Ian Jowett Consulting

Waikato Flood Routing with Land Use Change

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Client Report: IJC906
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Mighty River Power Ltd. and
Environment Waikato

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Executive Summary

Two studies (NIWA and SKM/EW) have developed models of the Waikato catchment between Lake Taupo and Karapiro Dam that enable predictions to be made about the effects of land use change on flood magnitude. These models were used to make predictions of flood inflows to the hydro-electric dam sub-catchments for current and future land use for rainfalls with average recurrence intervals (ARI) of approximately 5 years, 20 years, 50 years, 100 years and 500 years) and with examples of high and low intensity temporal patterns, as typified by the 1958 and 1998 storms, respectively.

The NIWA and SKM/EW model predictions of inflows to dam sub-catchments were routed through the hydro-electric system, according to a set of flood routing procedures, to evaluate the effect of land use on the magnitude of flood discharges from Karapiro Dam.

For rainfall events of up to 20 years ARI, the change in flood magnitude was negligible for inflows predicted by both models. For rainfall events of 20-50 years, a change in land use would slightly increase (up to 1%) the magnitude of flood discharges from Karapiro.

When Karapiro discharges simulated using model inflows with current land use were compared with recorded Karapiro discharges, the discharges using HEC/HMS inflows bracketed those of TOPNET, but both were generally in accord with recorded discharges at Karapiro

Taking all sets of model inflows and temporal patterns into consideration, the potential change in land use could increase flood discharges from Karapiro by 1.9% for rainfalls with a 100 year ARI, and 6.5% for rainfalls with a 500 year ARI.

1. Introduction

This report forms part of the larger study on effects of land use change on the flood hydrology of the Waikato River catchment between Taupo and Karapiro.

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

Two studies (NIWA and SKM/EW) developed models of the catchments that incorporated land use and were used to make predictions of flood inflows to the hydro-electric dam sub-catchments for rainfall magnitudes of average recurrence intervals (ARI) of approximately 5 years, 20 years, 50 years, 100 years and 500 years) with high and low intensity temporal patterns.

A separate report compares the predictions of models of current land use with other models that had previously been developed and hydrological data recorded in major tributaries of the catchment between Taupo and Karapiro.

This report summarises the results of the NIWA and SKM/EW model predictions and routes the dam sub-catchment inflows through the hydro-electric system according to a set of flood routing procedures to evaluate the effect of land use on the magnitude of flood discharges from Karapiro Dam.

The amount of change in Karapiro discharge can then be used to evaluate the potential effects of land use change on flood in the lower Waikato.

2. Flood routing

The flow of water from Taupo to the Karapiro Dam is controlled by the operations of the hydro dams and the amount of water that that flows from the tributary streams. Flood routing simulates the operation of the hydro dams to evaluate the effects of two land use scenarios (present and potential conversion to pasture) on flood discharges from Karapiro Dam.

A simplified set of flood routing rules was used for this land use comparison. These rules are based on the phase IV flood rules in the present flood routing rules as described below.

2.1 Existing flood rules

The primary purpose of flood routing rules is to protect the integrity of the hydro dams in large floods. The rules specify how floods should be handled in terms of reservoir levels and discharges thus manipulating flood storage to avoid overtopping dams whilst minimizing flood discharges.

Sophisticated flood routing rules for the Waikato (Waikato Flood Management Rules HD 1080A) from Lake Taupo to Karapiro were first developed in the early 1970's so that very large floods, such as the probable maximum flood, could be passed down the river with the least possible damage. Since then the rules have undergone a series of modifications, the most important being the result of the spillway upgrade at Arapuni. The latest flood routing rules were updated in 2005.

The rules are set up as a series of phases from I to V, depending on the severity of the flood.

Phase I is optional and may be entered to draw down reservoirs in advance of a severe storm warning. This creates storage that can be used to some degree to buffer flood volumes.

Phase II is used for small to moderate floods and allows a high degree of flexibility, essentially to allow discharges from Karapiro to be reduced to minimise discharges in the lower Waikato.

Phase III is mandatory and is entered when the Required Storage Volume (RSV) of 80 million m^3 is exceeded. The RSV is the expected flood volume from tributary catchments less an allowance for the volume of water discharged from Karapiro since the beginning of the storm. Phase III involves high initial discharges at downstream stations and lower discharges at upstream stations to create storage in the lower reservoirs. As the flood proceeds, discharges are gradually increased according to table discharges.

Phase IV is similar to Phase III and is entered if 4 or more reservoirs exceed MCL or any one reservoir is within 500 mm of the design flood level.

Phase V occurs in very exceptional floods when design flood levels are exceeded.

The present set of rules allows a high degree of flexibility unless a number of dams are over maximum control level (MCL) and dam safety is threatened. When dam safety is not threatened (< 20-50 year event), discharges from Karapiro can be manipulated with EW direction as statutory flood manager. A typical action would be to retain or even generate storage in the early stage of a flood so that Karapiro discharges can be reduced just before the Waipa peak or some other trigger flow is expected. In slightly larger events, pre-emptive draw down might be initiated under the flood rules. These kinds of action would obscure any effects of land use change on flood hydrographs. The present flood routing rules can be modelled as a complex series of switches between phases I to IV. Because of this, there is no guarantee of a consistent outcome when floods of different magnitude are routed through the dams (i.e., the discharge from Karapiro will not bear a consistent relationship with the magnitude of the flood inflows). For example, the switch from phase II to phase III increases the Karapiro discharge by about 50% in an attempt to draw down lakes in advance of the flood peak.

A simplified set of rules, as described below (actually using the phase II part of the flood routing rules) will give consistent flood routing and was used for this study.

2.2 Flood routing model

The model uses simple level pool routing described in Henderson (1966 p. 356). This method applies the continuity equation, where the inflow, outflow and volume of water in each reservoir are balanced at each time increment *dt*:

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

where *I* = inflow from tributaries and outflow from upstream dam, *O* = outflow and *dV* = the change in reservoir volume (reservoir area times change in level).

The outflow from the reservoirs is controlled and is determined from lookup tables that specify the outflow according to reservoir level. This corresponds to the physical operations that would be made by the system operators.

The model successively routes the discharge from Taupo and inflows from each of the contributing tributary catchments through Ohakuri, Atiamuri, Whakamaru, Maraetai, Waipapa, Arapuni and Karapiro dams. The storage behind these dams delays and regulates the discharge of flood waters to some degree, depending on the surface area of the reservoirs and the flood storage range.

Aratiatia was excluded from the modelling because its reservoir and catchment area is small and for the modelling exercise can be considered run of river.

Operating experience and detailed field measurements have shown that it takes a little time before water released from an upstream dam is sensed by the water level recorders at the downstream dam. These times are known as the lag times and will be applied in the model. The only significant lag time is the 12-13 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.

The discharge from Lake Taupo was set at a nominal release (median flow shown in Appendix) and this was maintained throughout the flood.

The discharge from each power station was initially considered to be steady with the outflow equalling upstream discharge plus the initial tributary discharge. An estimate of this start point is given in the Initial Conditions in the Appendix.

As the flood proceeds and reservoir levels begin to rise, each power station discharge increases up to maximum turbine discharge, thus attempting to hold the reservoir levels constant. When inflows exceed maximum turbine discharge, the reservoirs will rise to maximum control level and higher.

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

The method of simulating power station operation during the floods routing was the same for both land use scenarios (pre and post conversions).

The flood routing model requires a set of parameters for each dam:

1. Initial starting discharge and level.
2. Reservoir area and maximum control level
3. Lag time to downstream dam.
4. Discharge rules (table discharges).
5. Tributary inflows i.e., inflows to sub-catchments of the Ohakuri, Atiamuri, Whakamaru, Maraetai, Waipapa, Arapuni and Karapiro dams.

Values for starting levels, reservoir areas, lag times, and table discharges are included in the Appendix.

3. Results

3.1 Inflow hydrographs

The tributary inflows to Ohakuri, Atiamuri, Whakamaru, Maraetai, Waipapa, Arapuni and Karapiro dams were provided by the two land use catchment models, the SKM/EW HEC/HMS (SKM 2009) and the NIWA TOPNET models. The inflow hydrographs used storm rainfalls of varying magnitude and two different temporal patterns, one based on the long duration 1998 storm and the second based on the short duration 1958 storm. The distribution of rainfall used by the models also varied between the two storms, with the 1998 storm rainfall using the distribution of the 1998 storm and the 1958 temporal pattern using the distribution of high intensity rainfalls (HIRDS).

The rainfalls for the 5 to 500 year recurrence intervals used by the two models for the 1998 temporal patterns are slightly different (Table 1), and this should be taken into consideration when comparing between models.

Table 1: 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

3.1.1 HEC/HMS model inflow simulations

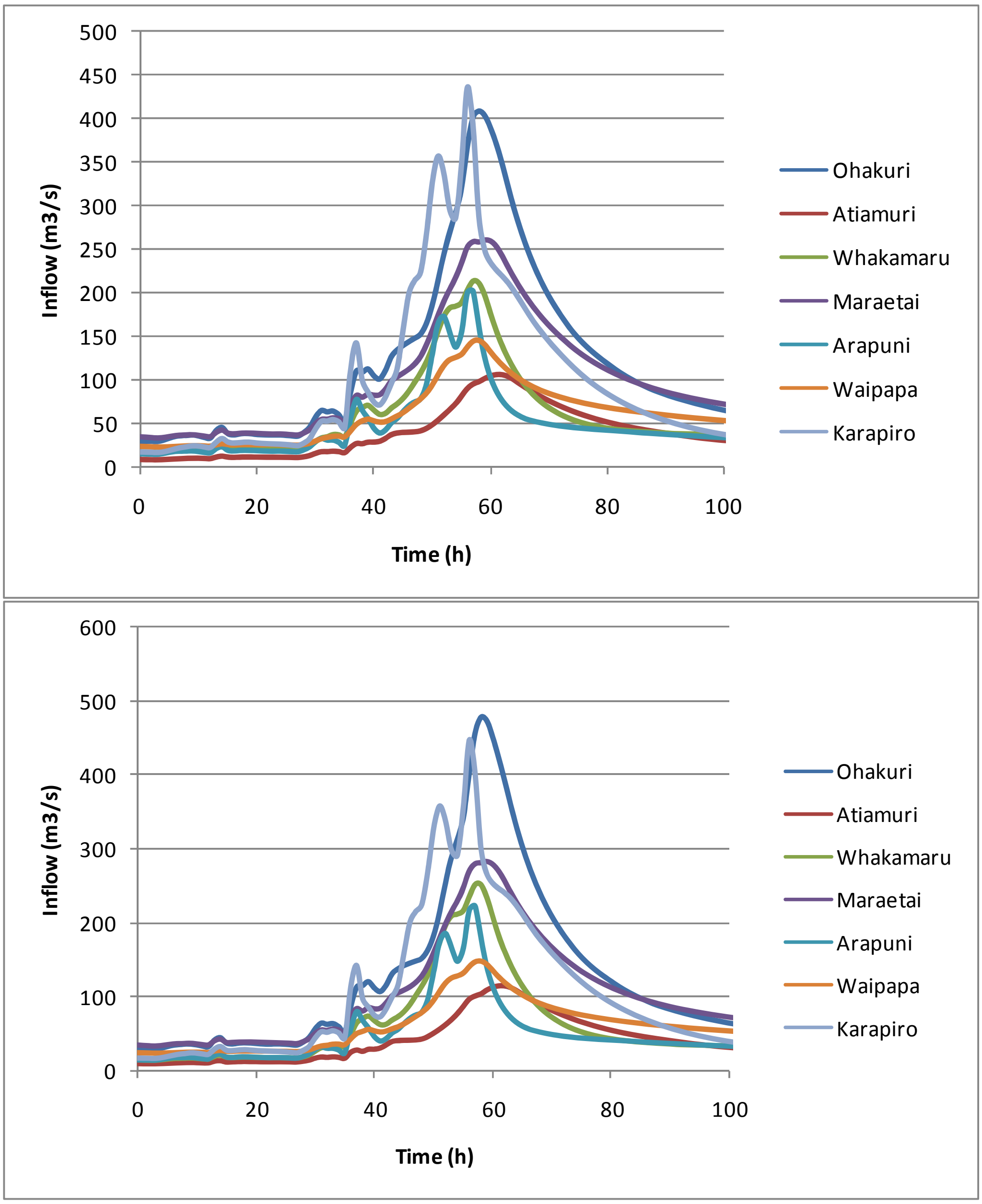


Figure 1: Current (above) and future (below) land use HEC/HMS inflow hydrographs for 100 year event with 1958 temporal pattern.

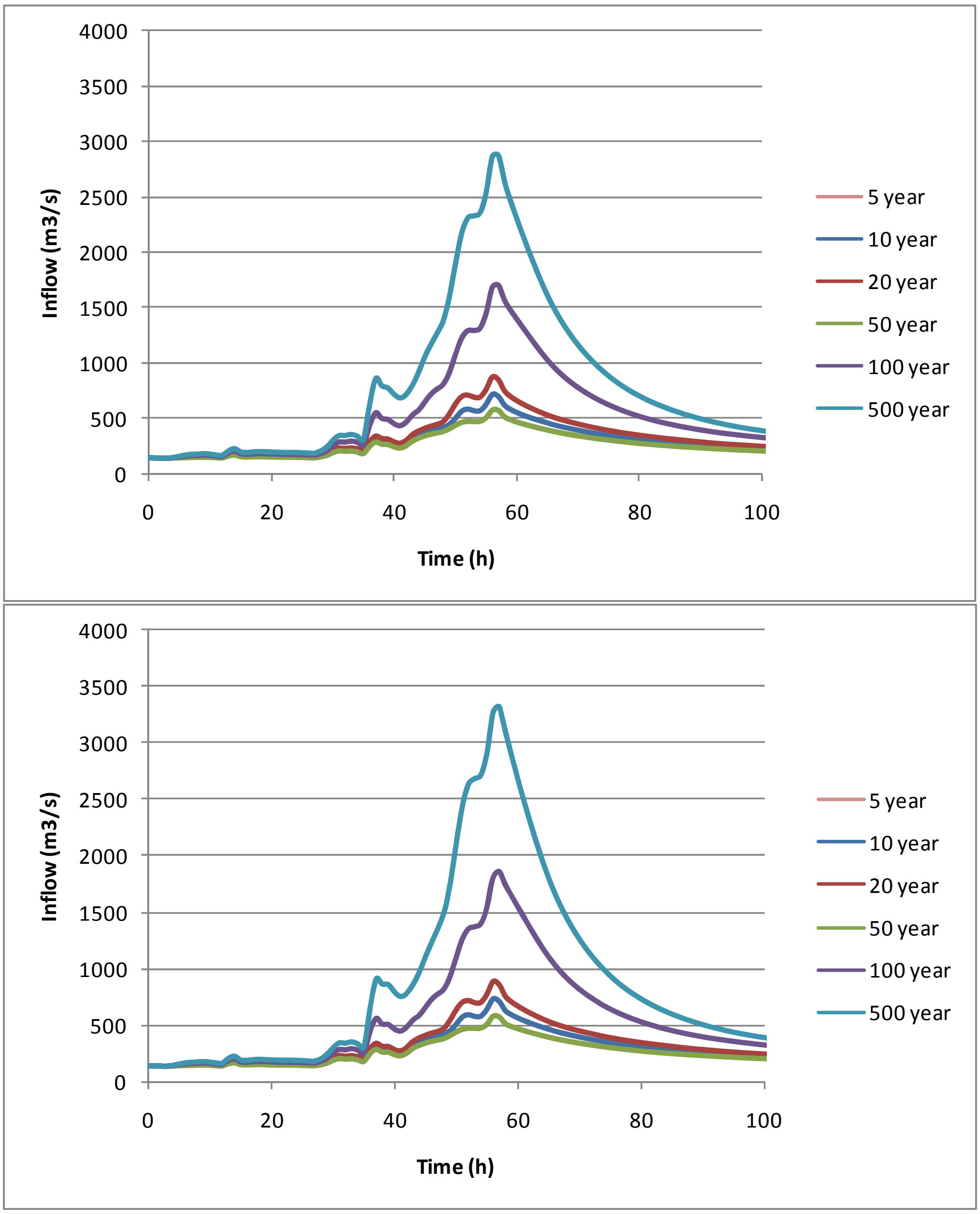


Figure 2: **Current (above) and future (below) land use HEC/HMS total inflow hydrographs for 5 to 500 year rainfalls with 1958 temporal pattern.**

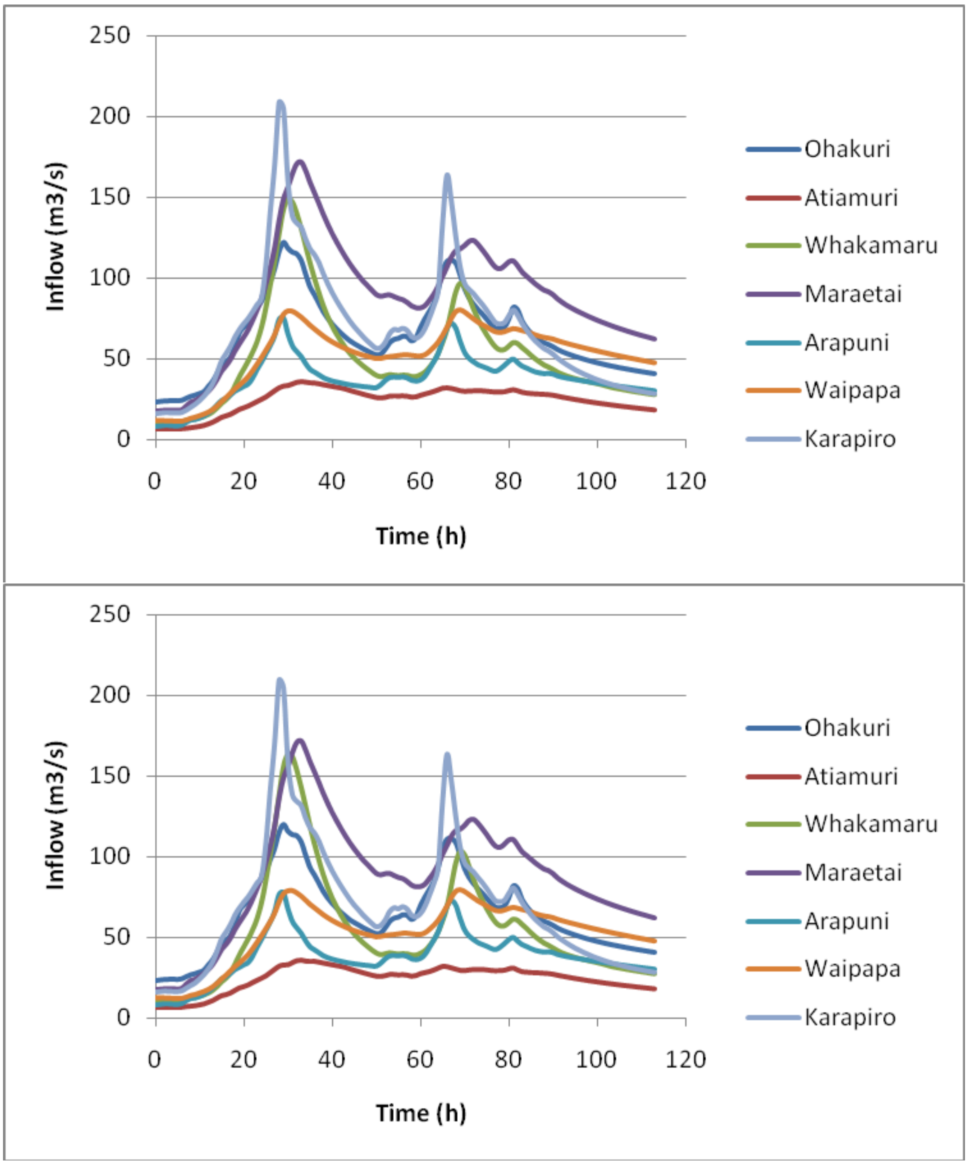


Figure 3: Current (above) and future (below) land use HEC/HMS inflow hydrographs for 100 year event with 1998 temporal pattern.

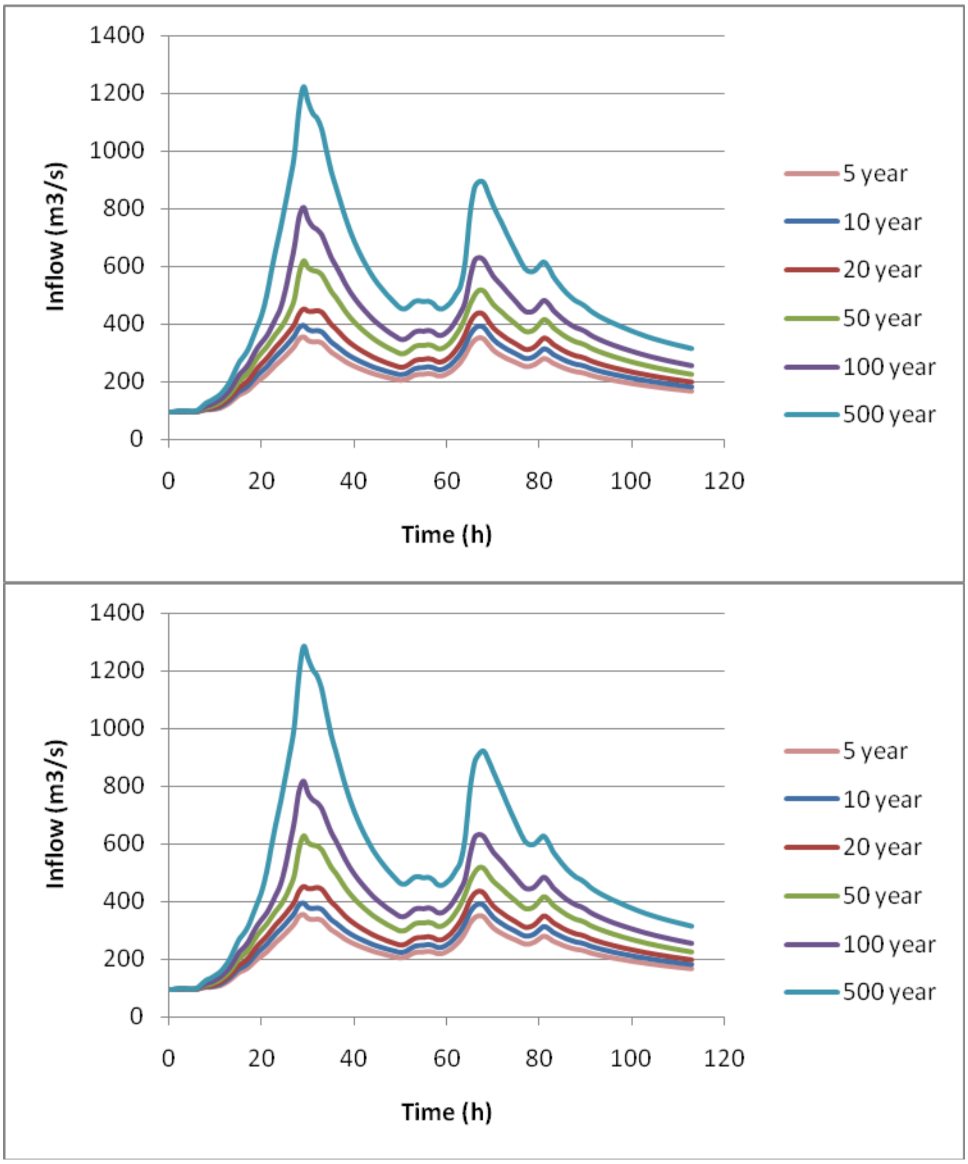


Figure 4: **Current (above) and future (below) land use HEC/HMS total inflow hydrographs for 5 to 500 year rainfalls with 1998 temporal pattern.**

3.1.2 TOPNET model inflow simulations

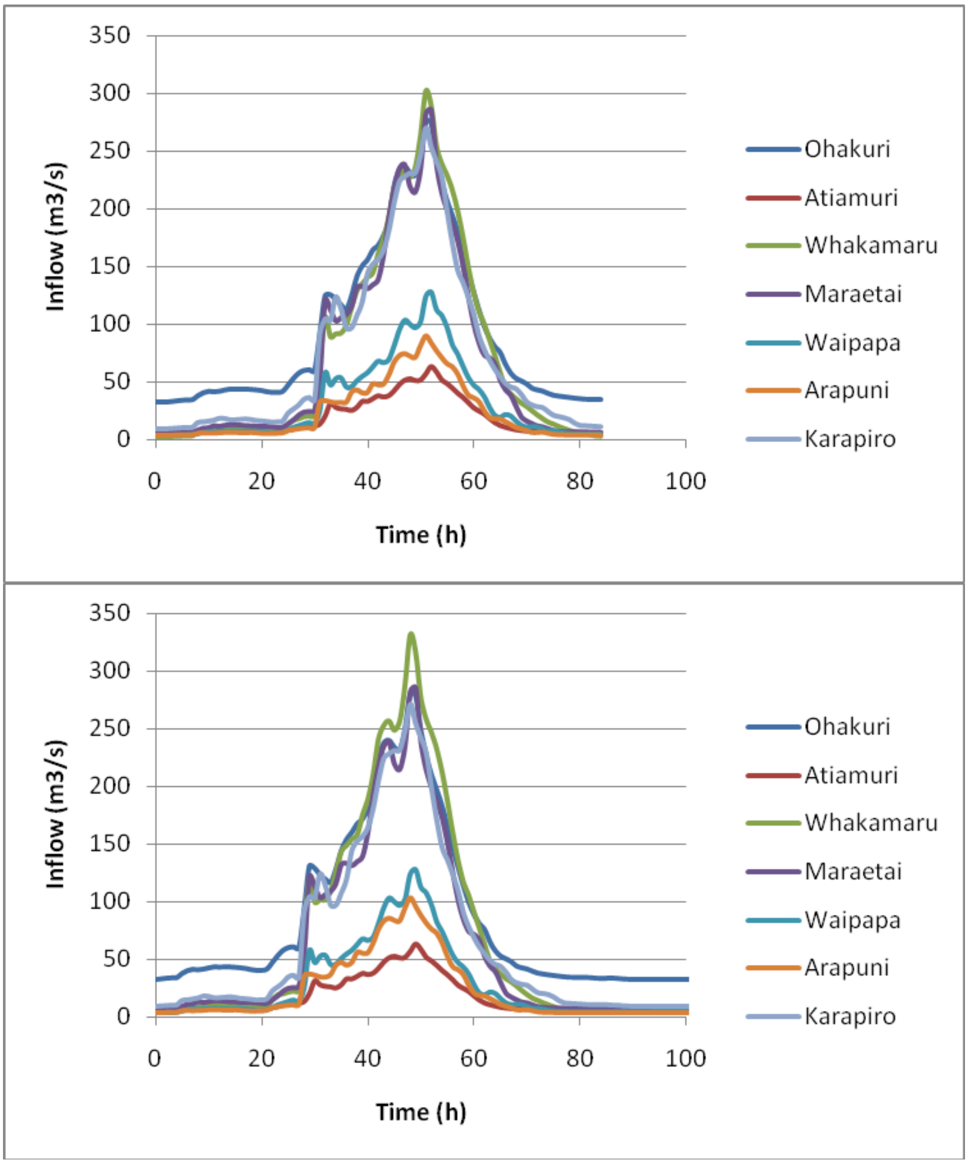


Figure 5: **Current (above) and future (below) land use TOPNET inflow hydrographs for 100 year rainfall with 1958 temporal pattern.**

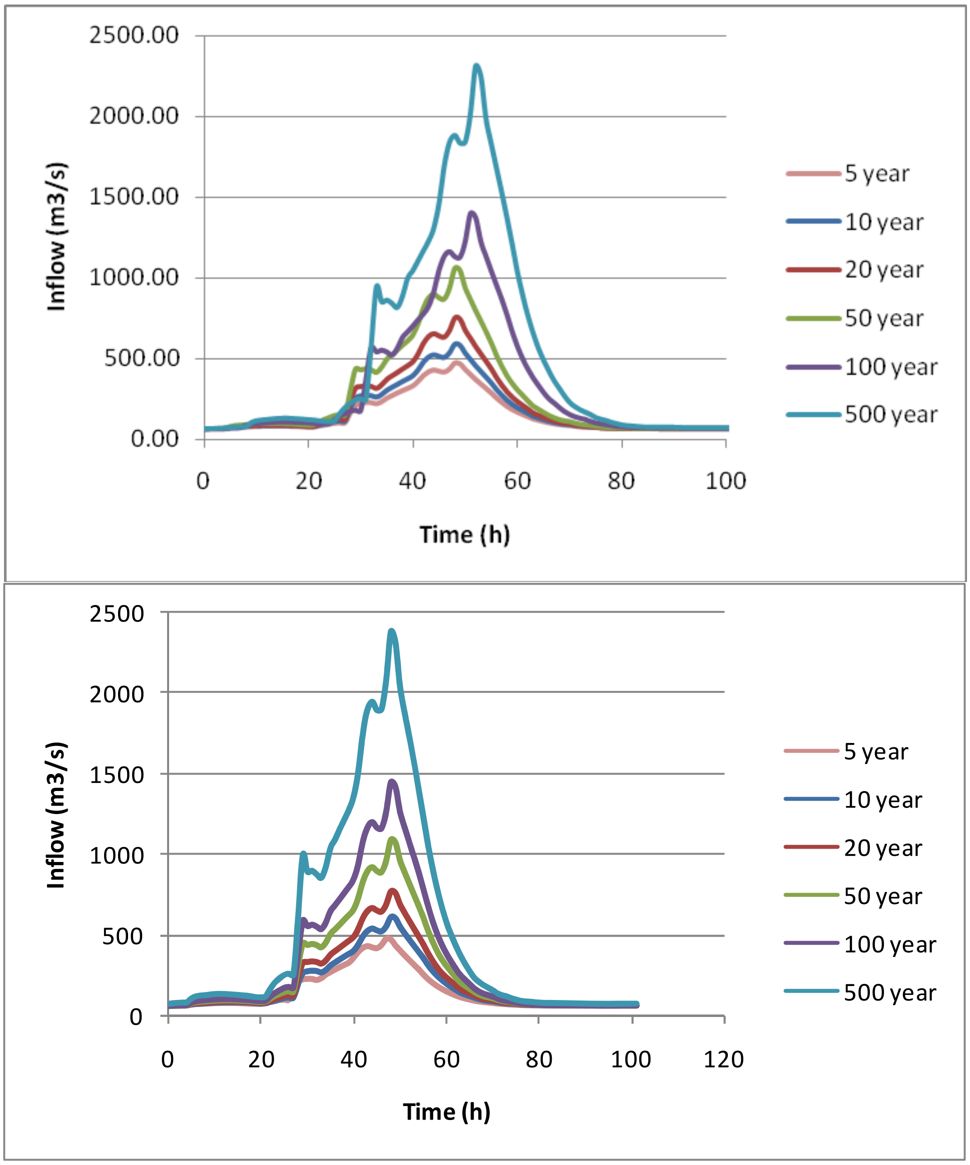


Figure 6: **Current (above) and future (below) land use TOPNET total inflow hydrographs for 5 to 500 year rainfalls with 1958 temporal pattern.**

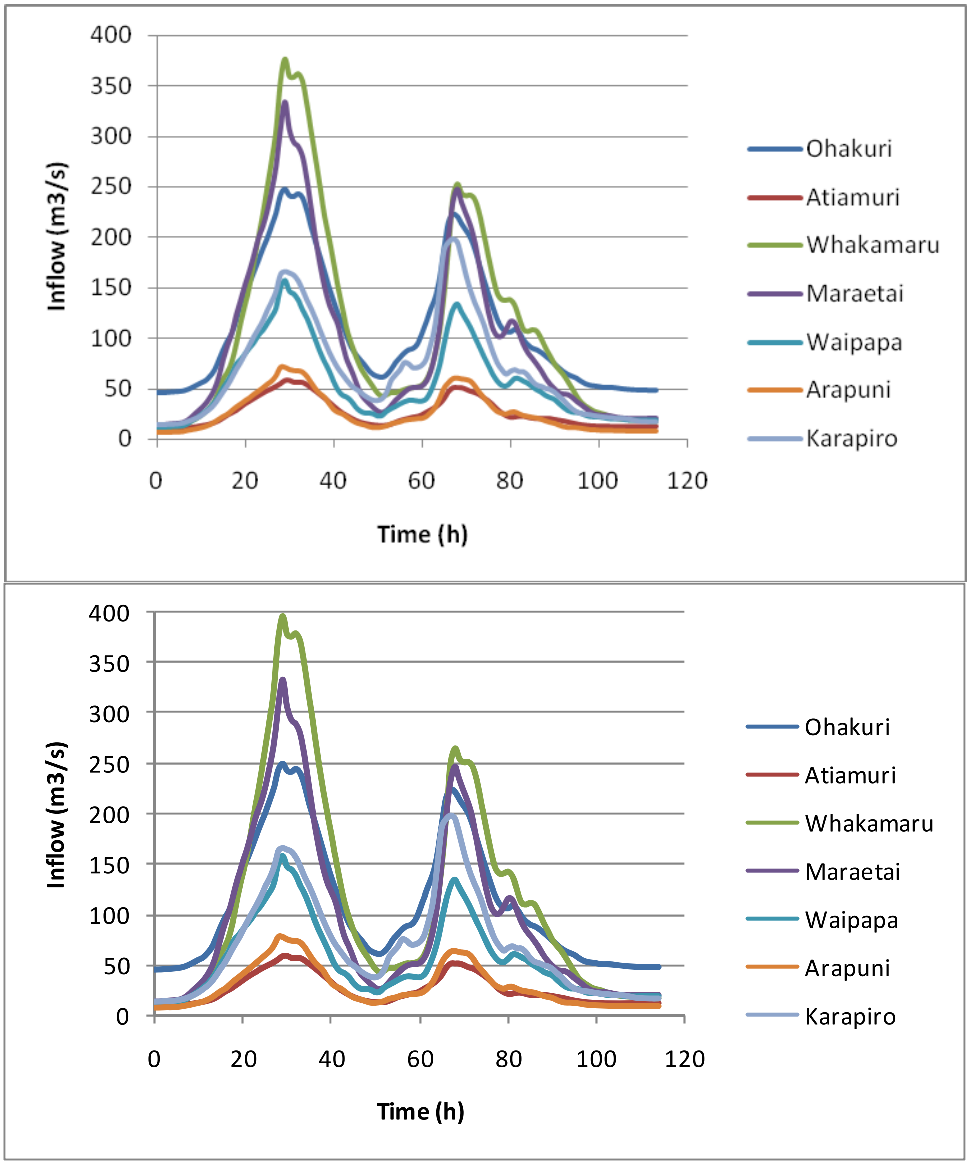


Figure 7: **Current (above) and future (below) land use TOPNET inflow hydrographs for 100 year rainfall with 1998 temporal pattern.**

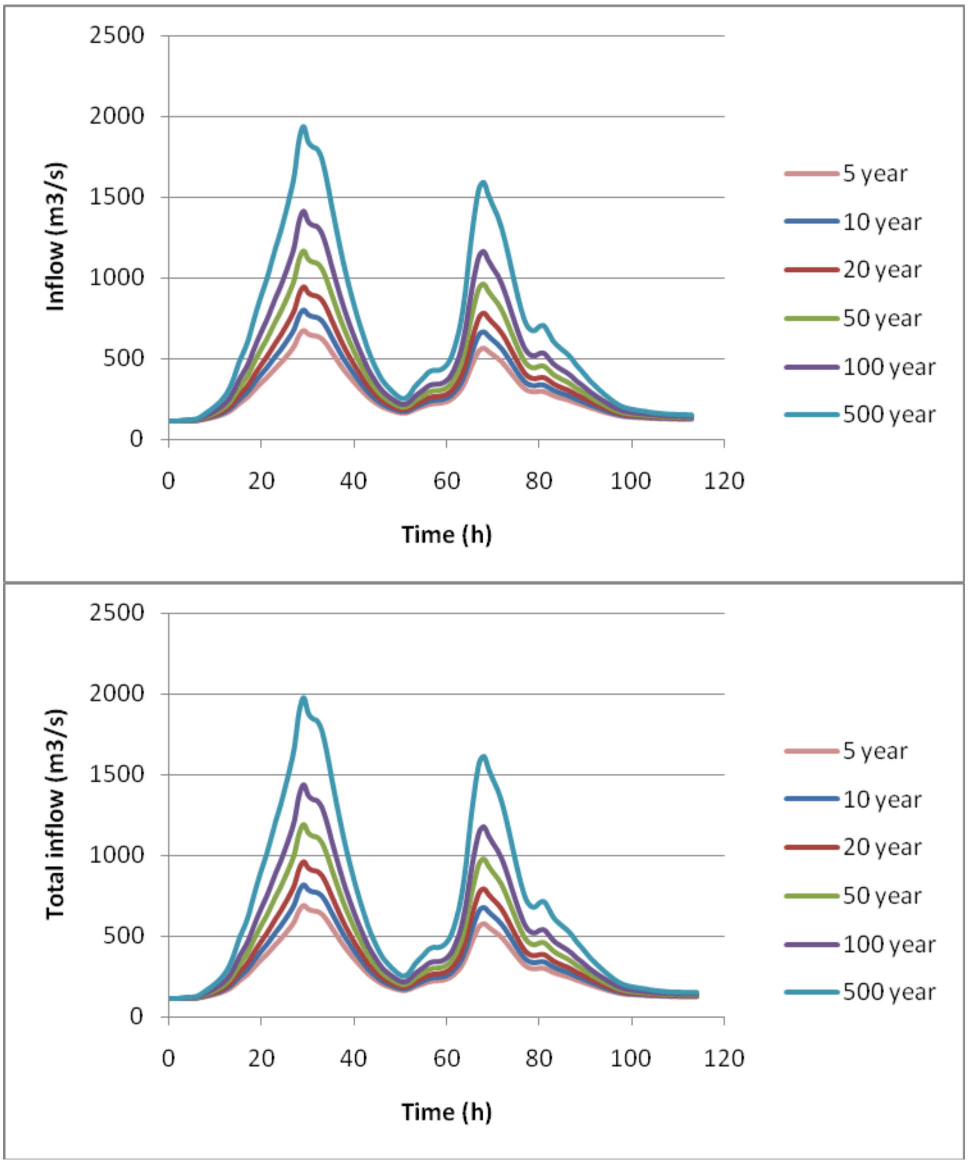


Figure 8: **Current (above) and future (below) land use TOPNET total inflow hydrographs for 5 to 500 year rainfalls with 1998 temporal pattern.**

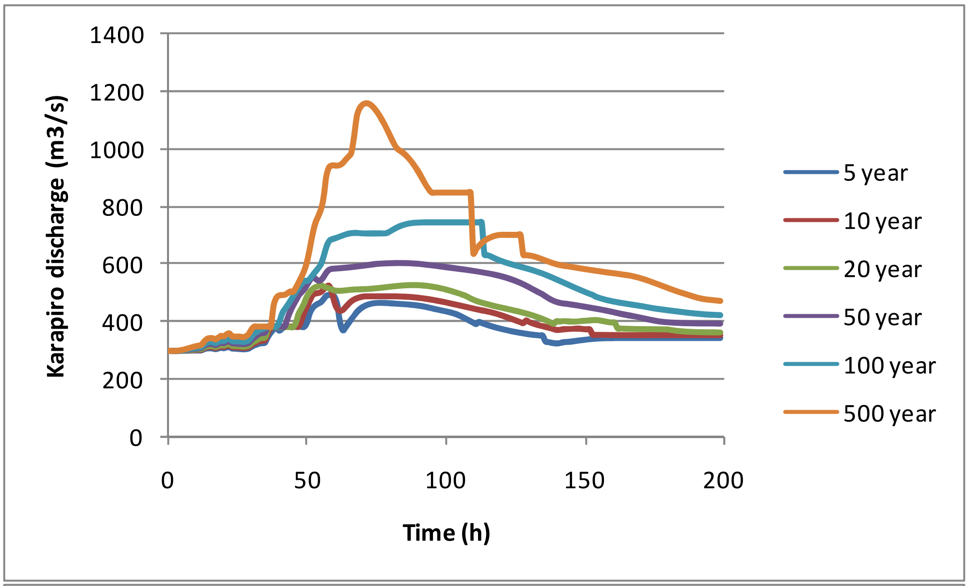
3.2 Flood routing results

The inflows simulated by the HEC/HMS and TOPNET models for the various rainfalls and temporal patterns were routed through the dam system using the flood routing rules described in Section 2.2.

Taupo discharge was held constant at 150 m^3/s throughout the flood. Each dam discharged inflows up to full machine capacity when reservoir levels were below maximum control levels. When the maximum control level was exceeded, each dam discharged water according to the tables listed in the Appendix.

The maximum discharges from each dam for the current and future land use scenarios were compared to calculate the percentage change in discharge that resulted from land use change.

3.2.1 HEC/HMS simulation flood routing



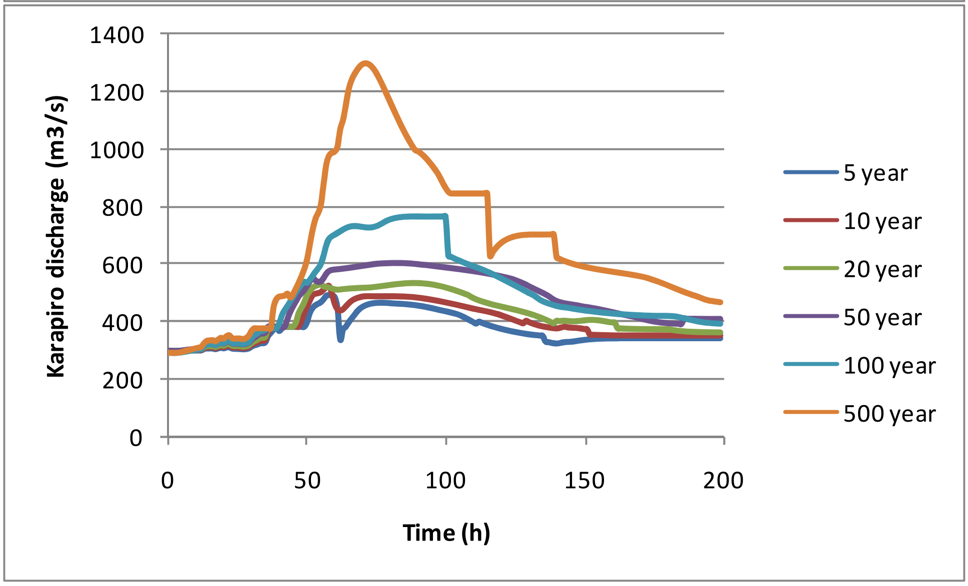
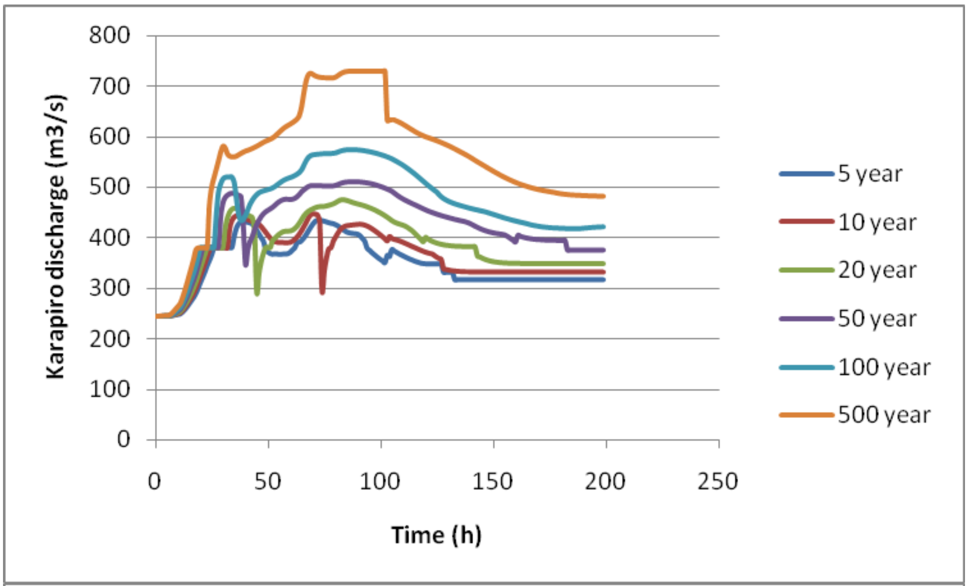


Figure 9: Hydrographs of Karapiro discharge simulated using HEC/HMS model inflow hydrographs for 5-500 year rainfalls with 1958 temporal pattern with current land use (above) and with future land use (below) scenarios.



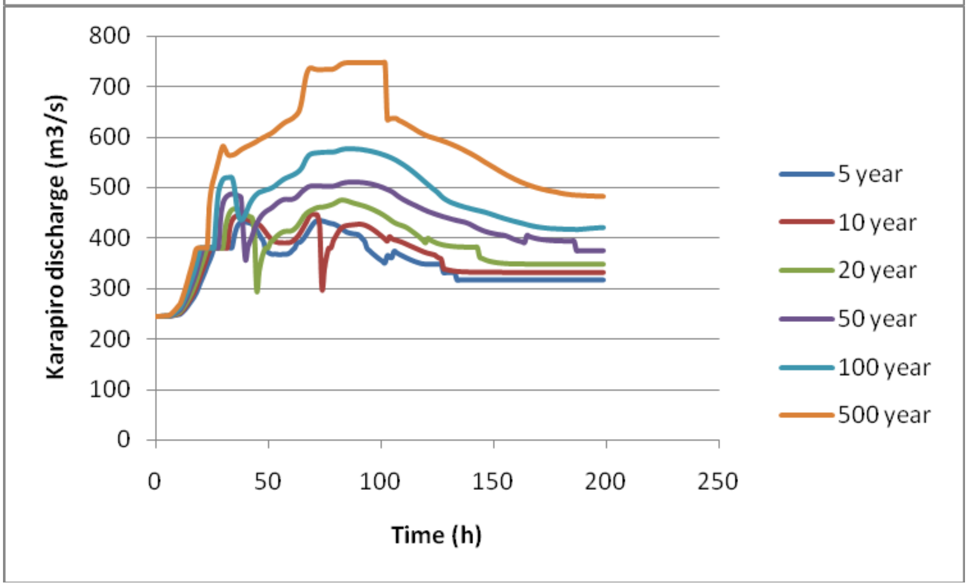


Figure 10: **Hydrographs of Karapiro discharge simulated using HEC/HMS model inflow hydrographs for 5-500 year rainfalls with 1998 temporal pattern with current land use (above) and with future land use (below) scenarios.**

Table 2: **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 3: 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

3.2.2 TOPNET simulation flood routing

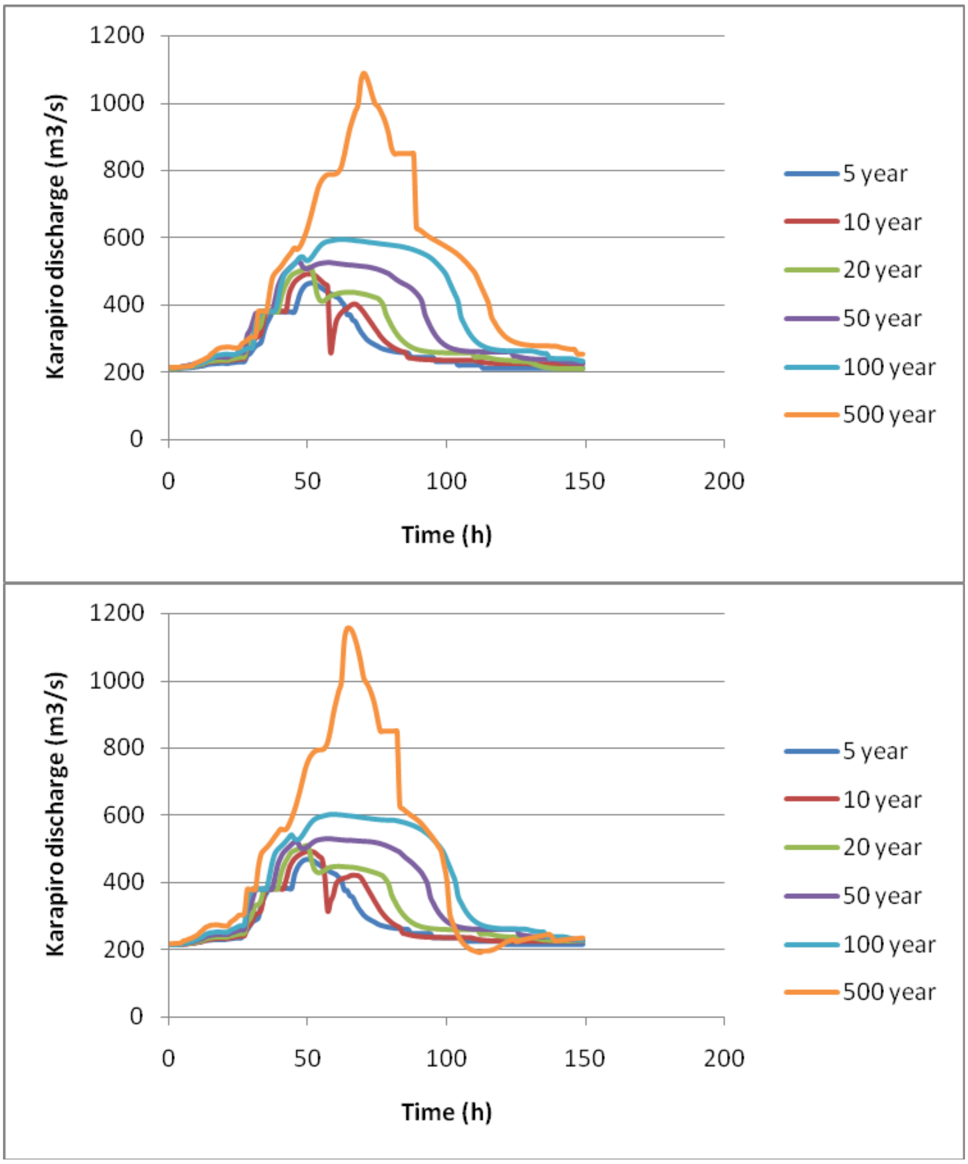


Figure 11: Hydrographs of Karapiro discharge simulated using TOPNET model inflow hydrographs for 5-500 year rainfalls with 1958 temporal pattern with current land use (above) and with future land use (below) scenarios.

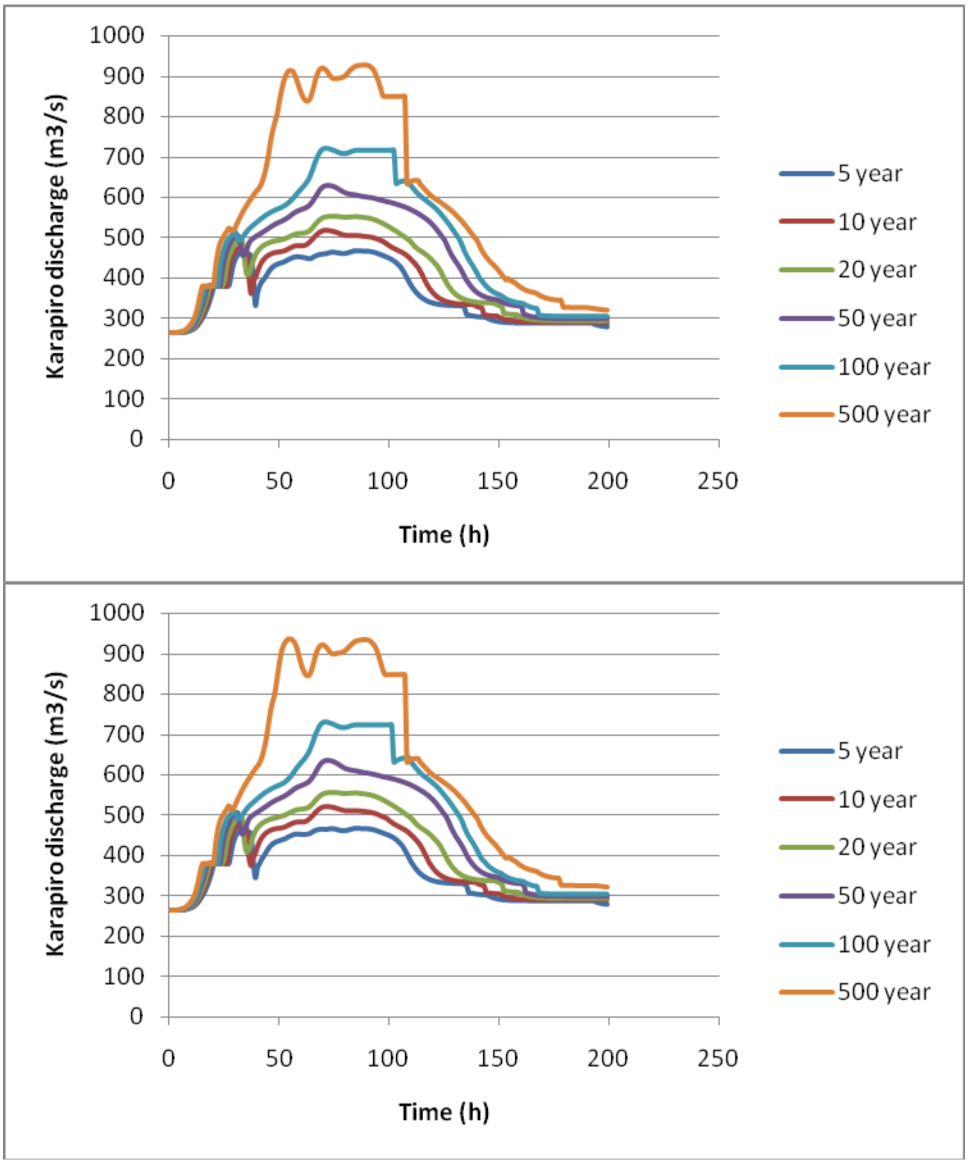


Figure 12: **Hydrographs of Karapiro discharge simulated using TOPNET model inflow hydrographs for 5-500 year rainfalls with 1998 temporal pattern with current land use (above) and with future land use (below) scenarios.**

Table 4: **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

Table 5: **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

4. Karapiro discharge and effect of land use change

Karapiro discharges simulated using inflows from the two models of current land use were compared with the 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.

Maximum annual flow series usually form a linear or close to linear series when plotted on a Gumbel frequency distribution scale. The maximum simulated Karapiro discharges were plotted on a Gumbel scale at the recurrence intervals periods of the rainfalls that were used in the models (Fig. 13).

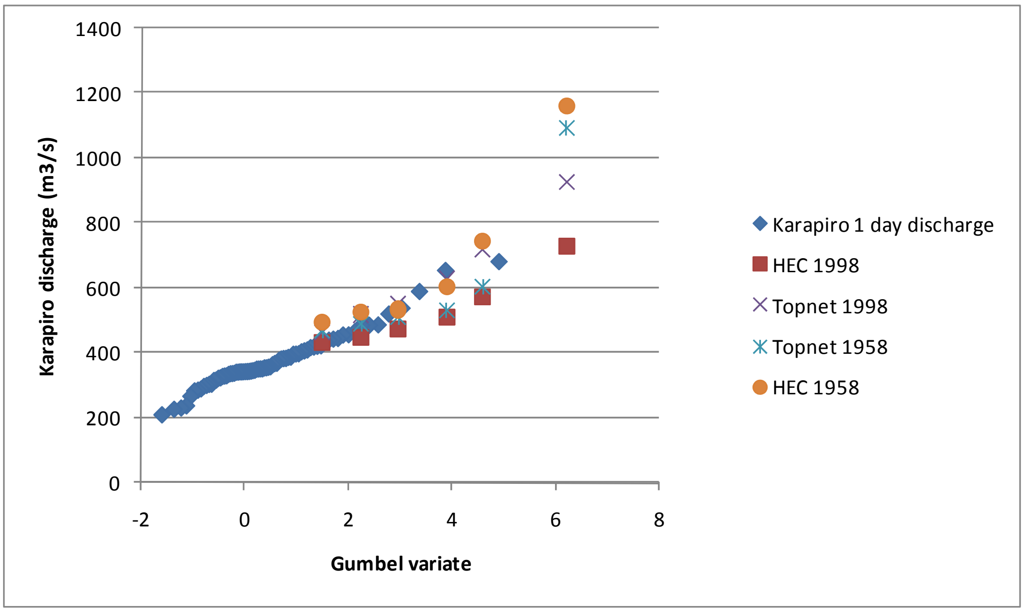


Figure 13: **Recorded annual maximum 1 day discharges from Karapiro compared with simulated discharges resulting from HEC/HMS and TOPNET model inflows for current land use and with temporal patterns matching the 1998 and 1958 storms.**

When Karapiro discharges resulting from model inflow predictions for current land use were compared with recorded outflows (Figure 13), both models showed that the change in inflows resulting from a change in land use would slightly increase (up to 1%) the magnitude of flood discharges from Karapiro for a rainfall magnitude of 50 years ARI (Table 6). For smaller rainfall events of up to 20 years ARI, the magnude 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 predictions about double those of TopNet.. Discharges resulting from HEC/HMS model inflows bracketed those of TopNet, but both were generally in accord with recorded discharges at Karapiro.

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 6: Percentage increase in Karapiro 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)
5 year	0.0	0.2	0.0	0.4
10 year	-0.2	0.2	0.0	0.2
20 year	0.0	0.7	0.2	-0.2
50 year	0.0	1.0	0.7	0.2
100 year	0.5	1.7	2.7	1.2
500 year	2.2	1.2	12.1	6.3

5. References

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

SKM (2009). Impact of Land Use Change on Floods in the Upper Waikato Phase 2: model calibration and flood hydrograph generation. Sinclair Knight Merz, Auckland.

Appendix – flood routing model parameters

The flood routing model requires a set of parameters for each dam. These are:

1. Reservoir area and maximum control level
2. Initial starting discharge and level.
3. Lag time to downstream dam.
4. Discharge rules (table discharges).

Dam reservoir areas and control levels

	Reservoir area(km^2)	Maximum control level (2008 hybrid levels) (masl)
Ohakuri	12.6	287.1
Atiamuri	2.3	252.9
Whakamaru	7.4	226.5
Maraetai	5.0	189.0
Waipapa	1.6	128.1
Arapuni	9.1	111.0
Karapiro	7.7	52.9

Initial discharge and level

Location	Initial Level (masl) MRP (2008)	Lag time (h) MRP (2008)	Initial discharge MRP+ (2008)
Taupo	Not used		150
Ohakuri	286.70	12	160
Atiamuri	252.50	0.33	164
Whakamaru	226.00	1.5	172
Maraetai	188.70	1.0	185
Waipapa	126.70	0.42	208
Arapuni	110.75	2.5	223
Karapiro	52.70	2.0	224

+ The initial outflow will equal the upstream discharge plus tributary inflow in order to start with steady reservoir levels, so that initial outflows will vary depending on the magnitude of the event being simulated.

Discharge Tables

Ohakuri Discharge Table

Level RL (m)	Discharge (cumecs)
287.20	115
288.40	115
288.50	135
288.60	155
288.70	175
288.80	195
288.90	215
289.00	235
289.10	255
289.20	270
289.30	280
289.40	295
289.50	315
289.60	335
289.70	355
289.80	375
289.90	395
290.00	415
290.10	430
290.10+	(1)

(1) At level 290.10 discharge equals inflow.

Atiamuri Discharge Table

Level RL (m)	Discharge (cumecs)
252.90	185
253.00	200
253.20	220
253.40	260
253.60	310
253.70	330
253.80	380
254.00	390
254.20	420
254.40	440
254.45	450
254.50	565
254.55	675
254.55+	[1]

[1] At 254.55 discharge equals inflow.

Whakamaru Discharge Table

Level RL (m)	Discharge (cumecs)
226.50	340
226.70	345
227.50	360
227.60	400
227.80	435
228.00	470
228.20	500
228.40	580
228.60	640
228.65	865
228.65+	[1]

[1] At level 228.65 discharge equals inflow.

Maraetai Discharge Table

Level RL m	Discharge (cumecs)
189.00	370
189.20	420
189.40	490
189.60	540
189.80	570
190.00	590
190.20	630
190.40	720
190.50	780
190.60	840
190.80	940
190.80+	[1]

[1] At level 190.80 discharge equals inflow.

Waipapa Discharge Table

Level RL m	Discharge (cumecs)
128.1	350
128.2	410
128.4	560
128.6	610
128.8	670
129.0	730
129.2	780
129.4	850
129.6	910
129.8	960
130.0	1010
130.2	1050
130.3	1090
130.45	1130
130.6	1520
130.65	1660
130.7	1790
130.8	2055
130.87	2240

Arapuni Discharge Table

Level RL m	Discharge (cumecs)
111.30	385
111.40	400
111.80	450
112.20	510
112.80	560
113.00	620
113.10	675
113.20	700
113.30	800
113.50	950
113.70	1110
114.00	1350
114.50	1460
115.00	1570

Karapiro Discharge Table

Level RL m	Discharge (cumecs)
52.90	450
53.00	490
53.20	550
53.40	600
53.60	670
53.80	750
54.00	800
54.20	910
54.40	1000
54.50	1485
54.50+	(1)

(1) At level 54.50 discharge to equals inflow.