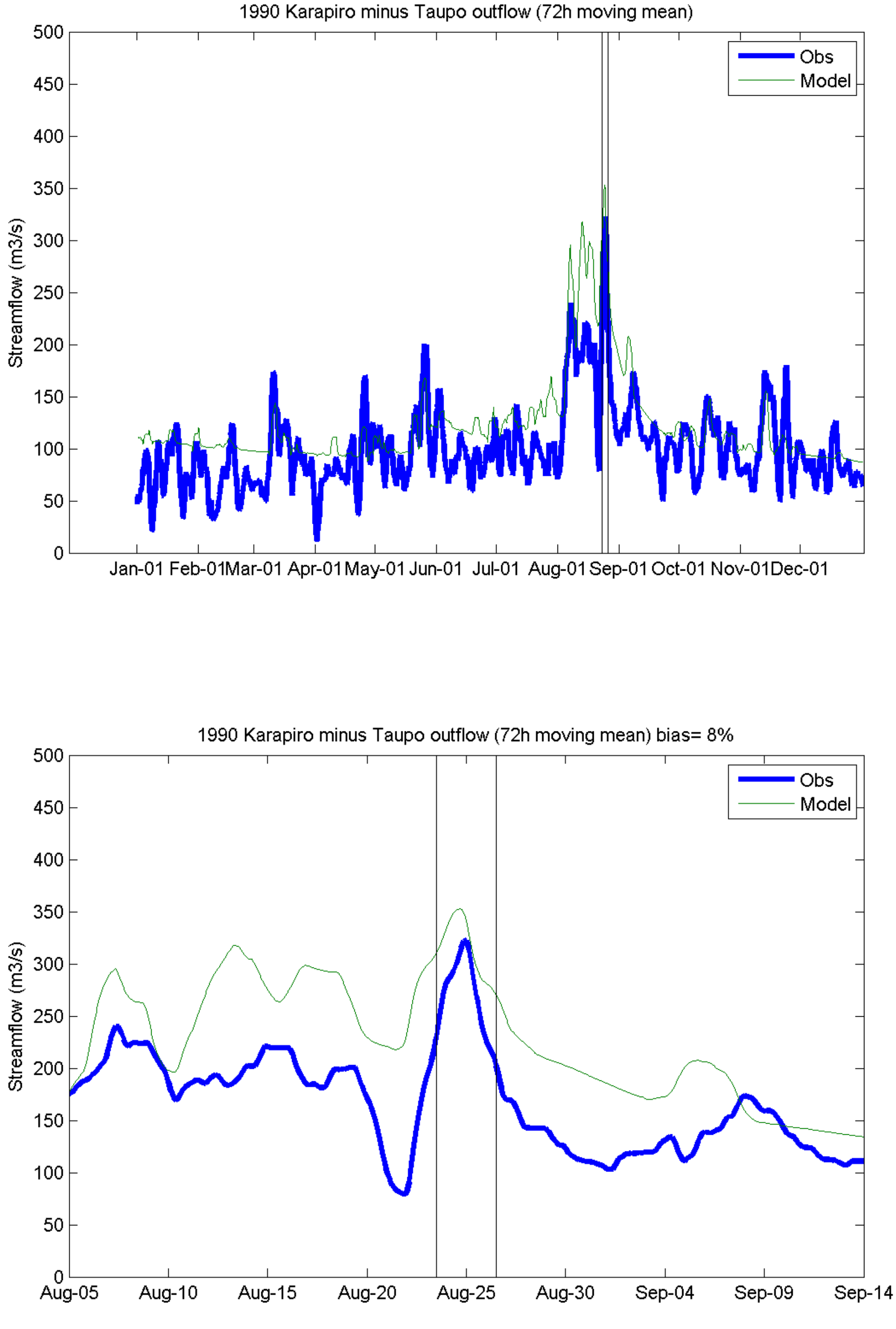


Figure A1.1: TopNet validation plot for 1990 flood, for the difference between Karapiro and Taupo outflows. Top panel shows observed and modelled 72-h moving mean flows for entire year; Bottom panel shows detail at time of flood.

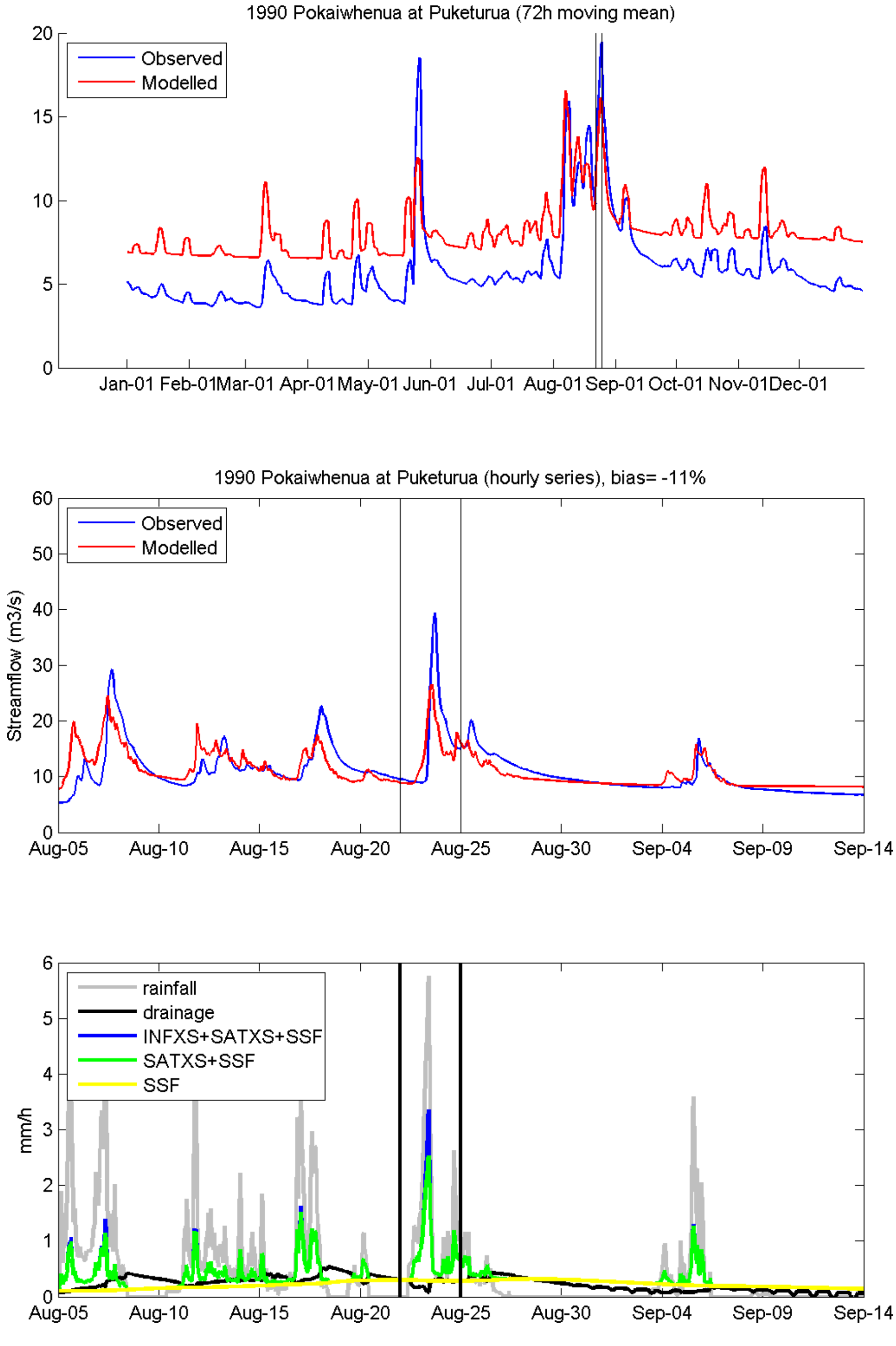


Figure A1.2: TopNet validation plot for 1990 flood, Pokaiwhenua at Puketurua. Top panel shows observed and modelled 72-h moving mean flows; Middle panel shows observed and modelled hourly flows; Bottom panel shows which runoff generation mechanisms were operating at one sub-catchment within each monitored catchment shown

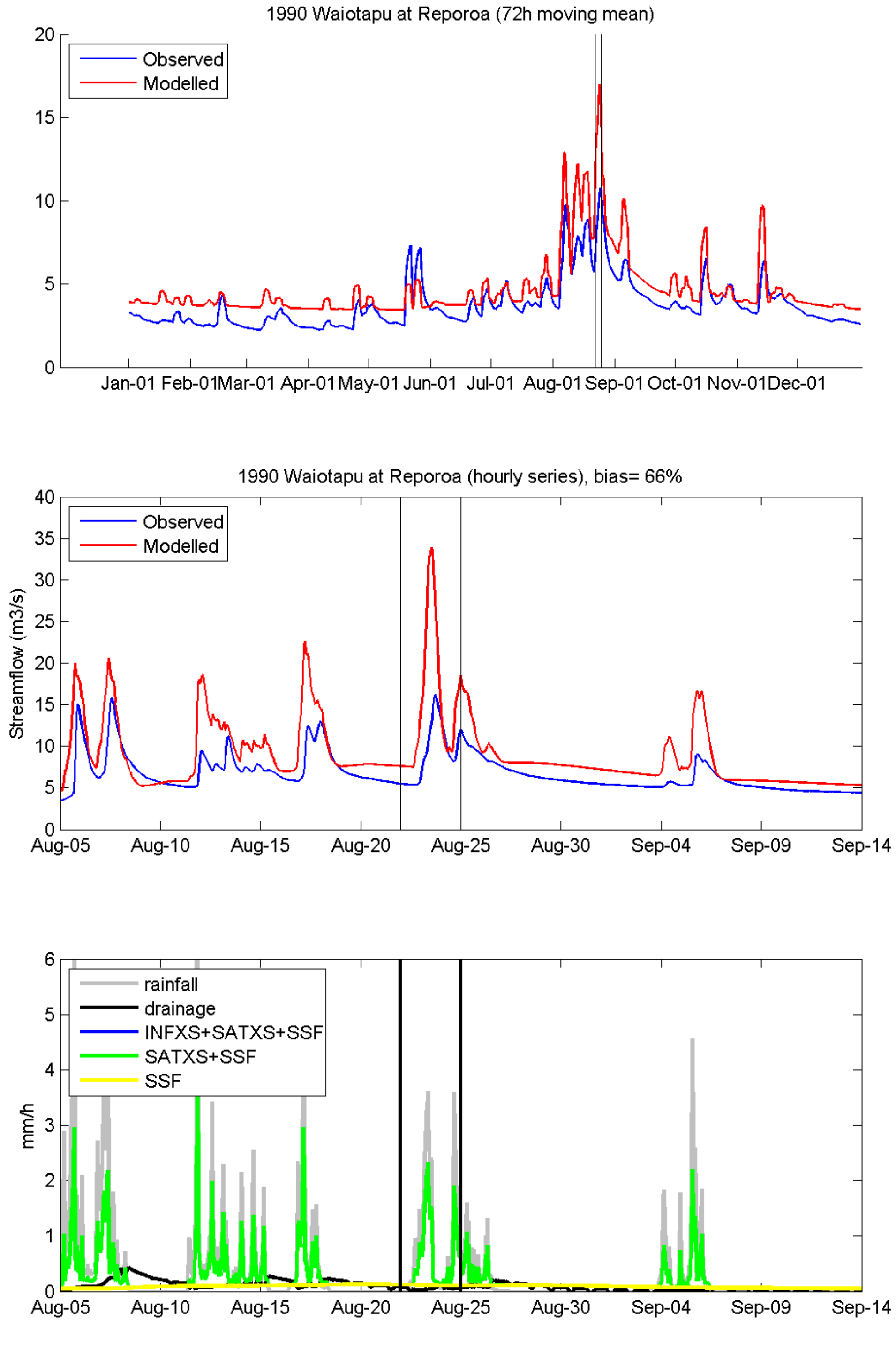


Figure A1.3: TopNet validation plot for 1990 flood, Waiotapu at Reporoa. Top panel shows observed and modelled 72-h moving mean flows; Middle panel shows observed and modelled hourly flows; Bottom panel shows which runoff generation mechanisms were operating at one sub-catchment within each monitored catchment shown

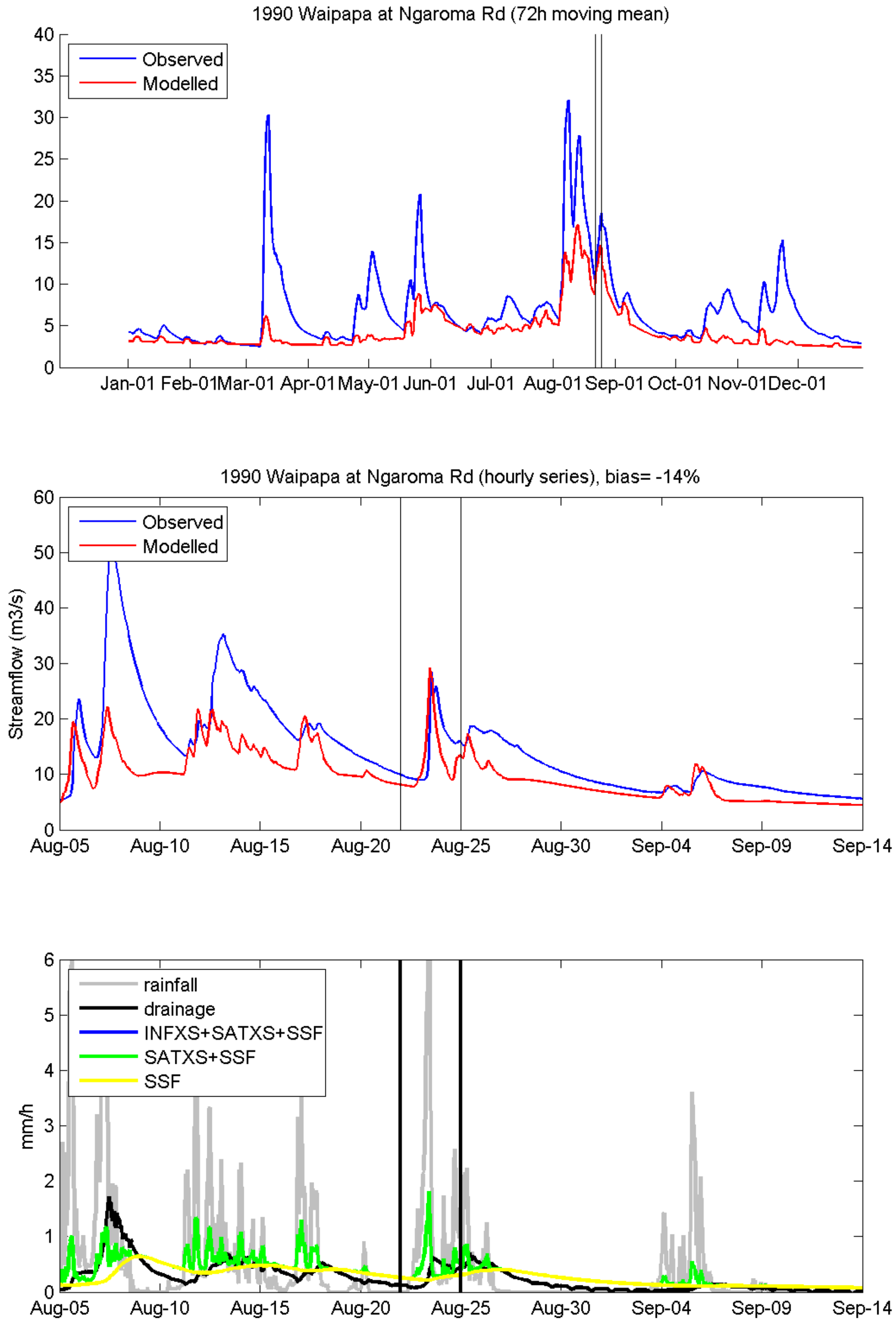


Figure A1.4: TopNet validation plot for 1990 flood, Waipapa at Ngaroma Road. Top panel shows observed and modelled 72-h moving mean flows; Middle panel shows observed and modelled hourly flows; Bottom panel shows which runoff generation mechanisms were operating at one sub-catchment within each monitored catchment shown

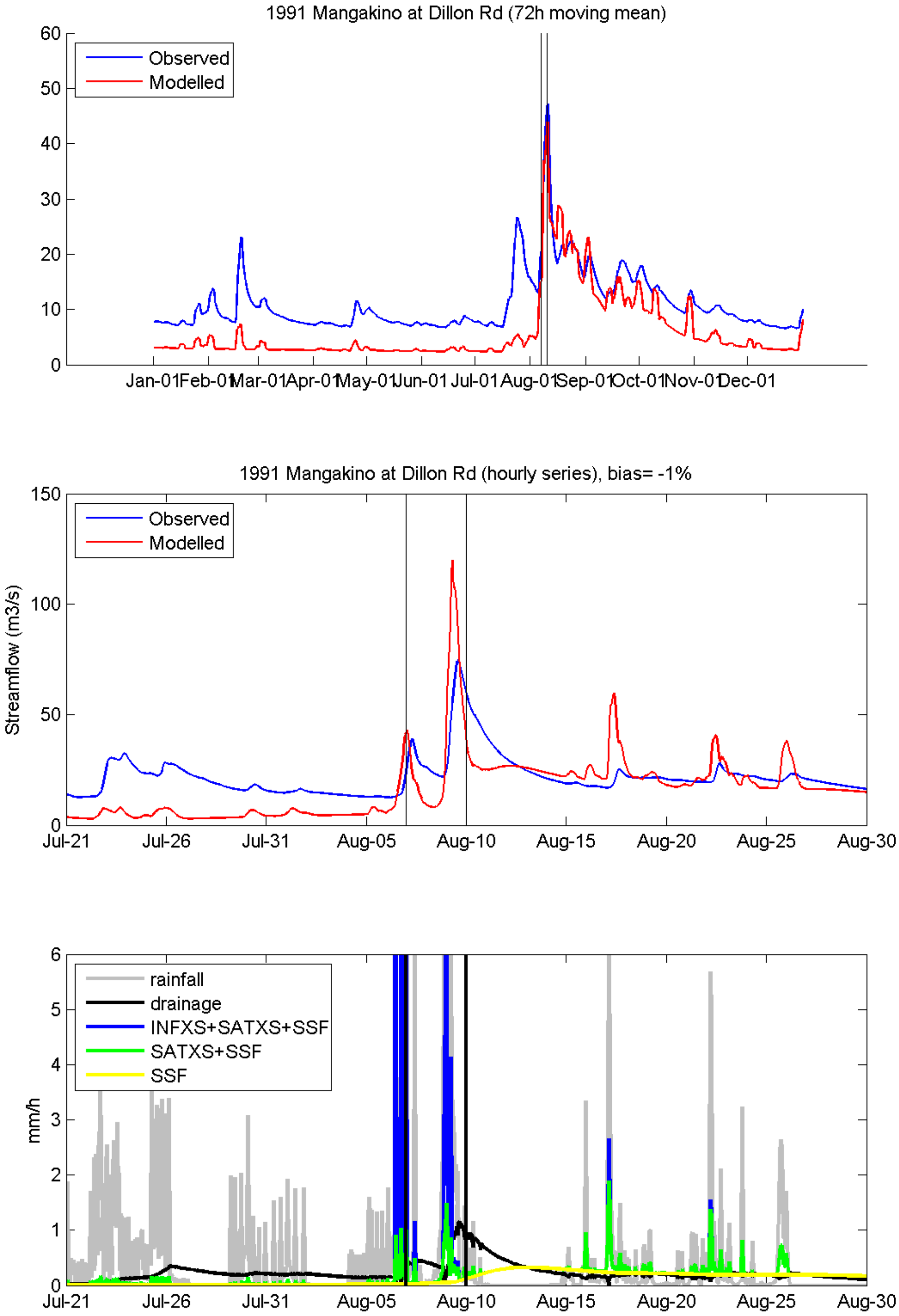


Figure A1.5: **TopNet validation plot for 1990 flood, Mangakino at Dillon Road. Top panel shows observed and modelled 72-h moving mean flows; Middle panel shows observed and modelled hourly flows; Bottom panel shows which runoff generation mechanisms were operating at one sub-catchment within each monitored catchment shown.**