Ian Jowett Consulting

Review of Waikato Flood Modelling with Land Use Change

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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 predictions of these two models of flood inflows with current land use were compared with other models that had previously been developed. The predictions were also compared to recorded inflows between Taupo and Karapiro and storm rainfalls and runoff recorded in major tributaries.

The storm rainfall-runoff responses predicted by the HEC/HMS (SKM/EW) model agreed with measured responses in tributary streams, except for large and intense storm events in the Ohakuri and Tahunaatara catchments. The predicted total inflows for the 1998 temporal pattern agreed reasonably well with inflows calculated by subtracting Taupo from Karapiro discharge and with other model estimates. However, predicted inflows for large rainfall events with the 1958 temporal pattern were higher than estimates from other models or from statistical analysis of recorded inflows.

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.

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) 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.

This report compares the flow predictions of models of current land use with other models that had previously been developed. The predictions are also compared to recorded inflows between Taupo and Karapiro and storm rainfalls and runoff recorded in major tributaries.

A companion report (Jowett 2009) calculates discharges from Karapiro and other dams by routing the sub-catchment inflows predicted by the two models through the Waikato hydro-electric system according to a set of flood routing procedures.

2. Rainfall

The SKM/EW HEC/HMS (SKM 2009) and the NIWA TOPNET models used storm rainfalls of varying magnitude and two different temporal patterns, one based on the long duration July 1998 storm and the second based on the short duration February 1958 storm. The distribution of rainfall used by the models also varied between the two storms, with the 1998 storm rainfall having the distribution of the 1998 storm and the 1958 temporal pattern using the distribution of high intensity rainfalls (HIRDS).

The rainfall totals were based on 72 hour HIRDS rainfalls derived from statistical analysis of point rainfalls. The HIRDS point rainfalls are multiplied by an area adjustment factor when applied to a large area. Table 1 shows the rainfalls that were used in model predictions.

The rainfalls for the 5 to 500 year return periods used by the two models for the 1998 and 1958 temporal patterns are not necessarily the same (Table 1), and this illustrates the uncertainties associated with the estimation of rainfall over such a large area.

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

As a check on the magnitude of the rainfalls for various recurrence intervals in Table 1, they can be compared to actual total catchment rainfalls of some large storms that have occurred over the Waikato.

The 1958 storm produced the largest discharge from Karapiro/Arapuni in the 88 years of record from 1921 to 2009 and was considered to be a 100 year flood event by Jowett (1972). Jowett (1972) estimated that the storm rainfall for the February storm was 157 mm (Table 2) and this has an ARI of about 100 years according to Table 1. The other largest rainfalls recorded over the Waikato catchment in the last 100 years (Table 2) are within the range of 50-100 year ARI rainfalls used in the models (Table 1).

Table 2: Largest flood producing rainfalls from storms of 2-3 day duration over the Waikato dam tributary catchments from Jowett (1972).

Year	Rainfall (mm)
1907	173
1944	157
1958	157
1967	165
1970	113

The estimated catchment PMP is 410 mm over 84 hours (Jowett 1999). This was based on Cyclone Bola centred on the eastern boundary (Kaimai Range) of the catchment. The pre-Bola estimate of the PMP was 305 mm based on the 1967 storm (Jowett 1972).

2.1 Temporal pattern

The catchment average rainfalls from HIRDS rainfalls in Table 1 are 72 hour rainfalls and were assumed to have the temporal patterns of the 1958 and 1998 storms. The 1958 storm temporal pattern assumed that most (52%) of the 72 hour 1958 rainfall fell within a 12 hour period, with 10% the first day, 61% the second and 29% the third day (SKM 2009). Jowett (1972) calculated a slightly less extreme temporal distribution for the 1958 storm, with 19 mm, 80.5 mm, and 56.9 mm (12%, 51%, and 36%) recorded on successive days to give a total of 157 mm.

The 1998 storm was included in the study because it was less intense than the 1958 storm. It contained three separate events (1 and 2 July, 8 through 10 July and 14 and 15 July 1998), of which the middle event was the largest. The heaviest rain occurred along the catchment western boundary and caused the extremely large floods in the Mangakino and Waipapa rivers. For two catchments, Mangakino and Waipapa, these events were exceptional, being nearly twice as large as previously recorded maxima, and the largest in 35 years of record. However for the total catchment between Taupo and Karapiro, the inflow was not so extreme, with an estimated recurrence interval of between 15 and 70 years.

In general, temporal patterns of extreme events tend to be more uniform than those in storm which occur more frequently (Tomlinson & Thompson 1992, IEA 1987). Intuitively, it seems logical to assume that for an event to be extreme, the rainfall must be very intense (and therefore uniform) throughout the duration of the storm. PMPNZ presents temporal patterns for extreme events where about 30% of the 72 h rainfall falls within 12 hours which is almost half that in the 1958 storm. Thus, the combination of the 1958 temporal pattern with 3 day rainfalls produces unusually intense rainfalls for 12 hours and that increases the effective recurrence interval of the event.

3. Runoff-rainfall relationships

The amount of flood runoff produced by a storm is closely related to the total storm rainfall over the catchment, with factors such as antecedent wetness and rainfall intensity having some influence. Jowett (1999) examined the relationships between runoff, rainfall and some other factors and concluded that storm rainfall was the most important predictor of storm runoff for most tributaries and that neither base flow at the start of the flood, antecedent wetness nor season had a significant effect on storm runoff in more than one stream.

The flows in the major tributary streams flowing into the Waikato hydro lakes have been monitored since 1964 and every major flood in these catchments up until July 2004 has been examined to determine the total storm rainfall and flood runoff. A simple plot of the amount of runoff produced by the storm rainfall shows the response of the catchment to rainfall.

The analyses of storm rainfall and runoff are described in Jowett (1999) who derived runoff-rainfall design curves that were used to estimate the maximum amount of runoff for the probable maximum flood. These curves enveloped most of the recorded runoff/rainfall events and are shown in the graphs below.

The measured flood runoff responses to rainfall were compared to the HEC/HMS and TOPNET model predictions of flood runoff for 1958 style storm rainfalls of nominally 5 to 500 year ARI. The 1998 style rainfall responses were not analysed because the storm had two peaks and that made baseflow separation difficult. The models predict inflows into dam sub-catchments rather than at the flow gauging sites but in most cases, the gauged tributary streams represent a high proportion of the area draining into the hydro lakes.

3.1 Karapiro and Pokaiwhenua Stream

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

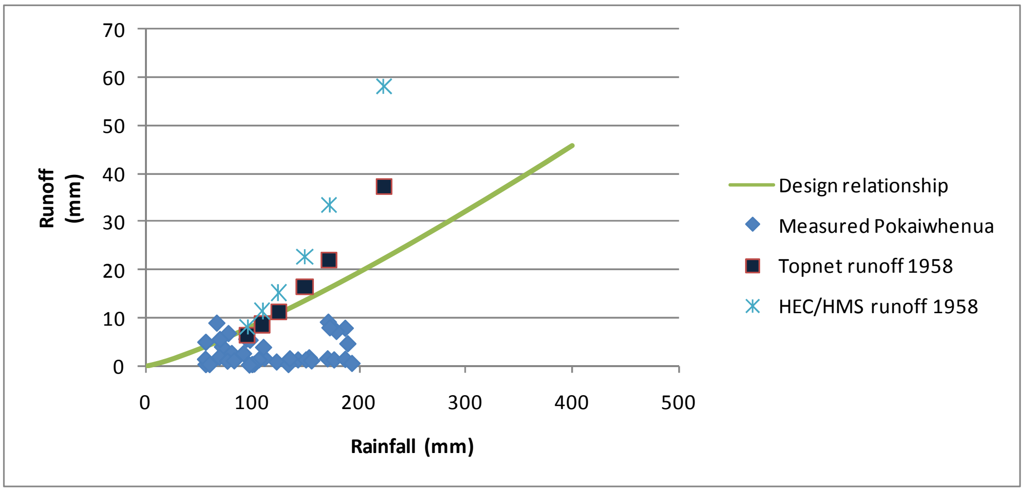

Figure 1: **Measured storm runoff produced by total storm rainfalls and maximum design relationship in the Pokaiwhenua Stream compared to storm runoff into Karapiro reservoir predicted by HEC/HMS and TOPNET models for rainfalls of 5 to 500 year ARI with 1958 temporal pattern.**

3.2 Waipapa and Waipapa River

This Waipapa River is a left bank tributary that has a greater response to rainfall than any other middle Waikato tributary. The small area on the right bank of the Waipapa reservoir is less responsive than the Waipapa River. The HEC/HMS model results plot through the centre of the measured runoff/rainfall points and the slope of the HEC/HMS relationship is similar to that for the Waipapa River (Fig. 2). This probably is a good estimate of the sub-catchment response. The TOPNET model under-predicts the amount of runoff produced by the Waipapa sub-catchment.

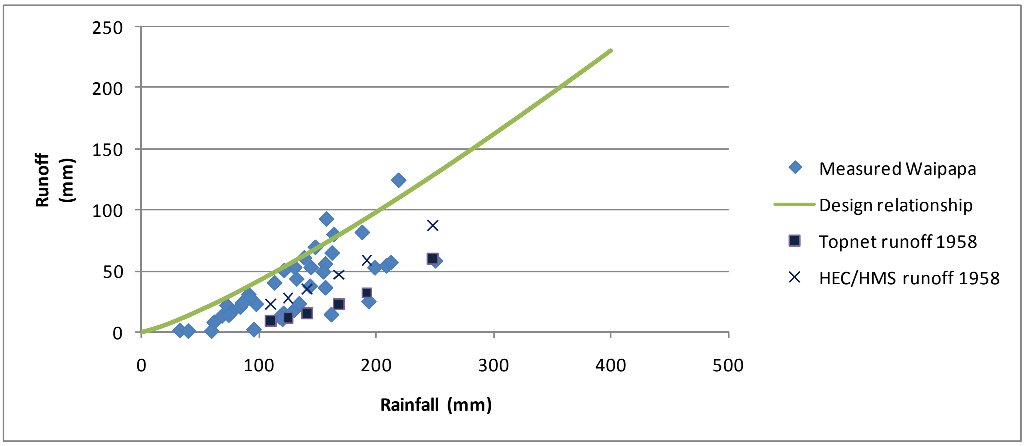

Figure 2: **Measured storm runoff produced by total storm rainfalls and maximum design relationship in the Waipapa River compared to storm runoff into Waipapa reservoir predicted by HEC/HMS and TOPNET models for rainfalls of 5 to 500 year ARI with 1958 temporal pattern.**

3.3 Maraetai and Mangakino Stream

The Mangakino Stream flows into Lake Maraetai from the left bank. The remaining catchment is considered to be less responsive than the Mangakino Stream (Jowett 1999). The HEC/HMS model results predict slightly more runoff than the TopNet model (fig. 3), , but both are a reasonable model of the whole Maraetai catchment.

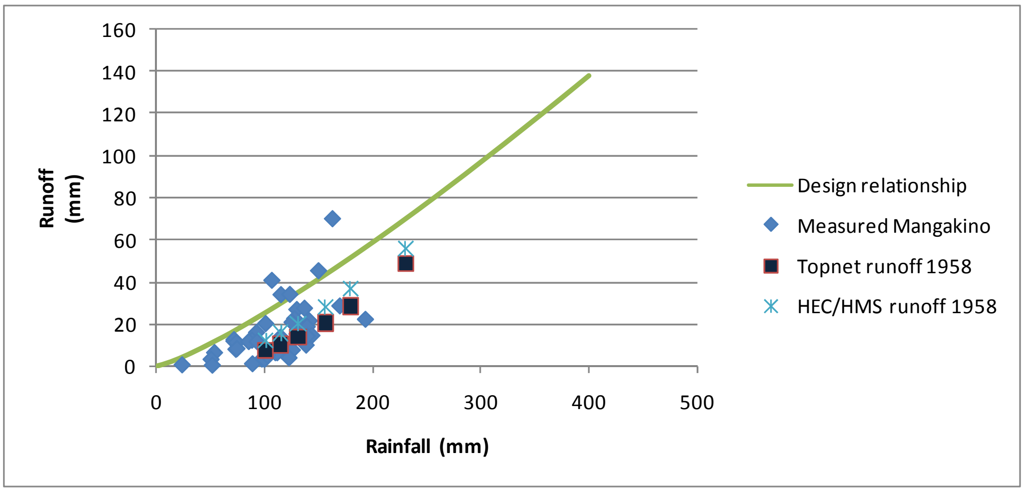

Figure 3: **Measured storm runoff produced by total storm rainfalls and maximum design relationship in the Mangakino Stream compared to storm runoff into Maraetai reservoir predicted by HEC/HMS and TOPNET models for rainfalls of 5 to 500 year ARI with 1958 temporal pattern.**

3.4 Atiamuri and Tahunaatara Stream

The Tahunaatara Stream is a right bank tributary than flows into Lake Atiamiuri and forms most of the drainage of that reservoir. The HEC/HMS model results plot through the centre of the measured runoff/rainfall points at low rainfalls, but the runoff percentage at high rainfalls equals the highest measured (Fig. 4). The slope of the HEC/HMS relationship is steeper than the maximum design relationship for the Tahunaatara Stream. The TOPNET model under-predicts the amount of runoff produced by this sub-catchment.

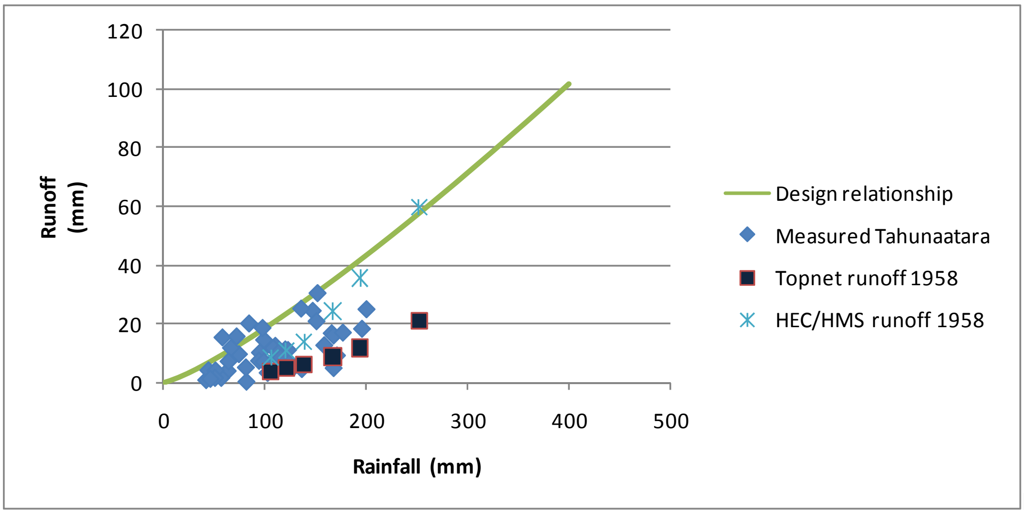

Figure 4: Measured storm runoff produced by total storm rainfalls and maximum design relationship in the Tahunaatara Stream compared to storm runoff into Atiamuri reservoir predicted by HEC/HMS and TOPNET models for rainfalls of 5 to 500 year ARI with 1958 temporal pattern.

3.5 Ohakuri and Waiotapu Stream

The Waiotapu is a right bank tributary that flows into Lake Ohakuri and only represents about 15% of the contributing area. The remaining area is thought to produce very little runoff (Jowett 1999). The HEC/HMS model results plot through the centre of the measured runoff/rainfall points at low rainfalls, but high rainfall model results exceed measured events (Fig. 5). The slope of the HEC/HMS relationship is steeper than the maximum design relationship for the Waiotapu Stream. When the characteristics of the remaining catchment are considered, the HEC/HMS model over-predicts runoff into Lake Ohakuri particularly with high rainfalls. The TOPNET model under-predicts Waiotapu Stream runoff, but will probably predict Ohakuri sub-catchment runoff well considering the low runoff characteristics of the remaining catchment.

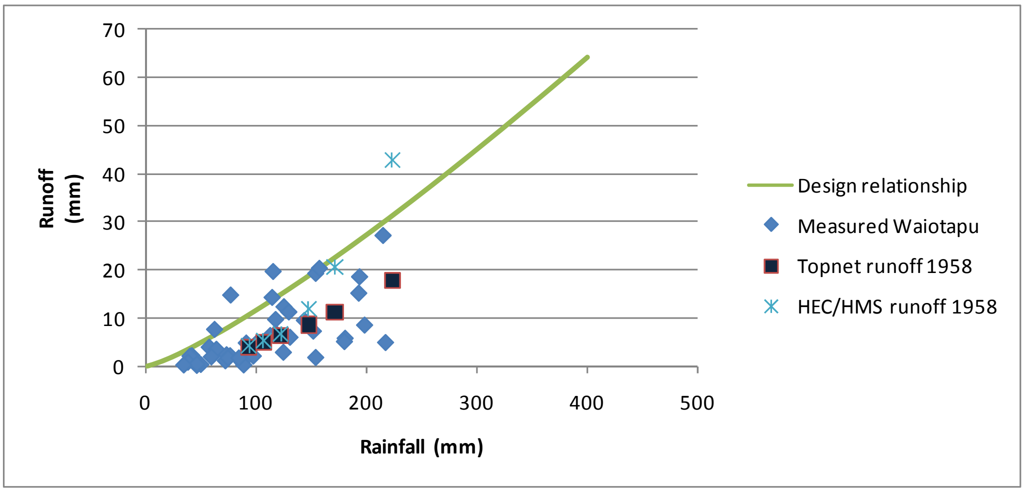

Figure 5: Measured storm runoff produced by total storm rainfalls and maximum

design relationship in the Waiotapu Stream compared to storm runoff into Ohakuri reservoir predicted by HEC/HMS and TOPNET models for rainfalls of 5 to 500 year ARI with 1958 temporal pattern.

3.6 Summary of runoff-rainfall relationships

The model results should plot through the middle of the measured data; in as far as, the tributary represents the catchment area contributing to dam inflows. The slope of the predictions should also be similar to the maximum design relationships.

In general, the HEC/HMS model predictions compare well with the measured tributary data, particularly for the Waipapa catchment. However for Ohakuri, and to a lesser extend Atiamuri, the model probably over-predicts runoff with high intense rainfalls. Overall, the response to low rainfall events seems to have been modelled very well in all catchments, but the predicted proportion of rainfall that appears as runoff in large and intense rainfall events is often greater than has been recorded in the tributary catchments.

The TOPNET model under-predicts runoff in the Atiamuri and Waipapa sub-catchments, but predicts runoff well in the Ohakuri and Maraetai catchments. With high intense rainfalls, the TOPNET model runoff predictions appear to be closer to measured events than HEC/HMS predictions. The slopes of the predicted rainfall/runoff relationships seem to be close to the maximum design relationships.

4. Predicted inflows into Waikato Dam sub-catchments

The tributaries that were compared with predicted sub-catchment inflows in the previous section only cover about 36% of the catchment between Taupo and Karapiro. The models assess the characteristics of the remaining area using mapped soil and infiltration characteristics and some subjective judgement, in the case of the HEC/HMS model. The abilities of the models to predict inflows for the large ungauged portion of the catchment can only be assessed by comparing total predicted flows with those of other models and recorded inflows into the river between Taupo and Karapiro.

4.1 Comparison with other models of Waikato flood inflows

Models of inflows into the Waikato hydroelectric system have been developed in earlier studies (Jowett 1999) and these can be compared to HEC/HMS and TOPNET models of present land use. The model developed by Jowett (1999) was a unit hydrograph flood model for the prediction of the probable maximum flood (PMF) based on measured and assumed maximum relationships between rainfall and runoff. The Hydroelectric Commission of Tasmania model (HCT) was a flow forecasting model using the Australian Water Balance Model (AWBM). Both the Jowett and HCT model predictions are for a 84 h storm, whereas the HEC/HMS model predictions that are compared here are for a 72 hour storm.

The rainfall distribution varies with the type of storm. The NW PMF has the highest rainfall in the north and west, whereas the NE PMF has the highest rainfalls in the north and east. The HEC/HMS and TOPNET rainfall distributions with the 1998 temporal pattern were based on a NW storm whereas the predictions with the 1958 temporal pattern were not based on any particular storm type and are a combination of NE, N, and NW rainfall distributions.

The relative contributions of each of these models to the dam sub-catchments were compared (Table 3) to see whether there were differences in the predicted distributions of runoff. This showed that the distributions of NW flood inflows in the HEC/HMS and TOPNET models were generally similar to the NW distributions predicted by the Jowett (1999) and HCT models. The main difference was that the HEC/HMS and TOPNET models predicted less inflow into Waipapa than the Jowett and HCT models. The TOPNET model predicted less inflow into Arapuni and more into Whakamaru than any of the other models and the HEC/HMS model predicted more runoff into Karapiro and Arapuni than any of the other models.

The total inflow volumes summed over 168 hours were also compared. The NW PMF rainfall was about 68% greater than the 1998 HEC/HMS and TOPNET rainfalls and the runoff volumes were correspondingly greater. However, the NW PMF rainfall was 47% greater than the 1958 500 year rainfall, and the PMF inflow volume was 30% greater than the HEC/HMS inflow volume and more than 100% greater than the TopNet volume.

Table 3: **Relative contribution of dam sub-catchments as a percentage of total inflow with PMF models and HEC/HMS model with 84 and 72 h storms and runoff, respectively with inflow volumes summed over 168 h.**

Dam	Jowett (1999) 336 mm NW PMF	HCT model (336 mm NW PMF)	HEC/HMS model (1998 210 mm)	TOPNET model (1998 191 mm)	HEC/HMS model (1958 228 mm)	TOPNET model (1958 228 mm)
Karapiro	14	12	19	14	18	19
Arapuni	12	12	16	5	8	6
Waipapa	16	17	9	11	11	9
Maraetai	23	19	22	20	18	18
Whakamaru	11	19	13	23	10	19
Atiamuri	6	5	6	5	8	5
Ohakuri	19	18	15	21	27	24
Total inflow (m^3x10^6)	440	482	222	268	364	200

4.2 Comparison with recorded flows in the Waikato River

Flow records have been kept on the Waikato River at the Lake Taupo outlet since 1905, at Arapuni since 1920, and at Karapiro since 1953. The annual maximum daily mean flows at Arapuni and Karapiro can be used to give an estimate of the magnitude of flood flows from Karapiro. The Arapuni/Karapiro flows less the Taupo flows provide an estimate of the flow coming into the river between Karapiro and Taupo. This calculation was carried out by Jowett et al. (1999) assuming a 16 h time lag between the two Taupo and Karapiro. The annual maximum daily mean flows were analysed to give estimates of Karapiro flood discharges and inflows between Taupo and Karapiro with ARIs of 5 to 500 years (Table 4).

A simple lagged difference of Taupo and Karapiro flows does not take potential changes in lake storage into account. However, the last dam to be completed and one with a large amount of flood storage was Ohakuri in 1961, so that flood storage effects are likely to be less before this. In addition, flood routing procedures were not introduced until about 1974, so that it is likely that little use was made of flood storage before this time. Taupo –Karapiro inflow flood estimates make no allowance for storage and flood routing and so should be less than total inflow predicted by the models.

On average, model estimates are 63% greater than inflow estimates based on the flow difference between Karapiro and Taupo. With a 2 year ARI the average difference is 16% and this increases to 130% for a 500 year ARI.

Table 4: Estimated maximum 1 day inflows (m^3/s) between Taupo and Karapiro and total inflows predicted by HEC/HMS and TOPNET models.

Annual recurrence interval	Karapiro minus Taupo (1 day)	HEC/HMS 24 h inflow (1998)	HEC/HMS 24 h inflow (1958)	TOPNET 24 h inflow (1958)	TOPNET 24 h inflow (1998)
500	611	845	1958	1517	1316
100	517	571	1174	945	973
20	421	365	620	531	666
5	335	285	437	349	492

Averaging flows over 3 days lessens the effect of storage and flood routing on the flow difference between Karapiro and Taupo and on average, model estimates are 0 to 62% greater than model estimates, with the difference increasing with ARI (Table 5).

Table 5: **Estimated maximum 3 day inflows (m^3/s) between Taupo and Karapiro and total inflows predicted by HEC/HMS and TOPNET models.**

Annual recurrence interval	Karapiro minus Taupo (72 h)	HEC/HMS 72 h inflow (1998)	HEC/HMS 72 h inflow (1958)	TOPNET 72 h inflow (1958)	TOPNET 72 h inflow (1998)
500	519	664	1076	731	906
100	439	480	699	474	680
20	359	331	417	293	478
5	286	263	315	203	365

5. Conclusion on catchment modelling

In large catchments, such as the Waikato where rainfall is strongly influenced by topography, it is very difficult, if not impossible, to predict flood events of given probability from rainfall, antecedent conditions, areal and temporal distribution and the models were not developed for that purpose. The models were developed to predict the effect of land use change on flood magnitude and can be used for this purpose. The temporal distribution of the 1958 storm is a rather extreme temporal pattern for high rainfall events, most of which will have more uniform rainfall.

The rainfall-runoff responses predicted by the HEC/HMS model agreed with measured responses in tributary streams, except for large and intense storm events in the Ohakuri and Tahunaatara sub-catchments. The predicted total volumes for the 1998 temporal pattern agreed reasonably well with inflows calculated by subtracting Taupo from Karapiro discharge and with other model estimates. However, predicted inflows for large rainfall events with the 1958 temporal pattern were considerably higher than any other estimates.

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

In evaluating the effect of land use change, the average of the predictions for the February 1958 and July 1998 temporal patterns probably give the best estimate of the average increase in flood estimate, although the predictions of the HEC/HMS model for high rainfalls with the 1958 temporal pattern appear to unusually high compared to other model estimates and recorded data.

5.1 Lower Waikato

The above analyses have shown how difficult it is to estimate floods of a given recurrence interval from rainfall in large catchments. This problem is exacerbated if the model is extended to the lower Waikato. However, the effect of increased discharge from Karapiro on floods in the lower Waikato can be estimated more simply than by use of hydrologic and hydraulic models.

An analysis of lower Waikato flood peaks would show the proportion of the peak that was due to the discharge from Karapiro and the lower Waikato flood peaks could be scaled proportionally to the predicted effect of land use change. For example, if Karapiro contributes 20% of the flood peak at Mercer, then a 10% increase in discharge from Karapiro will increase the Mercer flood peak by 10% of 20%, or 2%.

Thus, the effects of land use change in the middle Waikato on the lower Waikato can be evaluated by increasing lower Waikato flood estimates according to the predicted increase in Karapiro flood magnitude.

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