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The Effect of Land Use Change on the Flood Hydrology of Pumice Catchments

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Executive summary

Due to changes in economic returns from existing land uses, there is increasing pressure for conversion of forest to pastoral farming in the Central North Island. These areas consist of pumiceous soils, whose hydrological and erosion characteristics are sensitive to changes in land use. Conversion of forested areas to pasture within the Waikato Region is currently unregulated by statutory planning instruments and can occur ‘as of right’.

A large block of plantation forest between Taupo and Atiamuri (the Wairakei Pastoral Block, or WPL) is being converted from exotic forestry to pasture . This work is programmed to occur over 15 years and is already well advanced. This study is aimed at estimating the effect of the change of land use for this 22,500 ha Pastoral Block on the flood hydrology of the Waikato catchment. The bulk of the Wairakei Pastoral conversion (19,900 ha) falls within four major catchments which have a combined area of 34,900 ha. This equates to 57% of the total catchment area within these four catchments being converted to pasture. The quantitative assessment in this study focuses on the effects on flood hydrology of the conversion of this 19,900 ha area to pasture within these catchments. Other potential effects of this conversion are addressed elsewhere.

In addition to the WPL land, large areas of the Carter Holt Harvey Kinleith forest are being sold and converted to pasture (mainly for dairying). The effects of that process would be additional to those addressed in this report, but for a number of reasons have not been taken into consideration here.

As part of the investigation, a review has been undertaken of the existing literature regarding the effect of conversion from forest to pasture on flood hydrology. This literature indicates that changes for pumice soils can potentially be in excess of an order of magnitude in terms of both flood peaks and flood volumes. For non-pumice country, flood peaks for pasture are about twice those from forest.

Additional analytical work has been undertaken to investigate the effects of the proposed changes on flooding and flood effects. Four study catchments have been used as the basis for these analyses. The first two are small catchments (less than 1 km^2) within the Purukohukohu Experimental Basin in the Paeroa Ranges. The third is larger, being the Waiotapu Catchment at Reporoa (232 km^2). The fourth, Mangakara at Hirsts, is of intermediate size (22 km^2). All four catchments exhibit similar climate geology and soil types to the study catchments.

Data from these four catchments has been used to develop regional flood frequency curves whereby flood discharges are related to catchment area, return period and percentage of forest cover (Method 1). These curves have then been applied to the study catchments to estimate before and after development flood peak discharges.

The second method (Method 2) has involved using rainfall and flood discharge records from the calibration catchments to develop both an infiltration relationship in terms of percentage forest cover, and a generalised instantaneous unit hydrograph (IUH) parameterised in terms of percentage forest cover and time to peak. The infiltration model and IUH model have then been applied to the study catchments to estimate before and after flood peaks and flood volumes. This method provides estimates of changes in runoff volumes in addition to changes in flood peak. The analyses also provide valuable insight in to the mechanisms which cause the differences in runoff characteristics for pasture and forest.

Increases in peak discharges resulting from 100% conversion from forest to pasture were found to be between 550% (Method 1) and 900% (Method 2). This is primarily because of the very low runoff rates from catchments in forest. Specific peak discharges for pasture are not dissimilar from those for other similar catchments elsewhere in the Waikato Region.

It is estimated that increases in peak discharge from the combined Wairakei Pastoral catchments resulting from a 57% reduction in forest cover would be between 230% (Method 1) and 228% (Method 2). The expected combined increase in discharge from the four catchments is 97-116 m^3/s in a 20 year flood and 197-212 m^3/s in a 100 year flood as predicted by methods 1 and 2 respectively. When this is applied across the full 22,500 ha block which is undergoing conversion, increases of 110-131 m^3/s in a 20 year flood, and 222-239 m^3/s in a 100 year flood are expected. The estimated total increase in flood runoff volumes is 9.4×10^6 m^3, and 16.2×10^6 m^3 for the 20 and 100 year 72 hour events respectively.

The implications of the changes in flood peaks and volumes are expected to include changes in stream geomorphology and possible increased bank erosion within the catchments themselves. The increases in peak discharge and flood volumes is also significant in terms of the flood management of the Waikato Hydro System. The increased flood volumes flowing in to Lake Ohakuri would represent a 25% increase in the 48 hour, 500 year design storm for the hydro system for this lake. Similarly peak flows into the lake would be increased by between 60% and 90%.

There are also potential implications for flood protection works in the Lower Waikato, with protection standards being reduced for stopbanks. An approximate estimate is that up to 20% of the freeboard for the 20 year standard stopbanks may be lost, and up to 43% of that for the 100 year standard stopbanks lost.

The effects of conversion from forest to pasture on pumice soils can be minimised by adopting good land use practices aimed at minimising the compaction of the soil, and retaining gullies and watercourses in scrub or un-grazed grass. It is expected that such practices can limit the effects of forest to pasture conversion, but will not be able to fully offset them.

The effects of the land use changes can be expected to result in demand for increased river maintenance work in the Upper and Lower Waikato River and also within the tributary catchments where land use changes take place. The effect of increased peak flood levels in the Lower Waikato may also need to be dealt with by raising stopbanks. The cost of these works would normally fall on Environment Waikato in its River and Catchment Management role, and would require additional funding through Project Watershed. Rating for services under Project Watershed may need some adjustment to deal with the proposed land use changes in the areas of concern.

The effects on flood management for the Waikato Hydro System are potentially significant, though would require further investigation. Mighty River Power, as owner and operator of the system, are the appropriate agency to determine the implications of the potential changes, and whether offset works are necessary. The cost of any such work (if necessary) would not be funded through Project Watershed.

1 Introduction

Due to changes in economic returns from existing land uses, there is increasing pressure for conversion of forest to pastoral farming in the Central North Island. These areas have pumiceous soils, whose hydrological and erosion characteristics are sensitive to changes in land use. Conversion of forested areas to pasture within the Waikato Region is currently unregulated by statutory planning instruments and can occur 'as of right'.

Large areas of forest in the Upper Waikato catchment are expected to be converted from exotic forestry to pasture (mainly for dairy farming).

The approx 26,000 hectare Wairakei Pastoral Ltd block lies between Taupo and Atiamuri. Of this land, about 22,500 hectares will be converted from plantation forest to pastoral farming over a period of about 15 years. This is a largely contiguous area of land, and the work is already well advanced.

In addition, Carter Holt Harvey Ltd have been selling parts of the Kinleith forest to private landowners, and that land is generally then being converted to dairy pasture. The Carter Holt Harvey conversion is a series of sales of separate smaller blocks to private individuals and partnerships and although overall involves a significant area of land, is a more piecemeal activity than the Wairakei Pastoral project. The exact area of land sold is not known, but could be up to 15,000 hectares. No defined plan of the area for this conversion is available to Environment Waikato at present. Because of the lack of certainty as to the area and location of the CHH land being converted from plantation to pasture, no attempt has been made in this report to define the effects of that conversion on the flood hydrology of the Waikato River or its tributaries. The report addresses only the effects of the conversion of the Wairakei Pastoral land.

This study investigates the effect that the changes in land use on the Wairakei Pastoral land may have on the flood hydrology of the main catchments involved. The flood hydrology of the pumice soils of the central North Island is known to be particularly sensitive to changes in land use (Selby 1972).

The bulk of the Wairakei Pastoral conversion (19,900 ha) falls within four major catchments which have a combined area of 34,900 ha. This equates to conversion of 57% of the total combined catchment area to pasture. The quantitative assessment in this study focuses on the effects of the conversion of this 19,900 ha area to pasture within these four catchments. The block and four catchments are shown in Figure 1, while a summary of the proposed changes within each catchment is shown in Table 1.

No quantitative assessment has been made of the effects of conversion of the Carter Holt Harvey Block. This conversion area is not currently well defined and is likely to consist of non contiguous blocks. The soils are also less homogeneous than those of the Wairakei Block. While no quantitative assessment has been attempted, the effects are still potentially significant.

2 Background

Development of land from forested cover to intensive pasture is known to increase the rate and total volume of runoff during storm events (Selby 1972), (Rowe 2003), (Jackson, 1973). Such land use changes result in higher flood peaks, and greater fluctuations in flows and water levels (Hamilton 2001),

Foliage intercepts rainfall and, as it evaporates faster from forests than from pasture, a reduced amount of rainfall arrives at the ground surface under forest. The root structure of trees promote good infiltration and trees source soil moisture to a greater depth than pasture. Interception and transpiration of soil moisture to a greater depth under forest affects storm antecedent conditions so that there is a greater soil moisture deficit to be made up before runoff occurs. Pasture has a lower evaporation rate from the surface, is less effective in intercepting rainfall reaching the ground surface, and has a shallower rooting depth. Under pasture, stock trampling and vehicle use can also compact the soil and reduce infiltration capacity (Selby, 1972). Flood producing surface runoff and overland flow is therefore reduced for forested catchments when compared to pasture.

Pumice soils in a dry condition initially repel water until “wetted up” (Selby 1972). During heavy rainfall, infiltration at the start of the storm is often negligible, but after wetting the infiltration rate increases substantially. This effect appears to be more noticeable for pasture than forest and it contributes to making pumice flood hydrology sensitive to land use.

A number of concerns have arisen in regard to the effect of proposed changes in land use on hydrological processes. This report sets out an assessment of the potential impacts of the proposed land use change on the flood hydrology within the catchment.

The proposed change in land use effects four main catchments as shown in Figure 1 and Table 1.

Table 1 Major catchments effected by proposed land use changes

	Area in Ha									
	Orakonui Stream		Waiwhakarewaumu Stream		Kereua Stream		Pueto Stream		Combined catchments	
Land use	Current	Proposed	Current	Proposed	Current	Proposed	Current	Proposed	Current	Proposed
Forest	3655.3	391.9	3805.3	4.9	2840.4	1459.2	17510.5	6062.3	27811.5	7918.3
Pasture	3217.9	6481.3	0.0	3800.4	564.5	1945.8	2193.7	13642.0	5976.1	25869.4
Other	645.6	645.6	1.5	1.5	151.1	151.1	325.0	325.0	1123.2	1123.2
Total	**7518.8**		**3806.8**		**3556.0**		**20029.2**		**34910.8**	

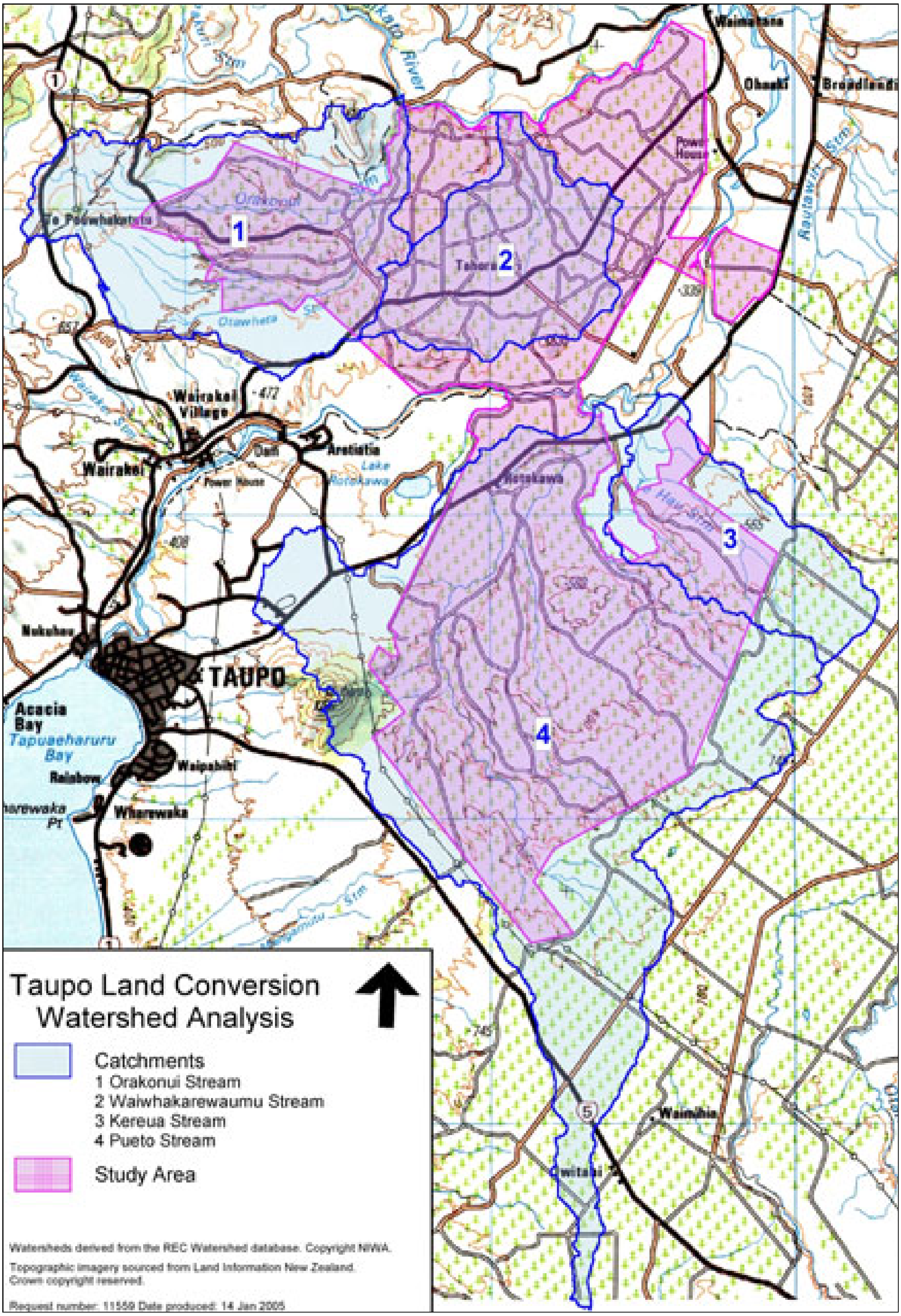

Figure 1 Map of areas and catchments affected by proposed land use changes (from Brown, 2005)

3 Existing knowledge

A comprehensive literature review of the state of knowledge on the effect of land use on flood hydrology was compiled by David Hamilton of David Hamilton and Associates Ltd for Project Watershed in May 2001 (Hamilton 2001). The following discussion draws on Hamilton's investigation, including additional information where appropriate.

There are essentially two ways in which the issue can be addressed (Jackson 1999):

- Using results of experimental catchment studies on the effects of land use on runoff.

- Modelling the underlying biophysical processes which govern the rainfall runoff generation process.

3.1 Catchment studies

Most catchment studies have looked at small catchments (Jackson 1999), and the response of larger catchments to land use changes is more complex. Additionally, most studies have focussed on "normal" soils rather than pumice soils. Pumice soils are known to respond atypically to heavy rainfall and to be more sensitive to land use changes than conventional soils. Only two experimental studies in the literature reviewed relate to pumice soils.

3.1.1 Selby (1972)

Selby (1972) undertook a study of runoff from small plots placed in areas of pasture grass, ungrazed grass, and scrub on pumice soils. The study concluded that surface water runoff from land in pasture was greater than that from areas covered in both un-grazed grass and scrub. Mean runoff (as a percentage of rainfall) from scrub, un-grazed grass, and grazed pasture were found to be:

Scrub:	0.67%
Ungrazed Grass:	0.89%
Pasture	4.60%

Therefore there was an almost sevenfold increase in runoff from scrub to pasture. In intense storms the percentage of runoff increased by a factor of up to 10. These figures also indicate that, because of the high infiltration capacities, runoff volumes from pumice soils are low when compared to other soil types regardless of vegetation cover.

3.1.2 Jackson (1973)

Jackson (1973) compared runoff for the three catchments within the Purukohukohu Experimental Basin for a single storm in 1971. Two of the catchments were in pasture, and the third in native forest. The storm comprised a total of 93 mm within a 24 hour period. Total runoff from the pasture catchments was 8.2 and 4.5 mm, whereas total runoff from the forest catchment was 0.3 mm. For peak discharges the figures were 3.8 mm/hr, 1.8 mm/hr and 0.1 mm/hr respectively. These figures demonstrate differences between pasture and forest of well over an order of magnitude for both total runoff and peak flows.

3.1.3 Rowe (2003)

Rowe (2003) investigated the difference in flood peaks for forest and pasture land uses for a small scale experimental suite of catchments (The Purukohukohu Suite) near Reporoa. He found that smaller flood peaks were approximately doubled and that larger peaks were increased by an order of magnitude for pasture over forest. This is consistent with Selby's results, particularly for the larger floods where an order of magnitude increase was seen. This is however inconsistent with a number of other studies (Duncan (1995), Fahey and Jackson (1997), Rowe and Pearce (1994), Smith (1997)) where it has been found that as flood magnitude (Average Recurrence Interval) increases, the relative difference in flood peaks between pasture and forest catchments decreases. It is notable however that each of these results was obtained from non-pumice catchments.

The Selby and Rowe studies, because they relate to runoff from very small catchments provide some guidance on the effect of land use change on the interception/infiltration process. The attenuation effects of surface and channel storage on runoff are not however accounted for. These effects may be expected to reduce the absolute difference in runoff between land uses for flood peaks on larger catchments. Selby and Rowe observed that the change in peak flows increases with storm rainfall and intensity, and this may be related to the hydrophobic effect observed for pumice soils.

3.1.4 Taupo Bay flood and erosion study (1978)

The Waikato Valley Authority published the report "Taupo Bay Flood and Erosion Study" in 1978 (WVA, 1978). The report included an assessment of the effect of land use and vegetation cover on flood runoff from small catchments around Lake Taupo ranging in size up to 2232 ha.

Various methods of predicting surface runoff from small catchments were examined in an effort to correlate prediction with the few known storm events which had been measured. Much of the difficulty associated with trying to predict runoff based on catchment characteristics including land use, was that pumice soils behave quite differently from non pumice soils under heavy rainfall. When in a dry condition infiltration in the upper soil horizon is negligible, but when the soil becomes wet there is a significant increase in infiltration (WVA 1978). This is the opposite to the behaviour of normal soils where infiltration capacity is normally high initially until the soil becomes saturated, and then the infiltration rate reduces. Pumice soils therefore tend to be sensitive to short duration high intensity storms, This effect is particularly noticeable on small catchments with short times of concentration.

The TM61 method was used as the basis for predicting surface runoff, with infiltration coefficients tuned to best reproduce historic floods.

Infiltration coefficients for the method (W_{ic}) were found to range from 0.6 for catchments with 0-10% bush or scrub to 0.5-0.4 for catchments with 30-50% bush/scrub cover. Runoff varies as W_{ic}^2. Therefore, using this method a reduction of forest/bush cover from 100% to 50% can be expected to increase peak discharges by a factor of 2.25 (125% increase).

It should be noted that the TM61 method is only considered applicable to small catchments in the 100 ha – 2000 ha range. It should also be noted that the method was developed over fourty years ago, and takes a somewhat simplistic approach to the rainfall-runoff process. Although it is still widely used for predicting flood flows for un-gauged catchments, its value as a basis for assessing the effect of vegetation change on flood hydrology is considered limited.

3.2 Analytical studies

As outlined above, the response of a catchment to different land uses can be considered in two parts:

- Firstly there is the interception/infiltration process whereby rainfall is transformed to excess rainfall after losses due to infiltration and interception are removed. This process is where it is expected the maximum effect of change in land use will be seen.

- The second part of the process involves the routing of surface runoff to the catchment outlet or location of interest. This process is attenuative because of storage in surface depressions, and channels etc. Changes in overall volume of runoff are not affected by this process.

3.2.1 Jackson (1999)

Jackson (1999) undertook an assessment of the difference between the runoff from pasture and forest for the Piako River Scheme, a non-pumice catchment. The results of this study show that the effect was dependent on the total storm rainfall depth which in turn depends on storm return period and duration. (Higher rainfall depths produce lesser increases in runoff, i.e. the effect of land use change reduces as storm rainfall increases).

Jackson found, percentage increases in runoff from pasture of 50%-200% for a 2 year storm and 11%-26% for a 50 year storm. Jackson investigated the expected difference in response of catchments under forest and pasture for different antecedent soil moisture conditions. His results show a less marked impact of land use change where soils are wetter prior to a storm.

Jackson observed that flood volumes for his analysis increased by 11-26% depending on antecedent soil water status.

3.2.2 Hamilton

By considering widely accepted values for the runoff coefficient "C" used in the Rational Method of flood discharge calculation under different land uses, Hamilton estimated expected increases in flood runoff of 20% for medium soil types and 33% on high soakage soils (Hamilton 2001). "C" values are however a relatively crude method of modelling the rainfall runoff process, and are not considered accurate for modelling the response to different land uses.

Hamilton also undertook an analysis using the HEC-HMS hydrological modelling package (US Army Corp of Engineers, 2000). Runs were carried out for a model catchment of 230 km^2, for forest and pasture, and for both pumice and clay soils. The model catchment was based on the Waiotapu at Reporoa, which is close to the area under consideration in this study. Two storms were modelled, both of 24 hour duration, and with total rainfall of 100 mm and 160 mm respectively. Two methods were used for calculating rainfall losses.

The Initial Loss/Continuing Loss method (ILCL), models rainfall interception and infiltration as an initial loss of all storm rainfall up to a certain depth followed by a uniform loss rate in mm per hour (US Army Corp of Engineers, 2000). The process is therefore characterised by the initial loss depth and constant loss rate (the Φ index) which are characteristic of the soil, vegetation cover, and antecedent soil moisture conditions. The other variables in the process are the depth and time distribution of rainfall.

The SCS Curve No. method is similar but models rainfall interception and infiltration as an initial loss followed by a time decreasing loss rate in mm per hour (US Army Corp of Engineers, 2000). The process is determined by the initial abstraction (I_a) and the potential maximum retention (S) which are again characteristic of the soil, the vegetation cover and antecedent soil moisture conditions. Depth and distribution of rainfall are the other parameters in the model.

Hamilton has undertaken modelling with HEC-HMS using estimates of the loss model parameters for forestry and pasture and a standardised temporal pattern of storm rainfall (Hamilton 2001). The assumption implicit in Hamilton's work is that vegetative cover affects only the infiltration process, and not the runoff process. He has considered two storms, one with total rainfall of 100mm over 24 hours and one with total rainfall of 160 mm over 24 hours. The HIRDS rainfall package (NIWA 2002) indicates these rainfalls have average recurrence intervals (ARI) of 10 years and 80 years respectively at Rotokawa. The initial loss parameters used by Hamilton for pumice soils have been derived from the work of Jackson (1999) and Petch (1984). The potential maximum retention (S) parameter in the SCS model has been derived from the recommended SCS Curve No.'s for Group A - high infiltration soils (US Army Corp of Engineers 2000).

The increased runoff due to conversion from 100% forest to 100% pasture on pumice catchments as estimated by Hamilton using the HEC-HMS model is set out in Table 2 following.

Table 2 HEC-HMS results for pumice soils after Hamilton (2001)

Rainfall	Loss method	Relative increase Absolute increase	
		Total volume	**Peak flow**
100 mm (10 year ARI)	SCS Curve No. method	198% 10.3 mm	194% 62.9 m^3/s
	Initial loss/constant loss rate	56% 3.1 mm	65% 56.6 m^3/s
160 mm (80 year ARI)	SCS Curve No. method	126% 24.1 mm	121% 141.9 m^3/s
	Initial loss/constant loss rate	19% 6.4 mm	12% 57.0 m^3/s

Note: – Refer to the text for a description of the model, parameters and assumptions used.

The two different loss methods resulted in quite disparate results. Additionally, Hamiltons results have not been verified against the actual flow record for the Waiotapu Stream at Reporoa. Hamilton also appears to have arbitrarily chosen a 24 hour storm as the basis for his modelling, rather than choosing the duration based on a time of concentration. He also does not appear to have used an area reduction factor for rainfalls.

4 Additional analysis

Additional analyses have been undertaken as part of this investigation to attempt to refine estimates of the effect of vegetation cover on the flood hydrology of pumice catchments. Two approaches have been used. The first is based on undertaking frequency analyses of peak discharges from flow records from hydrological sites with different percentages of forest cover within the general area of the study catchments. These frequency analyses have been normalised with regard to catchment area to provide curves of specific peak flood discharges as a function of return period and percentage of forest cover. The second method involved a unit hydrograph and infiltration analyses to derive an infiltration relationship and unit hydrograph in terms of percentage of forest cover.

4.1 Regional flood frequency analysis

To further investigate the effect of forest clearance on floods, use had been made of the data from the Purukohukohu experimental basin, the Waiotapu Stream Catchment at Reporoa, and the Mangakara Stream Catchment at Hirsts. These catchments have similar soils and climate to the study area. Two sites have been used from the Purukohukohu experimental basin. which is situated in the Paeroa Ranges near Reporoa. The Puriki recorder site has a catchment area of 0.344 km^2, consists of pumice soils, and the site has a continuous record of flows since December 1968. The catchment was in pasture until 1973 when it was planted in exotic forestry. A first thinning was carried out between 1979 and 1981, and the catchment was harvested in 1996-1997, and replanted by 30 September 1997. (Rowe, 2003). The Purutaka recorder site has a catchment area of 0.255 km^2 and was also installed in 1968 but the catchment has been maintained in pasture for the whole time until the present day. Additionally, flow records for the Waiotapu Stream at Reporoa (Catchment Area 232 km^2, 1961 - present) and the Mangakara Stream at Hirsts (Catchment area 22.3 km^2, 1969-1994) have also been used for the regional frequency analysis. These four sites; Purutaka, Mangakara, Waiotapu and Puruki (since 1974) represent catchments with a range of forest covers (0%, 28%, 54% and 100% respectively).

McKerchar and Pearson (1989) have shown that on average, mean annual flood varies as catchment area to the power of 0.8. The annual maxima flood series from the four sites used in this study have therefore been normalised by dividing by catchment area raised to the power of 0.8. McKerchar's and Pearson's flood frequency relationships were developed for catchments ranging in size from approximately 0.02 km^2 up to 9000 km^2. The catchments used in this study are within this range, although the Purukohukohu catchments are at the low end of it. Ideally it would have been preferable to use data from catchments which are closer in size to those within the study area, however such data is not available for either fully forested or fully pastured catchments in the vicinity of the study area. The series of normalised annual maxima are shown plotted for the four sites in Figure 2.

The Puruki annual maxima series shows a distinct change soon after the catchment was planted in pines. Prior to 1973 (pasture), flood maxima are typically an order of magnitude greater than those since 1975 (forest). It is also notable however that the flood magnitudes for the Purutaka Catchment (pasture) also seem to decrease after 1973, and in some cases are little different than the forested catchment (Puriki).

The correlation between corresponding flood maxima at the different sites has been investigated. These are shown plotted in Figure 3 for floods from 1975 on. It is apparent both visually and from the low correlation coefficients, that there is not a strong correlation between flood peaks for the four sites. This appears to be because catchments in different vegetation covers are sensitive to different types of rain events. In particular the events which cause the largest floods for the Puruki catchment in forest are typically of significantly longer duration than those which cause the largest peaks for the catchment when it was in pasture. This suggests that vegetation cover has an impact on the time of concentration of the catchment.

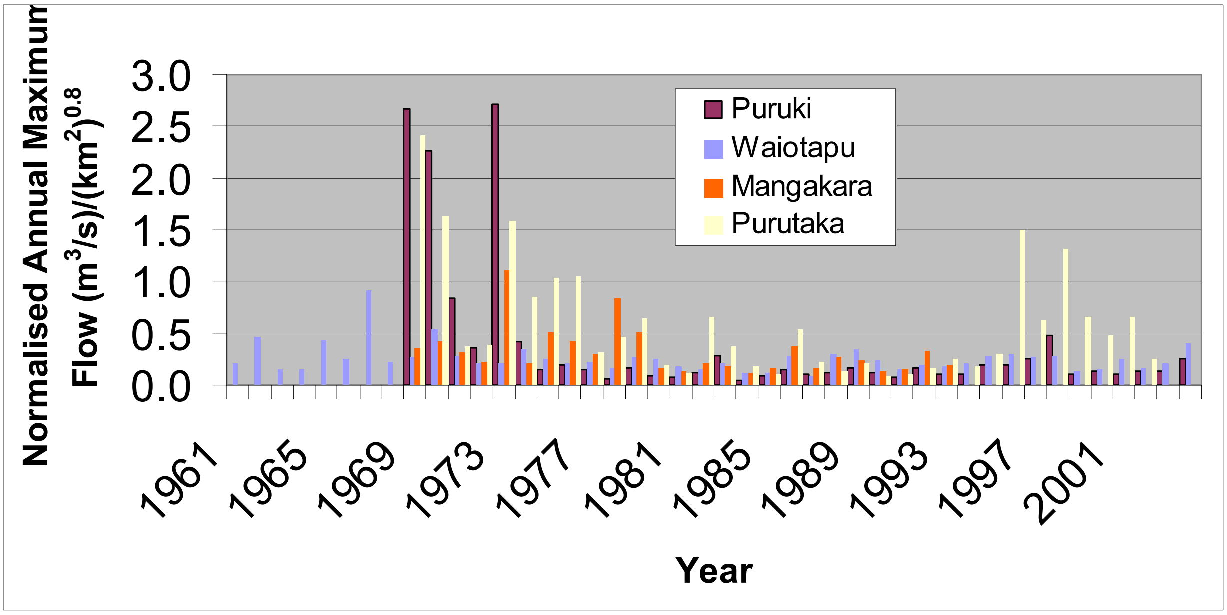

Figure 2 Comparison of normalised annual flow maxima for four sites with different vegetation covers

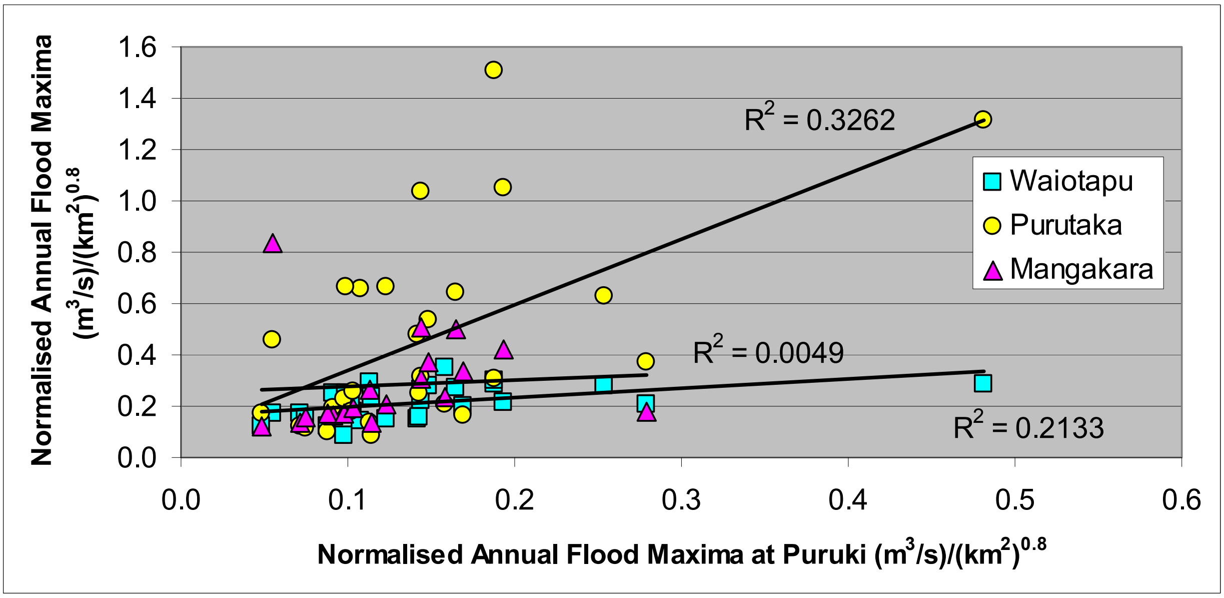

Figure 3 Normalised annual flood maxima at Waiotapu Mangakara and Purutaka versus normalised annual maxima at Puruki

While there is significant variation from year to year, on average Purutaka (0% forest) normalised flood peaks are approximately 3 times those of Puruki (100% Forest). Similarly, Mangakara (28% forest) normalised flood peaks are on average 2.2 times greater than those for 100% forest, and Waiotapu (54% forest) normalised peaks are on average1.75 times greater than those for 100% forest.

Flood frequency analysis has been undertaken for each site using the records of normalised annual maxima. For Puriki, only the record since 1975 has been used so that the results reflect 100% forest conditions.

It was found that a General Extreme Value Distribution fitted by the method of L-Moments fitted the four datasets best. The fitted distributions are shown in Figure 4. The resulting normalised peak flows for different return periods are shown in Table 3. For the Waiotapu Catchment the ratio of Normalised Flood Peak to that for the 100% Forested catchment decreases with return period, i.e. at large return periods there will be no difference in Normalised Discharge between the partially forested catchment and the forested catchment. The pasture catchment (Purutaka) and the 28% pasture catchment (Mangakara) display the opposite trend, that is, the ratios of peak discharge to that for forest increase with return period. Conventional wisdom is that extreme flood magnitudes are independent of catchment cover, although this is based on a limited view which assumes that as soils become saturated in large events vegetation becomes immaterial.

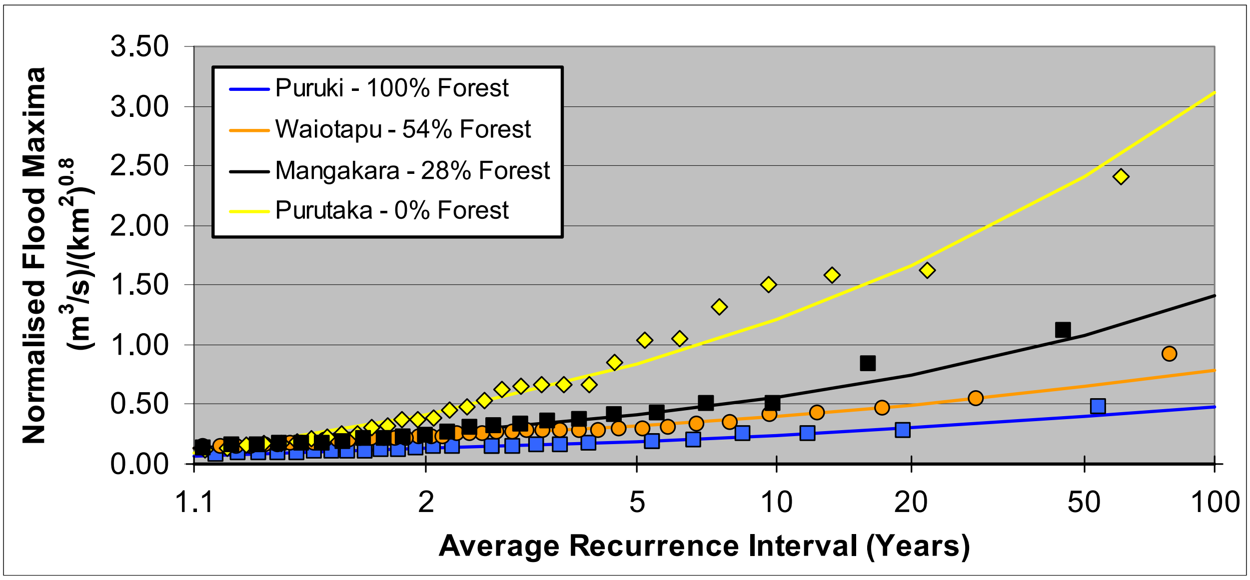

Figure 4 Frequency analysis of normalised flood peaks

Table 3 Results of frequency analysis

Average recurrence interval (years)	Normalised flood peaks $(m^3/s)/(km^2)^{0.8}$ (ratio to 100% Forest)			
	Puriki (100% forest)	Waiotapu (54% forest)	Mangakara (28% forest)	Purutaka (0% Forest)
2	0.127	0.223 (1.76)	0.248 (1.95)	0.419 (3.29)
10	0.245	0.415 (1.69)	0.557 (2.27)	1.214 (4.96)
20	0.304	0.506 (1.66)	0.745 (2.45)	1.661 (5.46)
50	0.397	0.641 (1.61)	1.073 (2.70)	2.404 (6.06)
100	0.479	0.757 (1.58)	1.405 (2.93)	3.118 (6.51)

Figure 5 shows a plot of normalised peak flood discharges versus percentage of forest cover based on the data from each of the four flow record sites. For the 2 year event, the relationship between Percentage Forest Cover and Normalised Flood Peak appears to be approximately linear. For higher return periods the relationship becomes increasingly non-linear.

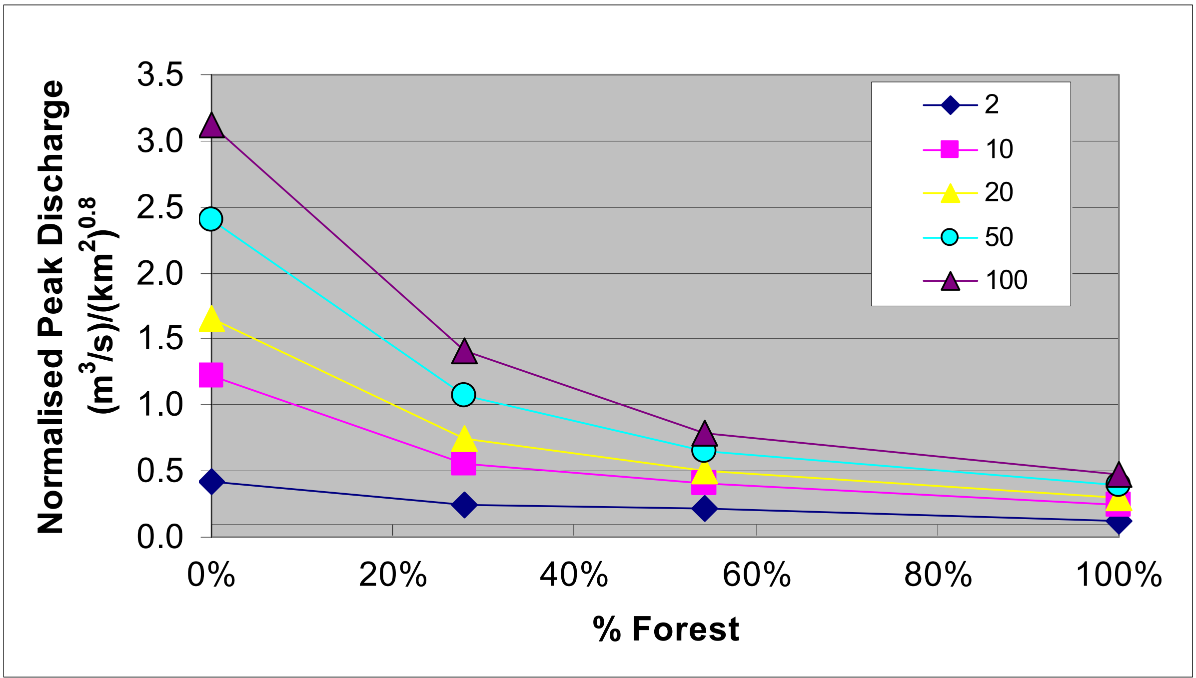

Figure 5 Normalised peak discharges versus % forest

The estimated normalised mean annual floods for the Puriki (forest) catchment, the Waiotapu catchment (54% forest) the Mangakara catchment (28% forest), and the Purutaka catchment (Pasture) are 0.15 $(m^3/s)/(km^2)^{0.8}$, 0.26 $(m^3/s)/(km^2)^{0.8}$, 0.32 $(m^3/s)/(km^2)^{0.8}$, and 0.46 $(m^3/s)/(km^2)^{0.8}$ respectively. McKerchar and Pearson (1989) give contour maps of mean annual flood normalised against catchment area for New Zealand. Their figures for the Waikato River catchment between Taupo and Karapiro range from 0.3 to 0.5. Elsewhere in the Waikato Region (Excluding the Coromandel) values range from approximately 1 to 2. Therefore, even for pasture, these figures are lower than typical values throughout the remainder of the region.

McKerchar and Pearson (1989) also provide contour maps of q_{100}, the ratio of the 100 year discharge to the mean annual flood discharge. The q_{100} ratios from the data are 3.3 for Puruki, 3.0 for Waiotapu, 3.0 for Mangakara and 6.8 for Purutaka. These figures are generally higher than those given by McKerchar and Pearson (1989), with their reported values generally ranging from 2.2 to 2.7 throughout the Waikato Region. The Purutaka value is higher than any of McKerchar and Pearson's reported values for the North Island.

The results from the regional frequency analysis have been used to interpolate estimates for changes in flood peaks within the four study catchments under the proposed changes in land use. These are shown in Table 4. The values for the combined catchments have been derived by adding the peaks for each of the four individual catchments. This may be somewhat conservative as it assumes all peaks are coincident in time, which will not be the case. The alternative approach would have been to treat the combined area as a single catchment and apply the interpolated normalised specific discharges to this. It was felt that this would be non-conservative, because the catchments are separate, and have separate outlets to the Waikato River.

The increases in flood peaks for the combined four catchment areas range from 93% for a two year flood to 230% for a 100 year flood. The largest percentage increase (550%) occurs for the Waiwhakarewaumu Stream under a 100 year event. This is because this catchment is to undergo virtual total conversion from forest to pasture.

Table 4 Estimated changes in flood peak discharges based on regional frequency analysis.

Average Recurrence Interval (Years)	Peak flood discharges (m^3/s)										
	Orakonui Stream		Waiwhakarewaunu Stream		Kereua Stream		Pueto Stream		Combined catchment		
	7518.8 ha		3806.8 ha		3556.0 ha		20029.2 ha		34910.8 ha		
	Current	Proposed	Current	Proposed	Current	Proposed	Current	Proposed	Current	Proposed	Change
	48.6% forest	5.2% forest	99.9% forest	0.1% forest	79.9% forest	41.0% forest	87.4% forest	20.3% forest	79.7% forest	22.7% forest	
2	7.2	12.0	2.3	7.7	2.8	4.1	10.3	19.9	22.6	43.7	21.1
10	13.7	33.3	4.5	22.3	5.3	8.3	19.5	47.8	43.0	111.7	68.7
20	17.2	45.3	5.6	30.4	6.6	10.6	24.2	64.3	53.6	150.7	97.1
50	22.9	65.6	7.3	44.1	8.6	14.5	31.5	92.8	70.3	217.0	146.7
100	28.1	85.2	8.8	57.2	10.3	18.3	38.0	121.2	85.2	281.9	196.7

Table 5 Estimated relative change in flood peak discharge based on regional frequency analysis

Average Recurrence Interval (Years)	Orakonui Stream 7518.8 ha	Waiwhakare waumu Stream 3806.8 ha	Kereua Stream 3556.0 ha	Pueto Stream 20029.2 ha	Combined catchment 34910.8 ha
	Reduction in forest as percentage of total catchment area				
	43%	100%	39%	57%	57%
	Percentage increase in peak discharge				
2	67%	235%	46%	93%	93%
10	143%	396%	57%	145%	160%
20	163%	443%	61%	166%	181%
50	186%	504%	69%	195%	209%
100	203%	550%	78%	219%	231%

4.2 Infiltration and unit hydrograph analysis

Selected storms were chosen to compare the infiltration and runoff characteristics of the Puriki catchment under forest and pasture respectively, and the Waiotapu catchment with mixed pasture/forest land use. The aim was to select between 5 and 10 events for each site based on the largest flood peaks available. No attempt was made to select storms with common dates because the response from the three catchments is quite different and the biggest floods for each are generally not coincident.

The first series of floods for the Puruki site occurred between 1969 and 1973 when the catchment was in pasture, and a total of 5 storms have been selected for analysis from this period. Ten storms were selected from the second period, between 1975 and 1998 when the catchment was in forest. Seven hydrographs have been analysed for the

Waiotapu Stream at Reporoa – representing the intermediate condition of approximately 50% forest. The details for each of the storms investigated are shown in Table 6. Rainfall records used for analysis of Puriki floods were taken from the Purukohukohu No 4 automatic rain gauge. This is within the Purukohukohu Basin, near the Puriki gauge. Analysis of the Waiotapu floods was based on the Reporoa automatic raingauge record, which is coincident with the water level recorder.

Table 6 Floods analysed

Site	Vegetation cover	Flood date	Total rainfall (mm)	Peak rain intensity (mm/hr)	Peak flow (mm/hr)	Recurrence interval (Years)
Purukohukohu at Puriki	100% pasture	Jun-69	43.5	4.5	2.8	3.3
		Dec-69	34.3	64.4	11.9	65.6
		Sep-70	120.9	14.0	2.9	3.4
		May-71	72.9	36.0	3.7	4.9
		Jan-72	28.2	29.1	1.6	1.8
		Jan-73	27.1	28.8	5.8	11.4
		Apr-73	143.2	46.9	12.1	68.8
	100% forest	Mar-75	83.4	40.7	0.63	2.4
		Jul-76	139.6	35.9	0.86	5.1
		Mar-77	118.9	30.9	0.64	2.5
		Mar-79	387.1	38.4	0.66	2.7
		Oct-83	280.0	20.7	1.22	14.3
		Jan-86	200.0	47.0	0.66	2.7
		Oct-89	272.0	27.9	0.70	3.1
		Dec-92	74.3	27.8	0.76	3.7
		Dec-95	113.1	31.6	0.84	4.7
		Jul-98	256.0	20.1	1.58	33.2
Waiotapu at Reporoa	54% forest	Jul-06	159.0	9.5	0.50	9.5
		May-96	83.5	23.5	0.36	3.8
		Jul-98	179.0	8.5	0.35	3.4
		May-95	90.0	21.0	0.34	3.3
		Dec-95	99.5	15.5	0.34	3.2
		Oct-97	71.5	22.0	0.33	3.1
		Jun-97	103.0	6.5	0.32	2.7

Because records are available for the Puruki site for both the forest and pasture, this provided an opportunity to investigate the effect of land use change when all other factors stay the same. Therefore pre 1975 Puruki record was used for analysis of the 100% pasture state in preference to the Purutaka record, because in the latter case, comparisons may be affected by differences in factors such as catchment area and topography etc.

The analyses indicate that the response of pumice catchments (particularly forested catchments) seems to be heavily influenced by interflow or groundwater flow. In forest, there doesn't appear to be significant true surface runoff. Even for catchments in pasture, the response seems to have a significant component of interflow or groundwater flow. Given this, it may be questioned whether a unit hydrograph approach is appropriate to model this process. The approach that has been adopted, is that groundwater flow or interflow response to rainfall is just as validly modelled as a linear process as is surface flow (arguably even more so). The question does arise however as to whether the rainfall separation methods used are appropriate to separate the interflow/rapid groundwater response component of rainfall from the baseflow component. The use of the SCS infiltration equation in this study does give adequate and consistent reproduction of the observed hydrographs, and therefore, while the true underlying process of flood generation may not be purely surface runoff, it is considered valid to treat it as a pseudo surface runoff process and model it using infiltration and unit hydrograph models. It must be noted however, that five of the largest floods for the Puruki in Forest catchment produced such a low peaked and long tailed unit hydrograph, that they were clearly a totally different response mechanism than the for the other hydrographs analysed. They were therefore excluded from the analysis. It is expected that exclusion of these events may to some extent bias the results for peak flows from the 100% forest catchment upwards, thus tending to reduce the differences between forest and pasture peak runoff.

4.2.1 Infiltration analysis

The first step was to estimate the surface runoff hydrograph and runoff volume for each flood. To achieve this baseflow separation was undertaken using a variation of the Straight Line Method (Chow et al., 1988). The baseflow component was estimated by drawing a horizontal line extending from the point at which the hydrograph starts to rise in response to rain, to a point directly beneath the peak of the hydrograph. This point was then extended to intercept the falling limb of the hydrograph at the point where the rate of fall indicates baseflow recession commences (i.e. where the recession curve starts to plot as a straight line on a semi logarithmic plot). For events which have multiple peaks some judgement has been used to estimate the baseflow component. Volume of surface runoff has then been calculated by integration of the surface runoff hydrograph.

The next step has involved estimating the infiltration characteristics of the catchment. Three infiltration models have been trialled; the first being the Initial Loss/Continuing Loss (ILCL) model, and the second being the SCS model (Soil Conservation Service, 1986). The third model trialled was the Green and Ampt infiltration equations, however this was quickly abandoned because it consistently significantly overestimated the initial rainfall losses. The ILCL models losses as an initial loss (mm), followed by a constant potential loss rate (mm/hr). The SCS method estimates total excess rainfall at any time during a storm as:

$$P_e = \frac{(P - I_a)^2}{(P - I_a + S)} \qquad (1)$$

Where:

P_e = Effective rainfall (mm)

P = Total rainfall (mm)

I_a = Initial Loss (mm)

S = Potential Maximum Retention (mm)

The initial loss value for both the ILCL and SCS methods was estimated by inspection of the rainfall and flow records to determine the amount of rainfall which occurred prior to the hydrograph commencing to rise. The second parameter of each method (the Continuing loss rate (Φ) for the ILCL method, and Potential Maximum Retention (S) for the SCS method were estimated by optimisation to achieve a balance between total excess rainfall and total surface runoff. The results are shown in Table 7.

The first point worthy of note is that the floods for the forested catchment tend to be of longer duration and higher total rainfall than those for the pasture catchment. This suggests forested catchments are not as susceptible to short duration high intensity storms as are pasture catchments, that is forest cover tends to increase time of concentration of the catchment. This is consistent with the hypothesis that forest cover tends to increase the interflow/rapid groundwater flow response of the catchment with an equivalent reduction in the pure surface runoff component.

It was apparent that five of the storms for the forested catchment have unusually high runoff percentages. These storms (marked with an * in Table 7) also displayed unusual instantaneous unit hydrographs (discussed further in Section 4.2.2), so have been excluded from the analysis. They have also been excluded from the means of the infiltration parameters given in the Table 7. While the storms rejected have some of the highest rainfalls, and also runoff's, they also tend to be of longer duration, and have low peak runoff response.

Table 7 Results of infiltration analysis

Site	Vegetation cover	Flood date	Total rainfall (mm)	Total surface runoff (mm)	Runoff percent	Initial loss (mm)	φ(mm/hr)	S (mm)
Purukohukohu at Puriki	100% pasture	Jun-69	43.5	8.7	20.0%	7.0	3.4	117
		Dec-69	34.3	11.1	32.3%	8.0	29.5	36
		Sep-70	120.9	31.4	25.9%	7.0	4.4	300
		May-71	72.9	7.0	9.5%	1.0	17.6	672
		Jan-72	28.2	1.8	6.4%	10.0	21.9	165
		Jan-73	27.1	4.9	18.0%	10.0	19.10	43
		Apr-73	143.2	26.2	18.3%	7.5	35.3	566
		Mean	67.2	13.0	18.6%	7.2	18.7	271
	100% forest	Mar-75	83.4	3.9	4.7%	3.0	25.0	1565
		Jul-76*	139.6	41.0	29.3%	1.0	4.6	330
		Mar-77	118.9	4.0	3.4%	7.0	25.0	2991
		Mar-79*	387.1	76.4	19.7%	8.0	9.3	1503
		Oct-83*	280.0	104.2	37.2%	5.0	2.6	451
		Jan-86	200.0	15.0	7.5%	8.0	18.5	2272
		Oct-89*	272.0	73.7	27.1%	3.0	3.6	712
		Dec-92	74.3	5.1	6.9%	3.0	18.8	924
		Dec-95	113.1	5.0	4.4%	4.0	22.0	2273
		Jul-98*	256.0	156.9	61.3%	2.0	1.6	157
		Mean[1]	117.9	6.61	5.60%	5.00	21.9	2005
Waiotapu at Reporoa	54% forest	Jul-06	159.0	27.3	17.2%	7.0	3.6	694
		May-96	83.5	15.3	18.4%	0.0	8.8	371
		Jul-98	179.0	39.5	22.1%	1.0	2.2	624
		May-95	90.0	12.0	13.3%	0.0	10.3	586
		Dec-95	99.5	9.9	10.0%	5.0	7.5	805
		Oct-97	71.5	7.6	10.6%	0.0	14.4	600
		Jun-97	103.0	16.8	16.3%	0.0	2.9	529
		Mean	112.2	18.35	15.4%	1.9	7.1	601

* These storms have been excluded from the analysis – refer to the text.
[1] Mean values do not include values for the excluded events.

Average initial loss rates are all relatively low with values for forest being surprisingly lower than for pasture (although only marginally). Values for the partially forested catchment, the Waiotapu, are also lower again. This parameter is however very dependent on catchment wetness prior to the individual storm, and some variation is expected. Average continuing loss infiltration rates are higher for the forested catchment than for the pasture catchment as would be expected. For the partially forested catchment (the Waiotapu) the continuing loss rates are significantly lower than for the pasture catchment, which is unexpected. This goes against conventional wisdom on the effects of vegetation on catchment infiltration. This may however be due to the fact that the storms for the Waiotapu catchment are of longer duration and higher total rainfall than for the pasture catchment. It is postulated that modelling infiltration as a simple constant continuing loss rate is unrealistic. The SCS infiltration method models infiltration as a time decreasing function and the Potential Maximum Retention (S) values for this method do behave as expected, with the highest values occurring for the fully forested catchment, then the next highest being for the partially forested catchment, with the minimum occurring for pasture.

The SCS infiltration formula has been adopted as the basis for further analysis. The estimation of infiltration parameters as set out in Table 7 shows that this method gives results which are more in line with accepted thinking in regard to the effect of vegetation cover on infiltration. In addition the ILCL model, which models continuing losses as a constant rate appears to be unrealistic and tends to result in a very spiky excess rainfall hyetograph because excess rainfall only occurs where the potential loss rate is exceeded. The hyetograph for the SCS method is smoother, and is considered to be more realistic.

The SCS method uses two parameters, the initial abstraction (I_a), and the Potential Maximum Retention (S). For the purpose of further analysis an I_a value of 5mm has been adopted. There did not appear to be any justification for adopting a different I_a value dependent on land use. Rather than adopting the arithmetic average value for S, the value for each land use type has been calculated from the average excess rainfall and the average total rainfall. This gave rise to the following S values:

Puriki 1968-1973	0% Forest:	327 mm
Waiotapu	54% Forest	783 mm
Puriki 1975-1998	100% Forest	1818 mm

A curve was then fitted through the three points to enable prediction of S as a function of percentage forest cover. An exponential relationship was found to provide a good fit as shown in Figure 6.

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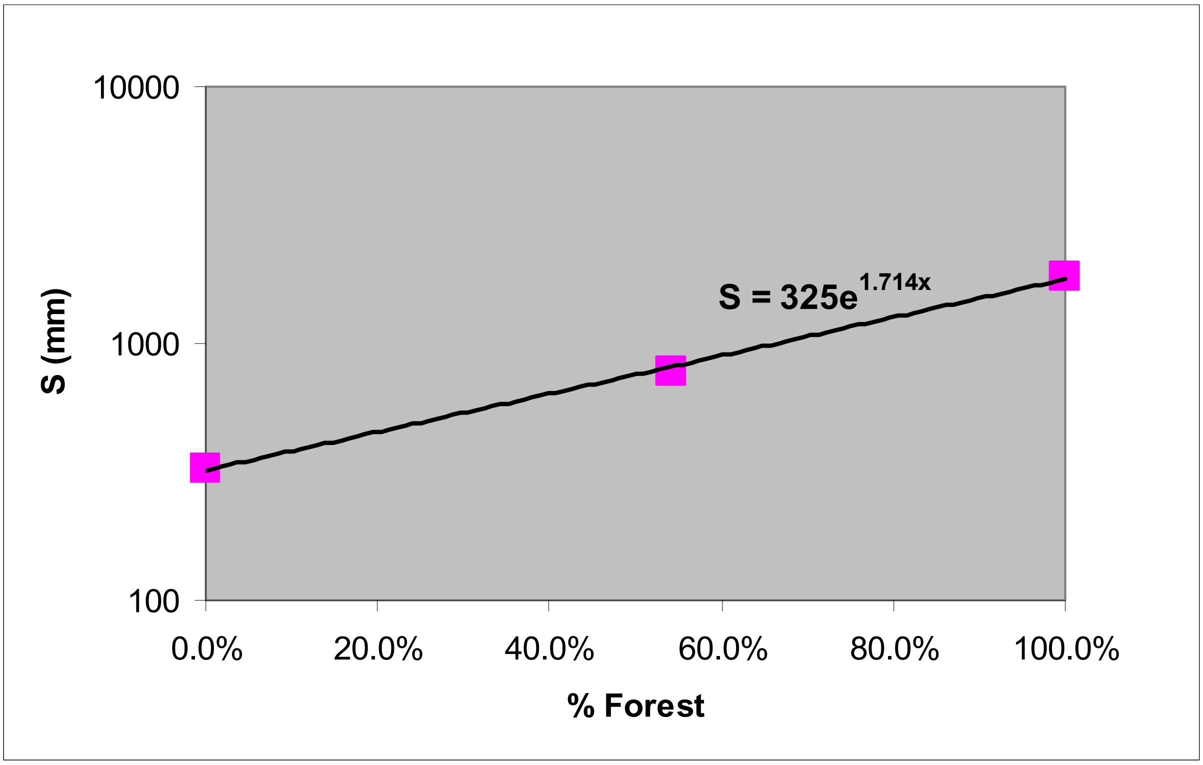

Figure 6 Variation of potential maximum retention (S) with vegetation cover

4.2.2 Unit hydrograph analysis

The next step in the process was to estimate a unit hydrograph for each storm from the excess rainfall hyetograph and surface runoff hydrograph. Initially a harmonic analysis approach was adopted, whereby a Fourier transform was applied to both the rainfall and surface runoff time-series. The resulting surface runoff spectra was then divided by the rainfall spectra to obtain the frequency domain impulse response function. The inverse transform was then applied to this to obtain the time domain impulse response function, or the instantaneous unit hydrograph (IUH). The resulting unit hydrograph tends to be uneven and “noisy” due to random errors in the underlying data, so a fitting procedure has been applied to obtain a best fit for a Gamma Probability Density Function (PDF) to the data. The Gamma PDF has been postulated as an appropriate form for the IUH based on the premise that it represents the outflow from a series of identical linear reservoirs due to a unit impulse input (Chow et al, (1988)).

The rainfall hyetograph, recorded flow hydrographs, and modelled hydrographs for each storm are shown in Appendix A. The details of the resulting best fits for each storm are shown in Table 8. The fitted Gamma IUH’s are characterised by two parameters, time to peak T_p (hrs), and peak discharge ordinate q_p (dimensionless). A generalised fitting procedure has been used to obtain the best fit IUH’s for each of the catchments across all the floods used, these values are shown as the optimised values in Table 8.

It was apparent that a number of the storms used for the 100% forest catchment (Puriki 1975 – 1998) resulted in IUH’s with a very low q_p value, and very long drawn out falling limbs (100-150 hours). The long response times indicate that this is clearly not surface runoff, and it appears to be a groundwater response. These are the same storms which had relatively high runoff percentages, which again tends to confirm the view that the hydrographs are primarily groundwater response. These storms have been excluded from the analysis.

Table 8 Details of fitted unit hydrographs

Site	Vegetation Cover	Flood Date	q_p	T_p (hr)	q_p T_p	RMS error (mm/hr)	Peak error (mm/hr)
Purukohukohu at Puriki	100% Pasture	Jun-69	6.775	0.220	1.490	0.654	0.000
		Dec-69	2.998	0.007	0.021	0.728	0.000
		Sep-70	0.229	0.750	0.172	0.354	0.000
		May-71	5.461	0.212	1.159	0.219	0.000
		Jan-72	5.456	0.743	4.053	0.369	0.000
		Jan-73	1.931	0.499	0.964	0.432	0.000
		Apr-73	2.727	0.189	0.516	1.218	0.000
		Optimised	1.244	0.434	0.540	0.718	0.914
	100% Forest	Mar-75	0.379	0.954	0.362	0.055	0.000
		Jul-76*	0.030	0.070	0.002	0.080	0.000
		Mar-77	0.363	0.845	0.307	0.031	0.000
		Mar-79*	0.027	2.663	0.071	0.097	0.000
		Oct-83*	0.031	9.318	0.286	0.099	0.000
		Jan-86	0.230	0.011	0.002	0.088	0.000
		Oct-89*	0.024	12.706	0.310	0.145	0.000
		Dec-92	0.515	0.004	0.002	0.057	0.000
		Dec-95	0.413	0.063	0.026	0.037	0.000
		Jul-98*	0.023	11.867	0.270	0.124	0.000
		Optimised	0.349	0.443	0.154	0.065	0.079
Waiotapu at Reporoa	54% Forest	May-95	0.039	7.947	0.307	0.015	0.000
		Dec-95	0.033	7.976	0.260	0.007	0.000
		May-96	0.031	9.006	0.282	0.012	0.000
		Jun-97	0.030	7.539	0.229	0.028	0.000
		Oct-97	0.046	7.004	0.321	0.007	0.000
		Jul-98	0.027	14.914	0.398	0.049	0.000
		Jul-04	0.022	8.980	0.197	0.024	0.000
		Optimised	0.030	7.550	0.230	0.025	0.041

* These storms have been excluded from the analysis – refer to the text.

The unit hydrographs obtained are catchment specific in the sense that the shape of the hydrograph will change with the time characteristics of the catchment. In general however it is assumed that the dimensionless unit hydrograph (where the time and response ordinates are normalised against q_p and T_p respectively) can be transferred to other catchments of different size etc by scaling. This is the assumption implicit in the SCS Unit Hydrograph method (US Army Corps of Engineers, 2000).

The Dimensionless Unit Hydrographs for the three sites analysed are shown in Figure 7. Comparing the dimensionless IUH's for pasture and forest shows that the forest IUH has a significantly longer falling limb, implying a longer time of concentration. It is postulated that this longer falling limb is due to the response from forest catchments being dominated by interflow or rapid groundwater response, as compared to pasture which has a greater true surface runoff response..

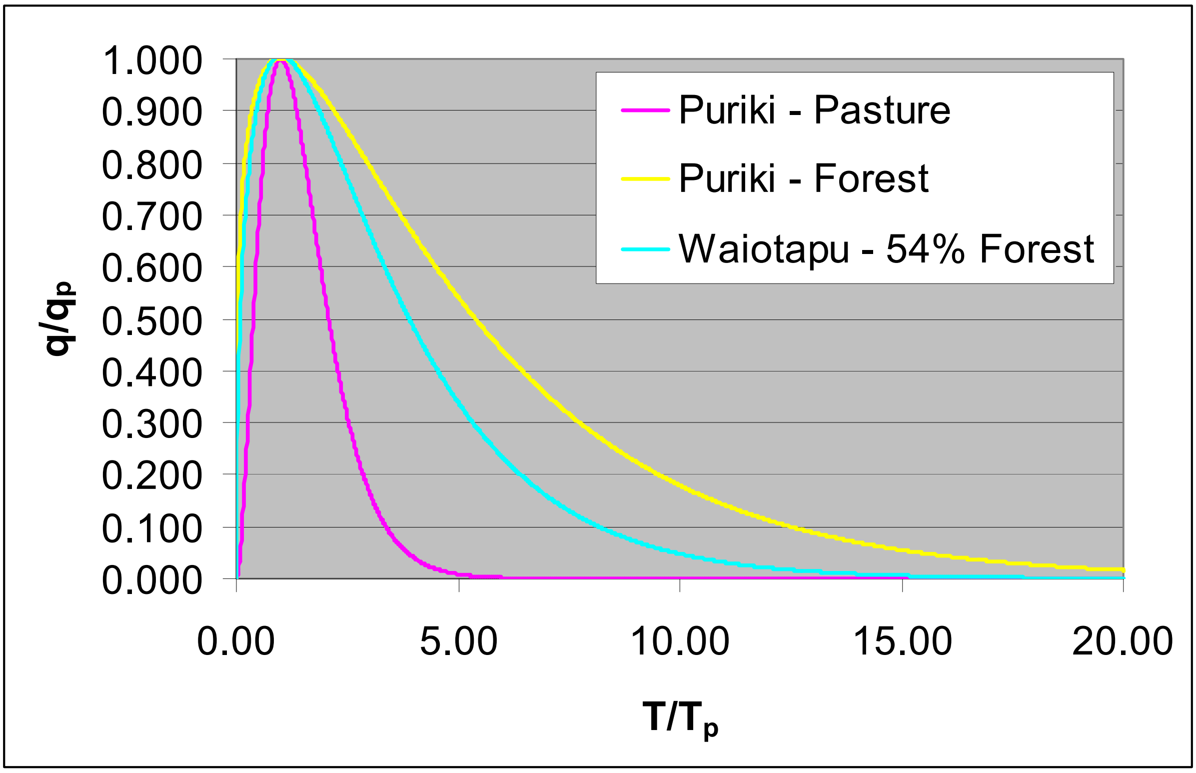

Figure 7 Dimensionless unit hydrographs

The scaling assumption for the IUH's implies that:

$$q_p \,.\, T_p \;=\; K \;\text{(constant)} \qquad (2)$$

where q_p is hrs^{-1} and T_p is in hrs, i.e. K is dimensionless. Alternatively, where the discharge ordinate of the IUH is in (m3/s) per (cm) of effective rainfall, and catchment area A is in km^2, then:

$$\frac{Q_p . T_p}{A} = \frac{K}{0.36} \qquad (3)$$

The process for estimating the IUH for a catchment is normally to estimate the time to peak T_p based on the physical characteristics of the catchment, and then to estimate q_p or Q_p from equations (4) or (5) as follows:

$$q_p = \frac{K}{T_p} \qquad (4)$$

or

$$Q_p = \frac{0.36 K A}{T_p} \qquad (5)$$

The following are the optimal values for K found from the fitting procedure:

Puriki 1968-1973	0% Forest:	K = 0.540
Waiotapu	54% Forest	K = 0.230
Puriki 1975-1998	100% Forest	K = 0.154

The equivalent value of K derived from the recommended conversion constant in the SCS Unit Hydrograph Transform Method is (US Army Corp of Engineers, 2000):

$$K = 2.08 x 0.36 = 0.749$$

Because they have lower K values, the derived IUH's for this study have lower peaks and longer tails than their SCS equivalents.

Clearly there appears to be a correlation between K and the degree of forest cover. This implies that the "surface runoff" characteristics of a catchment are dependent on vegetation cover in addition to the infiltration characteristics. The relationship between K and catchment cover is shown in Figure 8. The best fit for the three points was found to be an exponential curve as shown on the plot.

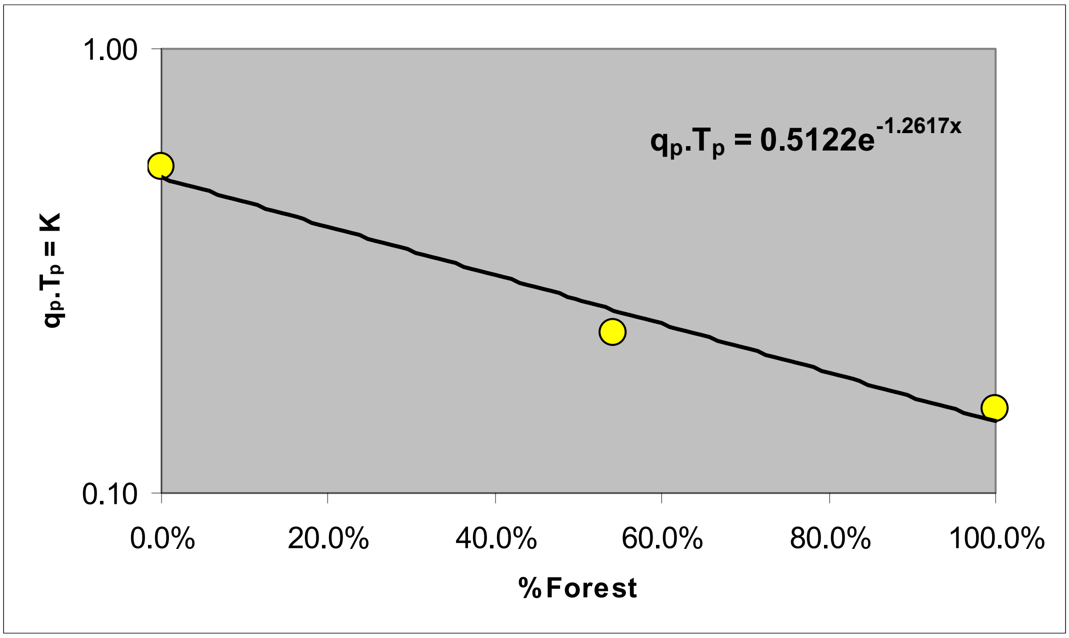

Figure 8 Variation of IUH shape with percentage forest cover

The fitted IUH's for the Puriki Catchment under both forest and pasture have almost identical time to peaks (approximately 0.4 hours). The theoretical time of concentration should be the time at which the IUH returns to zero. The Gamma IUH tends towards zero asymptotically, so a time of concentration is not well defined. The SCS method suggests that the lag time (which is equivalent to the time to peak or an Instantaneous Unit Hydrograph) can be related to the time of concentration, t_c, as:

$$T_p = 0.6 t_c$$

thus

$$t_c = 1.67 T_p$$

From the SCS Dimensionless Unit Hydrograph, this equates to a q/q_p value of 0.5 on the falling limb. Choosing the same point on the three IUH's developed in this study gives the following times of concentration for the three sites

Puriki	– 100% Pasture:	0.83 hrs
Puriki	– 100% Forest:	2.38 hrs
Waiotapu	– 54% Forest:	29.45 hrs

The Puriki pasture IUH has a t_c of around 0.8 hours, whereas the value for the same catchment in forest is 2.4 hours. This indicates significantly greater delay and attenuation of surface runoff for forest as compared to pasture. Additionally, even a t_c value of 0.8 hr for the small Puriki Catchment in pasture is greater than would be expected for surface runoff from a 34.4 ha catchment. It would seem therefore that the response to rainfall that is being measured is not wholly surface runoff, but consists of, at least in part, either an interflow or rapid groundwater response component. This effect is greater for forested catchments but appears to be present to some degree even for pasture. Pumice soils are known to have high infiltration rates (Selby 1972) even under pasture. Therefore it is postulated that these soils, while having a high capacity to absorb rainfall, may also correspondingly have a component of relatively rapid subsurface flow response which quickly transfers a part of infiltrated rainfall to the stream channel.

The time to peak for the Waiotapu Catchment IUH is 7.5 hours, and the time of concentration estimated from its IUH is 29 hours. Again this is significantly greater than would be expected for a 232 km^2 catchment (The Ramser Kirpich formula gives a Tc value of approximately 6.5 hours).

Finally a check has been made to determine whether the exclusion of the five Puruki hydrographs because of their substantially different response characteristics may have biased the results for the forested catchment.

Analysis of the five excluded hydrographs was undertaken to obtain average infiltration and IUH characteristics. These are shown in comparison to the values for hydrographs included in the analysis in Table 9.

Table 9 Comparison of Infiltration and IUH Parameters for Included and Excluded Hydrographs

Parameter	Excluded hydrographs	Included hydrographs
Initial Loss (I_a), mm	3.8	5.00
Potential Maximum Retention (S), mm	656	1818
IUH Peak (q_p), hr^{-1}	0.026	0.349
IUH Time to Peak (T_p), (hrs)	7.3	0.443
IUH Product of Peak and Time to Peak ($q_p.T_p$)	0.188	0.154

When comparing the parameters it can be seen that for the excluded hydrographs, the infiltration capacity is lower, the IUH time to peak is substantially greater, and the IUH peak flow is substantially lower. Flood hydrographs were calculated using these parameters and compared to those calculated from the hydrographs which were included in the analysis. The peak flows generated were approximately 50% lower on average, but the peak volumes were greater. Therefore the peak flows estimated for the forested catchment may be somewhat conservative (high) using the unit hydrographs developed in this study. The total runoff volumes calculated may however be un-conservative, i.e. the estimated changes in runoff volume may be conservative.

4.2.3 Application of results to known catchments

The results from the unit hydrograph analysis are applied to the catchments used in developing the unit hydrographs. The high intensity rainfall data used has been generated from the Purukohukohu No. 4 automatic rain-gauge and is set out in Table 10.

Table 10 High intensity rainfall frequencies - Purukohukohu No. 4 gauge

	Return Period				
Duration	**2yr**	**10yr**	**20yr**	**50yr**	**100yr**
15 min	11.4	16.3	18.2	20.6	22.4
30 min	17.7	24.0	26.4	29.5	31.8
60 min	25.1	34.4	38.0	42.6	46.0
2 hr	33.6	48.4	54.0	61.3	66.8
6 hr	53.5	76.8	85.7	97.3	105.9
12 hr	69.7	97.1	107.6	121.1	131.3
24 hr	86.4	117.1	128.9	144.1	155.5
48 hr	113.1	150.8	165.1	183.8	197.7
72 hr	122.5	162.0	177.1	196.6	211.3

A synthetic design rainstorm has been constructed for each return period by nesting the design rainfalls for different durations within an event of 72 hour overall duration. The alternating block method described by Chow et al (1988) has been used. A typical design hyetograph is shown in Figure 9.

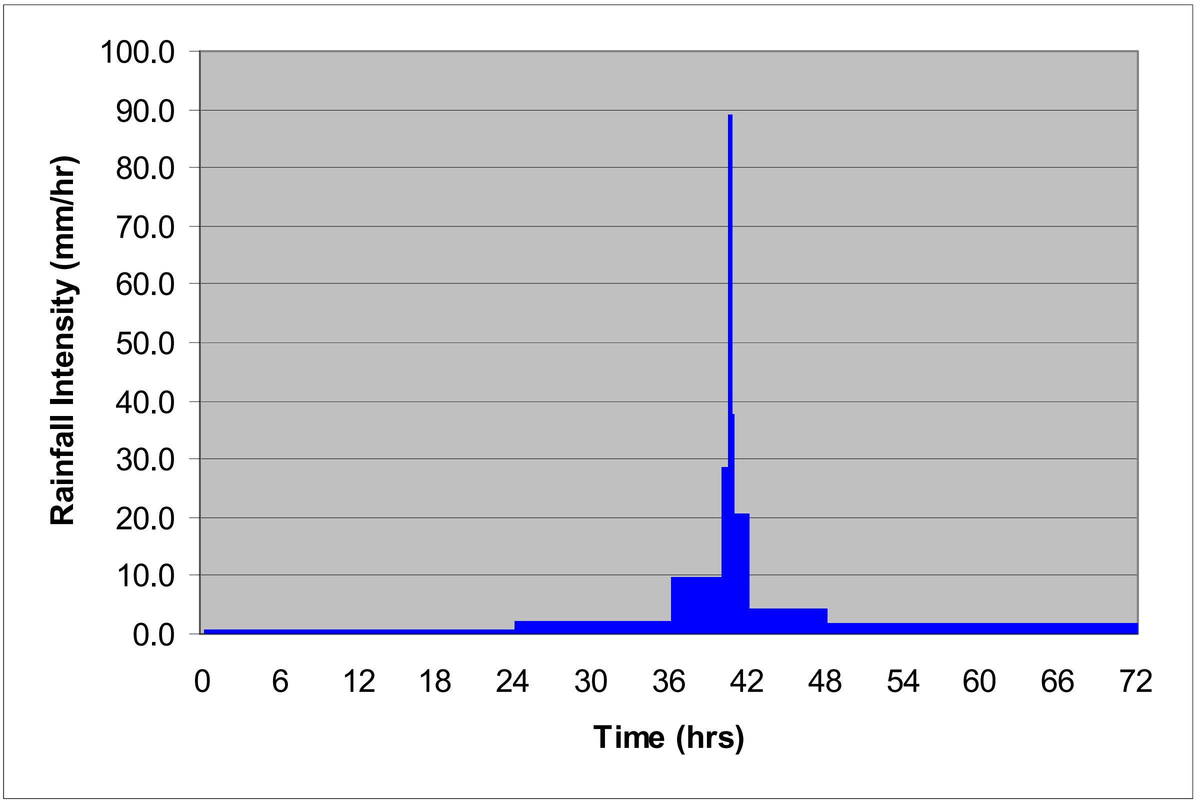

Figure 9 Typical design rainfall hyetograph

For the two Purukohukohu catchments no area reduction factor has been applied to rainfall because of their small size. For the larger Waiotapu Catchment, a duration dependent area reduction factor has been applied to the point rainfalls using the depth area curves presented in Chow et al (1988) to obtain estimates of catchment wide averages.

A summary of the normalised peak discharges compared with those obtained from frequency analysis is shown in Table 11. The comparison is shown graphically in Figure 10

The resulting modelled hydrographs for each of the three catchments are shown in Figure 11, Figure 12 and Figure 13.

Table 11 Comparison of modelled normalised peak discharge with those obtained from frequency analysis

		Normalised peak discharge $(m^3/s)/(km^2)^{0.8}$				
		2 Yr ARI	**10 Yr ARI**	**20 Yr ARI**	**50 Yr ARI**	**100 Yr ARI**
Puriki	Modelled	0.14	0.27	0.33	0.42	0.49
	Frequency analysis	0.13	0.24	0.30	0.40	0.48
Purutaka	Modelled	1.40	2.42	2.85	3.46	3.93
	Frequency analysis	0.42	1.21	1.66	2.40	3.12
Waiotapu	Modelled	0.23	0.41	0.49	0.60	0.69
	Frequency analysis	0.22	0.42	0.51	0.64	0.76

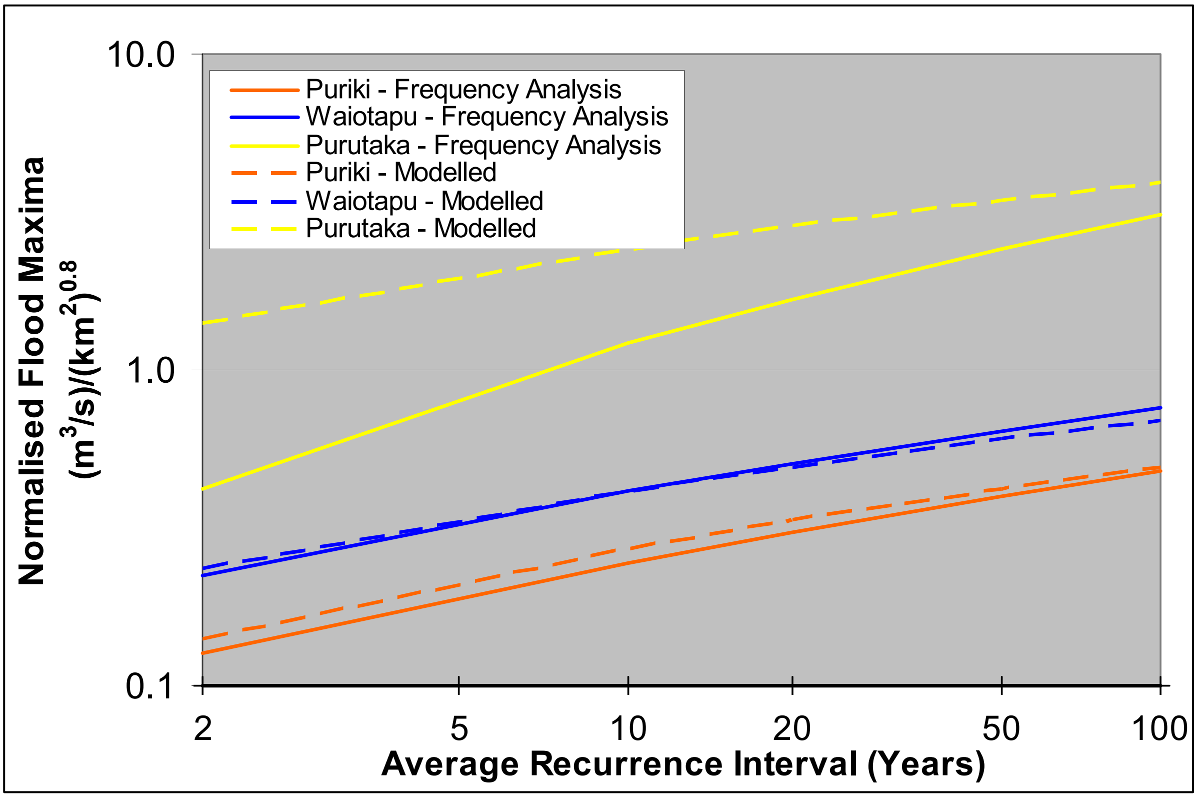

Figure 10 Comparison of modelled normalised peak flood discharges with those obtained from frequency analysis

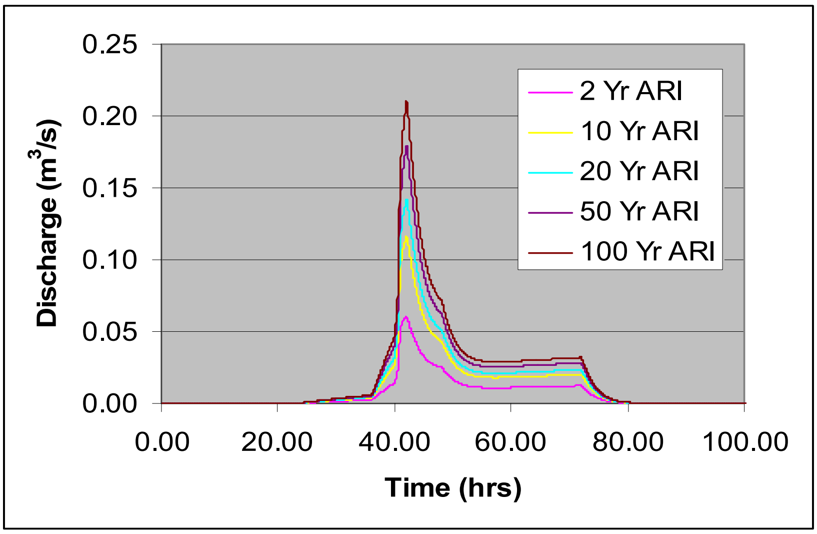

Figure 11 Modelled discharge hydrographs for the Purukohukohu at Puriki

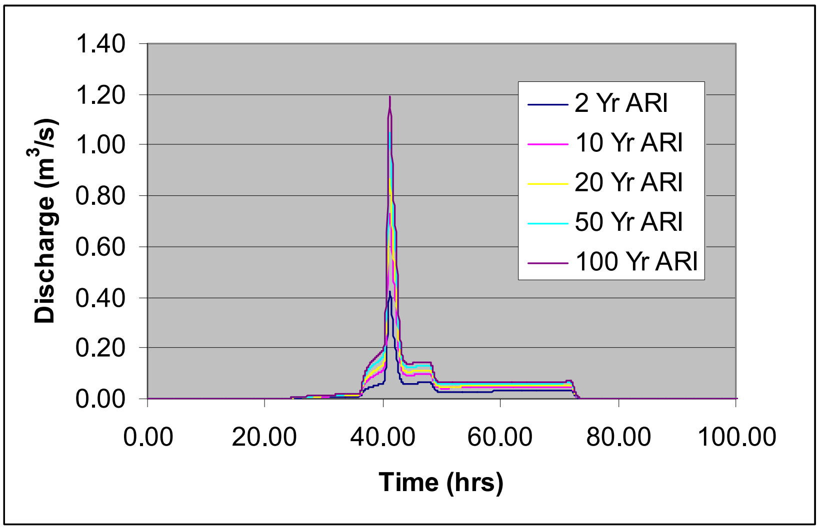

Figure 12 Modelled discharge hydrographs for the Purukohukohu at Purutaka

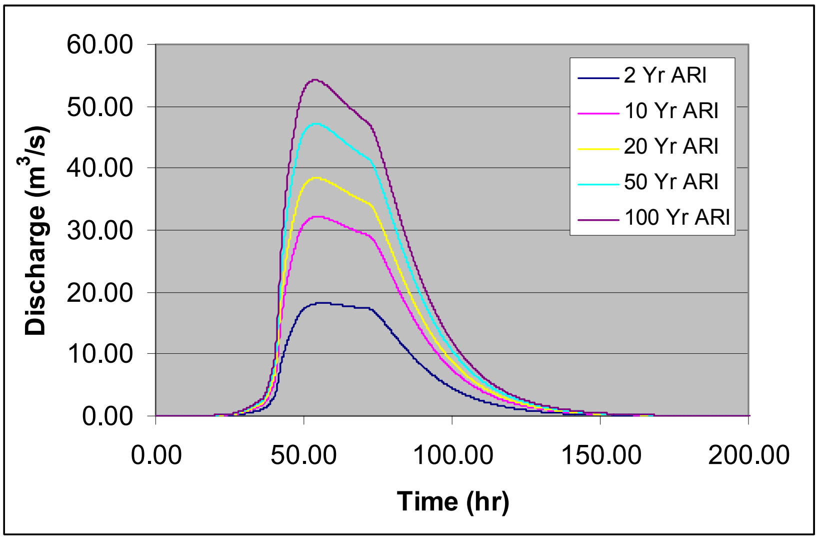

Figure 13 Modelled discharge hydrographs for the Waiotapu at Reporoa

In general, discharges resulting from rainfalls of a particular return period do not necessarily equate to the equivalent return period flood discharge from a frequency analysis. However comparing the discharges modelled from rainfall to the discharges obtained from frequency analysis is useful to indicate how well the model compares. The peak discharges estimated for the Puriki catchment (100% Forest) and the Waiotapu catchment (54.3% forest) agree quite closely with those from the frequency analysis. The modelled results for the Purutaka catchment (100% Pasture) however, are significantly higher than the frequency analysis values, particularly at low return periods. For a 2 year event there is a factor of three difference, between the predictions, whereas the results for a 100 year event are about 25% higher. The Purutaka frequency analysis curve shows some unusual characteristics in that the slope of the curve is much steeper than for the other curves (both modelled and frequency analysis). A measure of the slope of the frequency curve is the ratio of the 100 year flow to the mean annual flow, and McKerchar and Pearason (1989) have published contour maps of this parameter (q_{100}) for both the North and South Island. The frequency analysis value of q_{100} for Purutaka is 6.8, which is significantly higher any values of q_{100} reported in McKerchar and Pearson (1989) for the North Island. The modelled q_{100} value is approximately 2.6, which is close to the published values for the Central North Island. This tends to suggest that the modelled results may be more reliable at lower return periods.

4.2.4 Application of results to Wairakei pastoral catchments

The results from the unit hydrograph analysis are applied to the four catchments primarily affected by the conversion of the Wairakei Pastoral block (Table 1). The key assumption is that the characteristics of the Instantaneous Unit Hydrographs developed in 4.2.2 can be applied to catchments of different size by scaling according to q_p and T_p. For the four catchments investigated, the time to peak of the IUH, (T_p), is an unknown and has to be estimated.

The high intensity rainfall data used has again been that from the HIRDS high intensity rainfall software for Broadlands as set out in Table 12. For the purposes of analysis, a 24 hour nested storm containing all of the intensities for each duration has been constructed for each return period. Areal reduction factors have also been applied to rainfalls for each catchment.

Table 12 Hirds high intensity rainfall data for Broadlands

	Return Period				
Duration	**2yr**	**10yr**	**20yr**	**50yr**	**100yr**
10min	8.9	12.8	14.9	18.4	21.7
20min	12.5	17.8	20.7	25.4	30.0
30min	15.3	21.7	25.1	30.8	36.3
60min	21.5	30.3	35.0	42.7	50.1
2hr	28.3	39.8	46.0	56.1	65.7
6hr	43.9	61.5	70.9	86.4	101.1
12hr	57.9	80.9	93.3	113.4	132.7
24hr	76.3	106.5	122.6	149.0	174.1
48 hr	93.0	128.9	148.0	179.2	208.7
72 hr	104.4	144.2	165.3	199.6	232.1

The next step in the process is to estimate the time to peak (T_p) for each of the four catchments. Normal practice is to estimate T_p from the physical characteristics of the catchment, either directly, or via the time of concentration (T_c). It was shown previously however, that the times of concentration for the calibration catchments are significantly higher than those predicted by the Ramser Kirpich equation. Times of concentration also vary with the degree of forest cover. The “theoretical” times of concentration for the four study catchments as estimated by the Ramser Kirpich formula are shown in Table 13. The similarly estimated “theoretical” time of concentration for the Waiotapu Catchment at Reporoa is 6.4 hours, and the ratio T_p/T_c = 1.18. Therefore an estimate of Tp can be obtained from:

$$T_p = 1.18T_c \qquad (6)$$

T_p values estimated by using this ratio are also shown in Table 13. The other approach used is to assume there is a power relationship between catchment area and T_p, and interpolate T_p from the values found for the Puriki and Waiotapu analyses. The equation obtained is:

$$T_p = 0.693A^{0.439} \qquad (7)$$

Estimates of Tp obtained from this relationship are also shown in Table 13.

Table 13 Assessment of IUH time to peak (T_p) for study catchments

	Catchment			
	Orakonui Stream	**Waiwhakarewaumu Stream**	**Kereua Stream**	**Pueto Stream**
Area (km^2)	75.18	38.06	35.56	200.29
T_c (hrs)	3.19	3.25	1.91	5.51
T_p (hrs) Eqn 6	3.77	3.84	2.26	6.51
T_p (hrs) Eqn 7	4.61	3.42	3.32	7.08

The two methods generally agree to within an hour. The values obtained by scaling based on catchment area have been used for analysis purposes. Design rainfall hyetographs for a 72 hour storm have been constructed as per Section 4.2.3. Area reduction factors have again been applied using the depth area curves presented in Chow et al (1988). The loss parameters of the SCS method have been estimated for both current and proposed land use based on percentage forest cover. Similarly the Gamma IUH’s have been calculated based on T_p values from Table 13 and the percentage forest cover. The modelled before and after peak discharges are given in Table 14. The relative changes in peak discharge due to the proposed land use changes in the four catchments are given Table 15. Plots of the 2 year and 100 year discharge hydrographs are shown in Figure 14 and Figure 15.

Table 14 Estimated flood peak discharges based on the unit hydrograph method

Average recurrence interval (yrs)	Peak discharge (m3/s)										
	Orakonui Stream		Waiwhakare waunu Stream		Kereua Stream		Pueto Stream		Combined catchment		
	7518.8 ha		3806.8 ha		3556.0 ha		20029.2 ha		34910.8 ha		
	Current	Proposed	Current	Proposed	Current	Proposed	Current	Proposed	Current	Proposed	Change
	48.6% forest	5.2% forest	99.9% forest	0.1% forest	79.9% forest	41.0% forest	87.4% forest	20.3% forest	79.7% forest	22.7% forest	
2	10.7	25.3	1.7	14.3	3.3	8.1	9.0	29.5	23.5	72.5	49.0
10	19.3	45.8	2.7	25.8	5.8	14.9	14.3	52.7	39.9	130.4	90.5
20	24.8	58.5	3.3	32.9	7.5	19.2	17.8	67.4	50.6	166.9	116.2
50	35.2	81.7	4.6	45.8	10.7	27.4	24.3	94.5	70.7	233.5	162.8
100	46.4	106.0	5.9	59.2	14.1	36.2	31.5	123.5	92.6	304.2	211.6

Note that the peak flows for the combined catchments in Table 14 do not in general sum from the peaks of the individual contributing catchments because the time to peaks of the contributing hydrographs are not coincident.

Table 15 Relative change in flood peak flood discharge as modelled by the Unit Hydrograph Method

Average recurrence interval (years)	Orakonui Stream	Waiwhakare waunu Stream	Kereua Stream	Pueto Stream	Combined catchment
	7518.8 ha	3806.8 ha	3556.0 ha	20029.2 ha	34910.8 ha
	Reduction in forest as percentage of catchment area				
	43%	100%	39%	57%	57%
	Percentage increase in peak discharge				
2	137%	749%	145%	228%	208%
	137%	863%	155%	269%	227%
10	136%	888%	156%	280%	230%
50	132%	902%	157%	289%	230%
100	129%	897%	156%	292%	228%

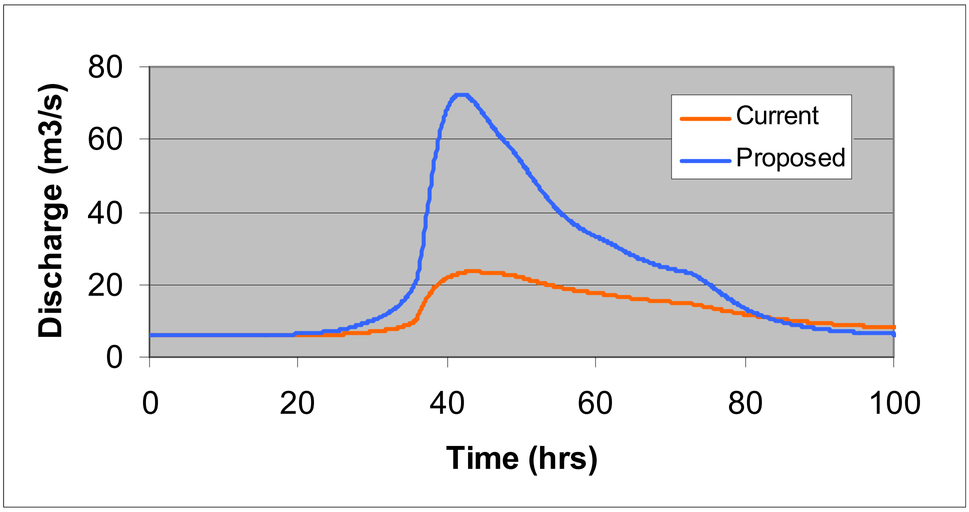

Figure 14 Wairakei pastoral block – modelled 2 Year flood hydrographs

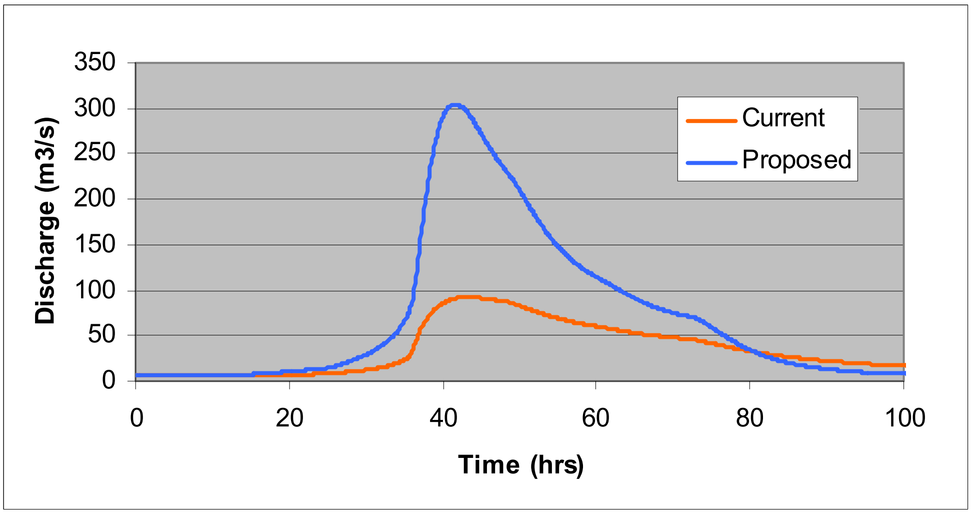

Figure 15 Wairakei pastoral block – modelled 100 year flood hydrographs

The percentage increase in peak flows in general have an increasing trend with Average Recurrence Interval. This is similar to the results obtained using the Regional Frequency Analysis where percentage changes generally increase with ARI The prevailing wisdom is that increases in discharge due to intensification of land use should decrease with storm return period/ magnitude, until at some point when the soil becomes fully saturated, vegetation differences have no effect. It appears from this study however that pumice soils remain highly absorbent even in the largest storms considered. For very large storms beyond the magnitude of those used in this study the opposite may well apply however. For pasture catchments, short duration storms produce the highest flood peaks, whereas for forested catchments these events produce very little runoff at all. The average increase in peak discharge for the combined catchments ranges from 208% in a two year event up to 228% for a 100 year event, whereas the Regional Frequency Analysis approach values ranged from 93% to 231% for the same respective events.. Therefore the unit hydrograph approach produces higher percentage increases in flood peaks at low return periods, but similar increases at high return periods.

The Waiwhakarewaumu Stream catchment, where there is to be 100% conversion from forest to pasture, has increases in peak discharge ranging from 749% - 897% - i.e. approaching an order of magnitude change. The Regional Frequency Analysis estimate for the this catchment ranges from 229% (2 Yr) to 548% (100Yr).

The reason for the very high percentage increases in runoff is because of the relatively low rates of runoff from forested catchments. For example, for the Waiwhakarewaumu Stream catchment in forest, the normalised peak discharge for a 2.33 year event (Approximately the normalised mean annual flood) is 0.098 $(m^3/s)/(km^2)^{0.8}$ by the unit hydrograph method. The equivalent figure for the same catchment in pasture is 0.85 $(m^3/s)/(km^2)^{0.8}$. McKerchar and Pearson (1989) give contour maps of mean annual discharge normalised against catchment area for New Zealand.: Their figures for the Waikato River catchment between Taupo and Karapiro range from 0.3 to 0.5, probably reflecting the fact that many of the catchments used in the study have significant amounts of forest cover. Elsewhere in the Waikato Region (Excluding the Coromandel) values range from approximately 1 to 2. Therefore, even in pasture, the runoff from pumice catchments is at the lower end of the typical range for "normal" soils in the rest of the region.

McKerchar and Pearson (1989) also provide contour maps of q_{100}, the ratio of the 100 year discharge to the mean annual flood discharge. This gives a measure of how flood magnitude varies with return period. For the Waiwhakarewaumu Stream catchment the modelled q_{100} ratios from this study are 3.3 in forest and 3.8 in pasture. These figures are 40%-50% higher than those given by McKerchar and Pearson (1989), with reported values generally ranging from 2.2 to 2.7 throughout the Waikato Region.

4.2.5 Changes in runoff volume

The runoff volumes for each catchment in a 72 hour storm as modelled using the unit hydrograph method are shown in Table 16.

For the combined catchments total runoff volume in a 2 year event increases by 3.7 x 10^6 m^3. For a 100 year event the increase is 14.3x 10^6 m^3. The percentage increases in volume are shown in Table 17. The relative increase in volume of runoff for the combined catchment ranges from 151% in a 2 year event to 122% for a 100 year event. For the Waiwhakarewaunu Stream catchment where there is effectively 100% conversion from forest to pasture, the relative increase ranges from 350% to 270% for the 2 year and 100 year events respectively. The relative increase in volume decreases with return period.

Table 16 Runoff volume for a 72 hour storm based on the SCS method

Average recurrence interval (years)	Total runoff volume (m^3 x 10^6)										
	Orakonui Stream		Waiwhakarewaunu Stream		Kereua Stream		Pueto Stream		Combined catchment		
	7518.8 ha		3806.8 ha		3556.0 ha		20029.2 ha		34910.8 ha		
	Current	Proposed	Current	Proposed	Current	Proposed	Current	Proposed	Current	Proposed	Change
	48.6% forest	5.2% forest	99.9% forest	0.1% forest	79.9% forest	41.0% forest	87.4% forest	20.3% forest	79.7% forest	22.7% forest	
2	0.8	1.5	0.2	0.8	0.2	0.4	1.2	3.3	2.5	6.2	3.7
10	1.6	2.8	0.4	1.5	0.5	0.8	2.3	6.1	4.7	11.3	6.6
20	2.0	3.6	0.5	1.9	0.6	1.1	3.0	7.9	6.1	14.4	8.3
50	2.9	4.9	0.7	2.6	0.9	1.5	4.3	11.0	8.8	20.1	11.3
100	3.8	6.3	0.9	3.4	1.2	2.0	5.8	14.3	11.7	26.0	14.3

Table 17 Relative change in total runoff volumes for a 72 hour storm based on the SCS infiltration method

Average recurrence interval (years)	Orakonui Stream 7518.8 ha	Waiwhakarewaunu Stream 3806.8 ha	Kereua Stream 3556.0 ha	Pueto Stream 20029.2 ha	Combined catchment 34910.8 ha
	Reduction in forest as percentage of catchment area				
	43%	100%	39%	57%	57%
	Percentage increase in runoff volume				
2	87%	350%	83%	178%	151%
10	80%	320%	79%	167%	141%
20	77%	307%	77%	161%	136%
50	72%	287%	74%	153%	129%
100	68%	270%	71%	146%	122%

5 Results for the Full WPL Block Area

The analyses undertaken in Section 4 have been based on the four catchments within which the bulk of the Wairakei Pastoral Limited proposed conversion is to occur. The area of conversion is 19,893 ha out of a total area to be converted of 22,500. Adjusted figures for peak flows and peak runoff volumes for the full 22,500 ha conversion area are shown in Table 18

Table 18 Estimated Increase in Flood Peak Discharges and Volumes for the full 22,500 ha Wairakei Pastoral Limited proposed conversion

Average Recurrence Interval	Increase in Flood Peak Discharge (m^3/s)			Change in Flood Runoff Volume (m^3)	
	Regional Frequency Analysis Method (m^3/s)	Unit Hydrograph Method (m^3/s)	Average increase per km^2 of Forest Converted	SCS Method $m^3 \times 10^6$	Average increase per km^2 of Forest Converted
2	23.9	55.4	0.18	4.2	0.019
10	77.7	102.4	0.40	7.5	0.033
20	109.8	131.4	0.54	9.4	0.042
50	165.9	184.1	0.78	12.8	0.057
100	222.5	239.3	1.03	16.2	0.072

6 Discussion

This paper presents a review of the current knowledge regarding the effect of land use changes on the flood hydrology of pumice catchments. Data from the Purukohukohu experimental basin, and from both the Waiotapu Stream at Reporoa and the Mangakara Stream at Hirsts are then used to estimate the effects of land use changes in the Wairakei Block. The study identifies that the potential effects associated with the proposed land use changes in the upper Waikato River catchment are significant.

The increases in runoff rates due to conversion from forest to pasture on pumice soils reported in the literature vary widely between different studies.

- Selby (1972): 700%-1,000% magnification of storm runoff from pasture as compared to scrub.

- Rowe (2003): From 100% increase up to 1,000% increase in peaks between 100% pasture and 100% forested catchments.

- WVA (1978) 125% increase in peak flows for 50% reduction in forest cover.

- Hamilton (2001): Varies depending on rainfall depth and model used, but between 12% and 200% increase in flood peak flows for pasture over forest.

- This Study Approximate 550% to 900% increase in peak flow for 100% conversion of forest pasture. The equivalent increase in runoff volume is approximately between 270% and 350%.

Potential increases in flood peaks of up to 230% are indicated for the Wairakei Pastoral area resulting from removal of forest cover from 57% of the combined catchments. In absolute terms increases in peak flows of 110-131 m^3/s are estimated for a 20 year ARI event, and a 222-239 m^3/s increase for a 100 year ARI event. The increase in volume of runoff is estimated to be 16.2×10^6 m^3 for a 100 year event, representing a 122% increase within the four main catchments.

Note that the above data applies only to the Wairakei Pastoral block. The Carter Holt Harvey Block where significant conversion from forestry to pasture is also expected, is further north and the soils are less homogeneous. The effect on peak flows is also likely to be less easy to determine because the development is expected to include a number of non-contiguous areas within a wider catchment. Because the soils are less pumiceous, it is also unlikely that the effects of land use change on flood peaks will be as great.

Because of the planting and harvesting cycle, typically up to 25% of a production forest may not have a closed canopy at any one time (i.e., over a typical harvesting cycle of 28 years, canopy closure does not occur until about the seventh year. Duncan, pers. com). It may be argued that there will be larger flood peaks and volumes from a staged forest development than from 100% closed canopy forest. This is because immediately after harvest the land is bare and as weeds and the new forest grows there is a smaller amount of foliage available to intercept water, and the shallower rooting depth of immature forest (shallower rooting depth for extraction of water from the soil results in on average wetter antecedent soil moisture conditions): This aspect has not been specifically accounted for in this study. It may be possible to model the runoff changes by adjusting the model parameters to reflect this, however it is the writers opinion with the currently available data, that any such adjustment would be arbitrary. There is very little quantitative information as to how the runoff characteristics of forest catchments with pumice soils change with the stages of forest development, but there is likely to be some effect.

- The differences between response of forest with a fully closed canopy compared to one that is between cutting, replanting and full canopy closure will largely be due to differences in canopy interception and the greater rooting depth to source water of mature forest. Interception losses from a wet forest canopy are typically around 0.4 mm per hour (Jackson, 1999). The average infiltration rate calculated for the storms used in this study on the Puruki (forested) Catchment were 21.9 mm/hr., Therefore canopy losses only account for approximately 2% of the total losses. The effect of mature forest on antecedent soil moisture conditions, by virtue of the fact that antecedent soil moisture conditions are likely to be drier, is more difficult to estimate but could be substantial (Duncan 1995) given the large rooting depth of pines in pumice.

- The analysis of runoff from forest is based on the Puruki flow record over the better part of one full lifecycle of development, i.e. from 2 years after planting in 1973, to first thinning in 1979 and 1981, and then harvest and replanting in 1997. The results therefore represent a substantial part of one full lifecycle and the temporal changes within it, including times of partial canopy closure. The first two years of flow data following planting was not however included in the analysis.

- As Selby (1972) has pointed out, a significant part of the response of pasture catchments is due to compaction and grazing. There will be some compaction due to logging.

- Cut over areas are left in an undeveloped state and normally allowed to grow scrub and rank long grass prior and subsequent to replanting. This growth continues but reduces as canopy closure progressively occurs after planting.

- Selby (1972) reported that runoff from pasture was between 5 to 7 times greater than that from scrub and long grass. In intense storms he reported differences of up to 10 times. This is not dissimilar to the differences in runoff observed between pasture and forest, i.e. it seems that scrub and long grass behave in a similar fashion to forest. Therefore, even relatively soon after harvesting, when scrub and long grass has re-established, it is expected that the runoff response from harvested areas would be significantly less than for pasture.

Vegetated areas of production forest that are not in a state of full canopy closure are likely to produce little more runoff than mature forest. Rain falling on bare, recently harvested areas is likely to produce much larger floods than when it falls on pasture or forest. Even though the time when the ground is bare or partly vegetated is short relative to the life cycle of a forest it can have a significant effect on the mean size of floods from large forested catchments. Duncan (1996) has calculated that mean flows from a staged forest development may be 20% more then from full canopy forest. It is not unreasonable to expect differences of the same order in flood flows between staged forest development and 100% closed canopy forest.

The difficulty for this study is the lack of information on interception capacities, infiltration rates and rooting depths for the various stages of forest development on which to base the calculations of flood size for each stage. For this study data has been taken from vegetated stages of forest development to derive flood sizes for forested catchments. The resultant floods are probably lower than for a staged forest development, thus the relative increases in floods due to conversion are possibly overestimated, and thus giving a conservative result to the study.

7 Impacts of potential changes

The above discussion shows that increases in runoff from the four primary Wairakei Pastoral Block catchments due to change from forest to pasture is expected to be significant within the context of these catchments. The increase in peak flood flows may cause changes in stream geomorphology. The increased water levels and velocities may impact on bank erosion, sediment transport and channel stability.

There are also potential downstream effects which could result from these changes. The additional peak flows and volumes could impact on the ability of the hydro dams to manage floods and there may also be impacts further down the catchment below the hydro dams in terms of increased peak flood discharges. The area where this could be of concern is in the Lower Waikato where large areas are protected by the stopbanks and structures of the Lower Waikato Waipa Control Scheme (LWWCS). Any increased flood discharges would degrade the design standards for these scheme works.

The Waikato River Flood Rules Review (Freestone, Ong and Purves, 1990) sets out the basis for managing floods through the Waikato Hydro System. The design 500 year, 48 hour storm inflow volume to the Ohakuri Reach (Lake Taupo to Ohakuri Dam) is given as 69.99 x 10^6 m^3. The equivalent increase in flow volume from the Wairakei Pastoral Block as a result of the proposed land use changes is estimated as 17.5x 10^6 m^3 for a 500 year 48 hour storm. This represents an increase of 25% in the design flood inflow volume for Lake Ohakuri, which is significant. Four methods were used by Freestone et. al. (1990) to obtain design reach inflow hydrographs. These four methods gave peak 500 year inflows to Lake Ohakuri ranging from 406 m^3/s to 615 m^3/s. The peak flows obtained from this study by the unit hydrograph method have been extrapolated to a 500 year return period and thus an estimate of the increase in peak flow from the Wairakei Block obtained. This increase in the peak flow is estimated to be 366 m^3/s, which represents a 60%-90% increase in the design peak flow depending on which method is used. Based on the above analysis, there are potentially some significant downstream effects in respect of managing the hydro system during floods.

The additional flows may also result in significant increases in flood flows in the Middle and Lower Waikato Rivers. Undoubtedly there will be some attenuation of peak flows through the hydro dams, however this is difficult to quantify and is dependent on lake levels prior to a storm, and operating strategy for the dams. Additionally the Waipa River has a significant effect on the floods in the Lower Waikato, and peak flows are dependent on the relative timing of the peaks of the Waipa and Waikato rivers. Therefore an increase in peak flood flows into Lake Ohakuri may be somewhat reduced by the time it reaches the Lower Waikato. An investigation of the impact of the changed flood peaks on flows in the Lower Waikato would require a comprehensive investigation which is beyond the scope of this study.

Even allowing for a significant reduction in peak flow due to attenuation however, the expected increase in peak flows may have implications for the protection standards of the Lower Waikato flood protection works. The flood protection works along the Lower Waikato River generally have either a 20 year ARI standard of protection with 0.6 metres freeboard or 100 Year ARI standard of protection with 0.3 metres freeboard. The equivalent 20 year and 100 year increases in peak flow to Lake Ohakuri assessed in this study are 131 m^3/s and 239 m^3/s respectively. As a rough approximation, it is assumed that these increases would be attenuated by 50% before reaching the Lower Waikato, giving increases in peak flow of 66 m^3/s and 120 m^3/s. For the 20 year flood, the peak flow increase represents an increase in water level at Rangiriri of approximately 0.12 metres (loss of 20% of freeboard). For the 100 year event the increase in peak flow represents an increase in water level of approximately 0.13 metres (43% loss of freeboard). While the estimate is very approximate only, it does indicate that there are potentially significant effects on the Lower Waikato flood protection works.

The effects analysed in this study have been based on the total effect of a change which is expected to occur over a number of years (The Wairakei Pastoral Block conversion is scheduled to occur over a 15 year period). The expected impacts will therefore not be immediate.

8 Means of addressing potential changes

Selby (1972) identifies that the flooding and erosion effects of conversion from forest to pasture on pumice soils can be minimised by adopting good land use practices aimed at minimising the compaction of the soil, and retaining gullies and watercourses in scrub or un-grazed grass. Fencing from grazing of waterways, bridging of stock races over waterways, and growing of shade trees on the waterways can all help to reduce the effects of forestry to pasture conversion on water quantity and quality. Such practices can limit the effects of forest to pasture conversion, but will not be able to fully offset them.

The effects of increased peak flows on channel stability and bank erosion would be expected to result in demand for increased river maintenance work in the Upper and Lower Waikato River and also within the tributary catchments where land use changes take place. The effect of increased peak flood levels in the Lower Waikato may also need to be dealt with by raising stopbanks. The cost of these works would normally fall on Environment Waikato in its River and Catchment Management role, and would require additional funding through Project Watershed. Rating for services under Project Watershed may need some adjustment to deal with the proposed land use changes in the areas of concern.

The effects on flood management for the Waikato Hydro System are potentially significant, though would require further investigation. Mighty River Power, as owner and operator of the system, are the appropriate agency to determine the implications of the potential changes, and whether offset works are necessary. The cost of any such work (if necessary) would not be funded through Project Watershed.

As the development is programmed to occur over an extended time period, the effects on channel geomorphology, bank erosion etc should be monitored in some of the first areas to be developed to determine their significance.

9 Summary and conclusions

The quantitative assessment in this study focuses on the effects of conversion of the 22,500 ha Wairakei Pastoral Block to pasture. The study has focussed on effects within the four main catchments where the conversion is proposed, comprising approximately 19,900 ha of the total 22,500 ha to be converted. The block to be converted is well defined in terms of its areal extent and the pumice soils are similar to the soils in the Purukohukohu Experimental Basin, the Waiotapu Stream at Reporoa catchment, and the Mangakara Stream at Hirsts catchment which have been used as the basis for assessing the flood hydrology.

Increases in peak flood flows of up to 230% are conservatively estimated collectively from the four main catchments affected. Potentially, peak flows in to the Waikato River are increased by between 222-239 m^3/s in a 100 year event.

It has been identified that the effects of the proposed conversion are potentially significant. Geomorphological changes, increased bank erosion, scour and deposition may occur in the streams within the four catchments themselves. There are also potential implications for flood management of the Waikato Hydro system, as the additional peak flows and volumes are significant in terms of design values for Lake Ohakuri. Additional flows in the Lower Waikato under flood conditions are difficult to quantify, but are potentially significant. This may have implications for the Lower Waikato Flood protection works.

No allowance has been made for the effects of a staged forest development when estimating floods from forests due to lack of suitable data. Thus estimated flood sizes from forests may be understated producing a conservative result for the study.

No quantitative assessment has been made of the effects of conversion of several thousand hectares within the Carter Holt Harvey Block or other privately owned land where similar forest to pasture conversion will occur. This conversion area is not currently well defined and is likely to consist of non contiguous blocks. The soils are also less pumiceous in these areas than those of the Wairakei Block. The impacts however, may potentially be of a similar order of magnitude to those assessed for the Wairakei pastoral Block.

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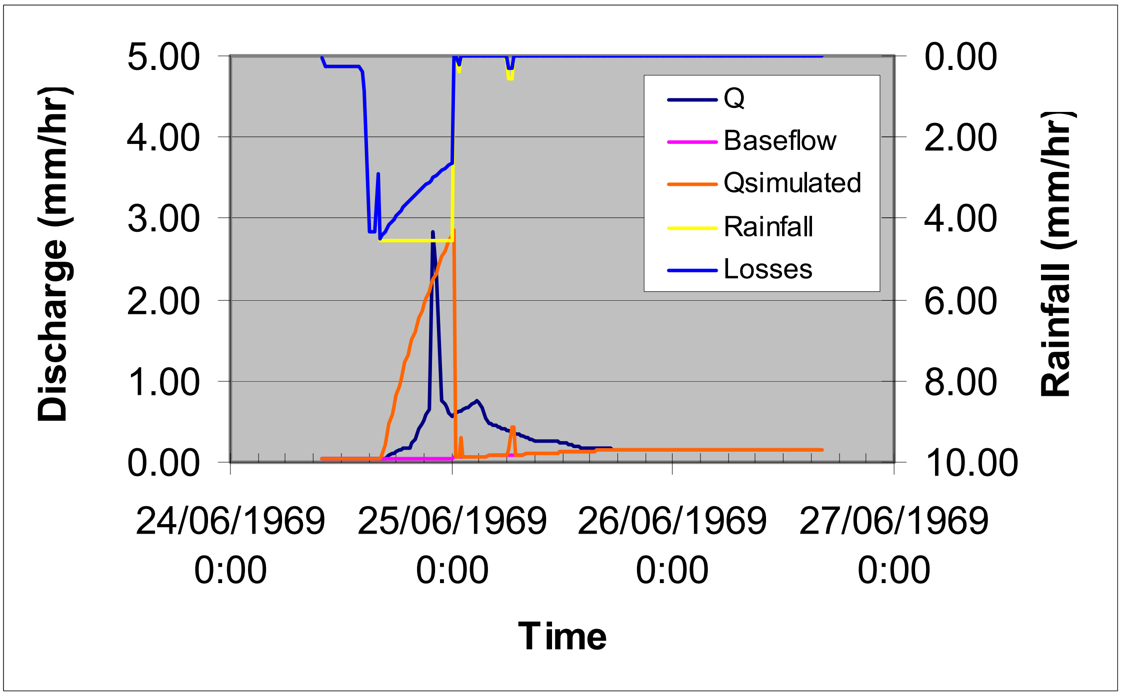
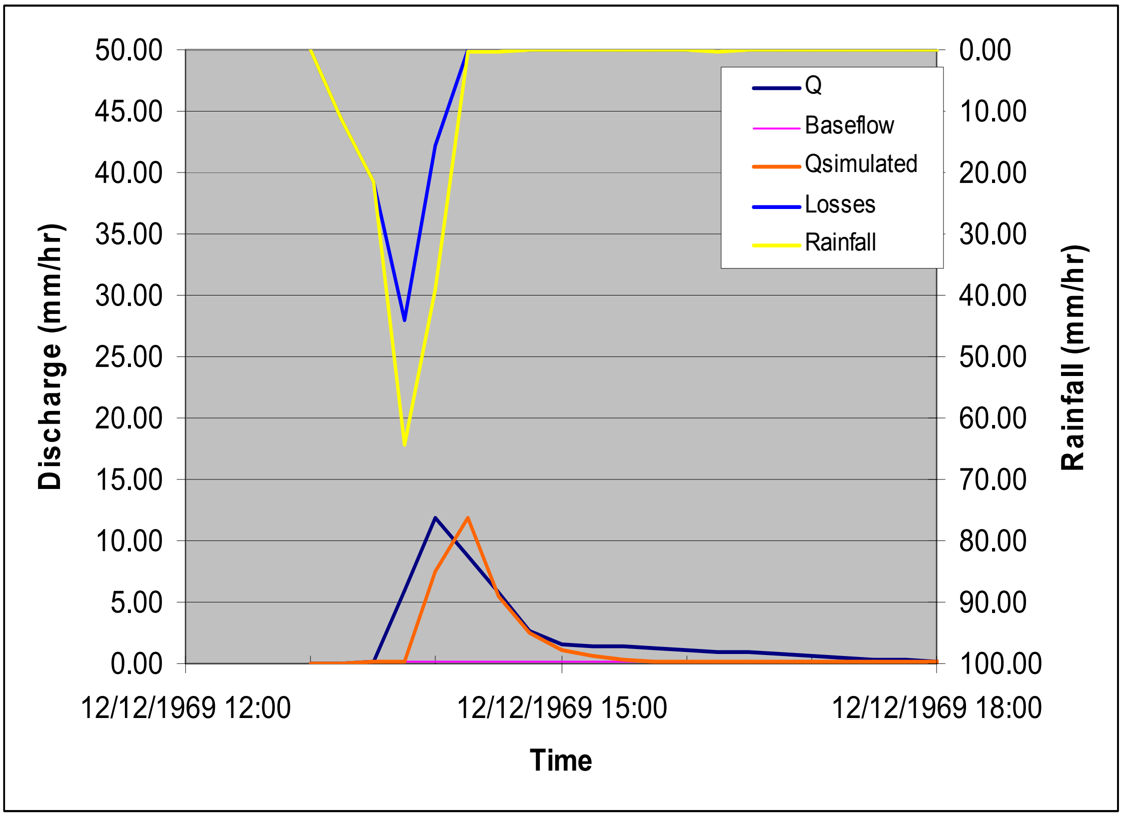
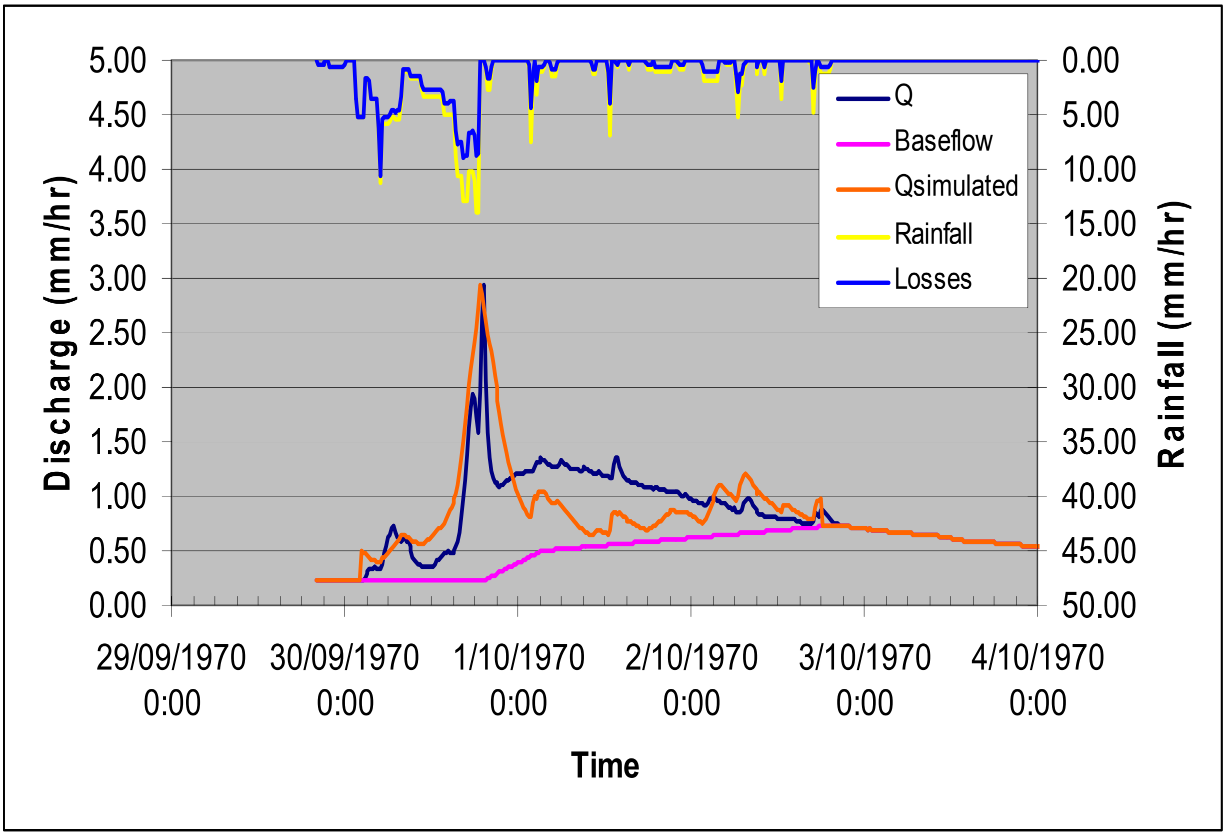
Appendix A Analysed Flood Hydrographs

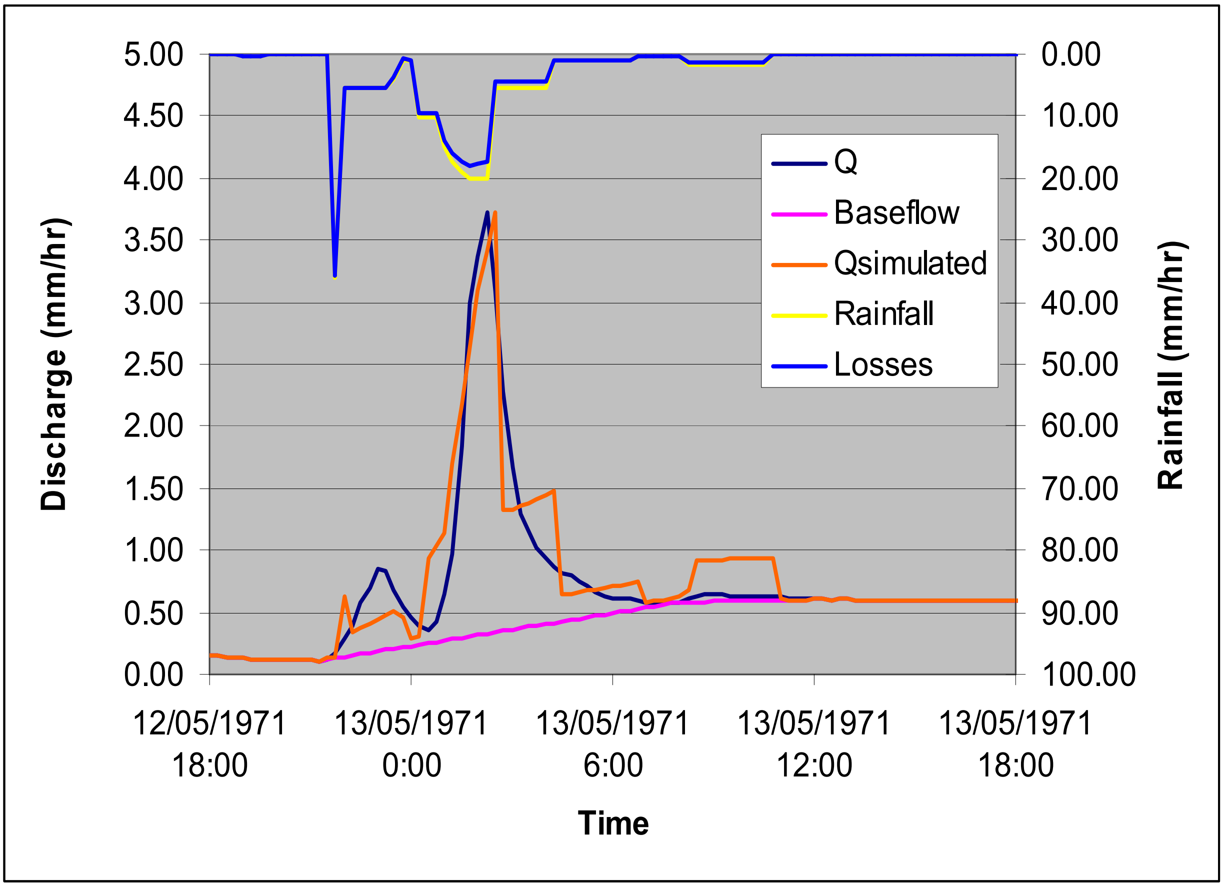
A.1 Purukohukohu at Puriki in Pasture



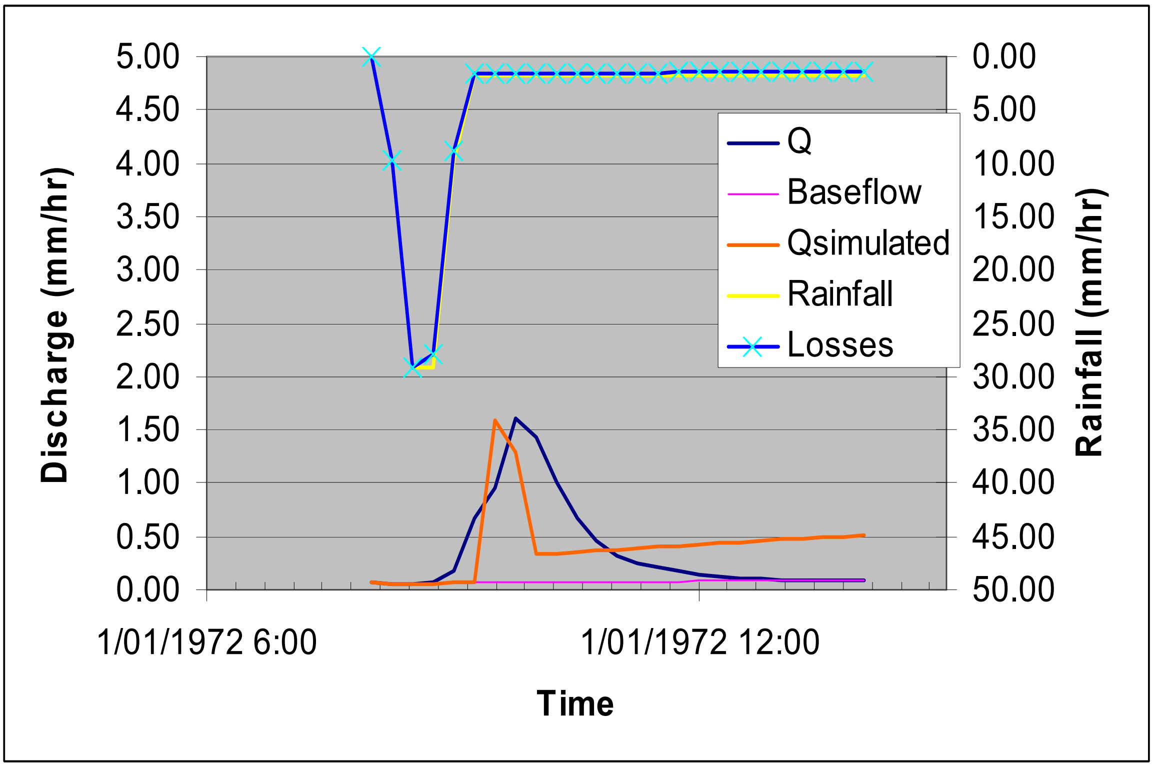


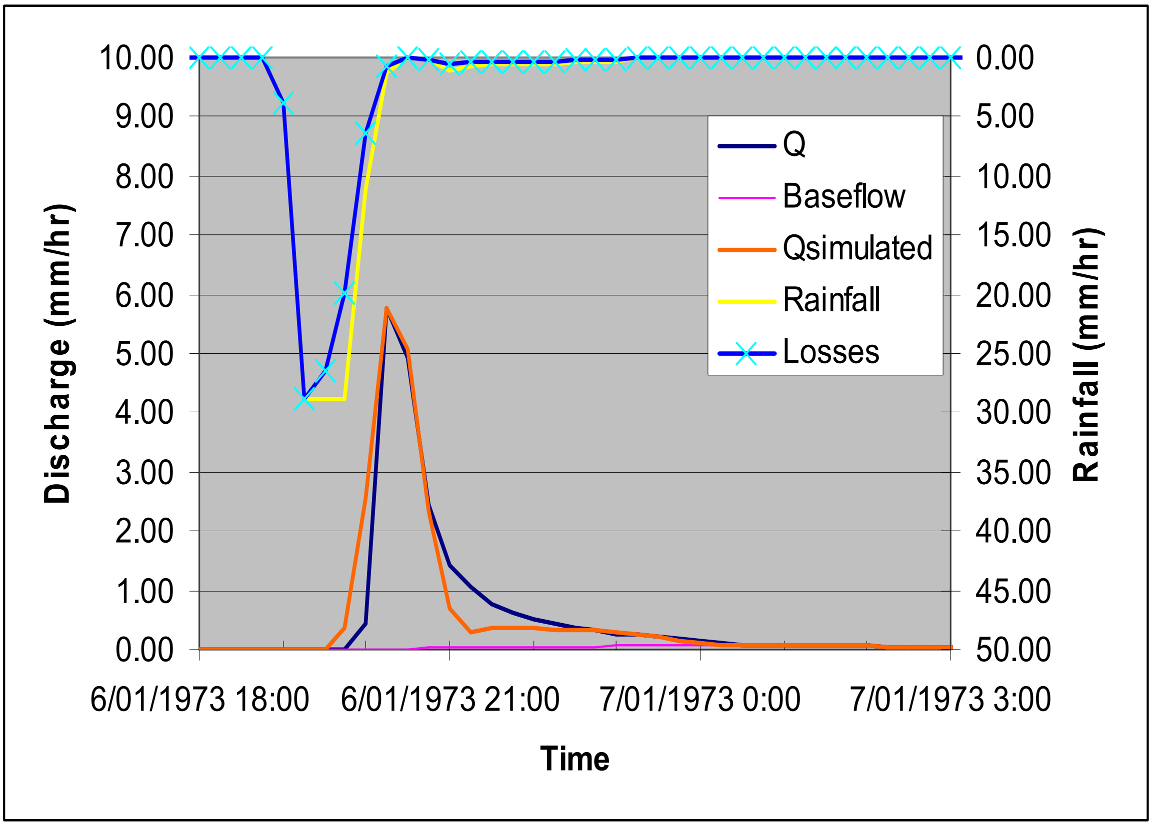


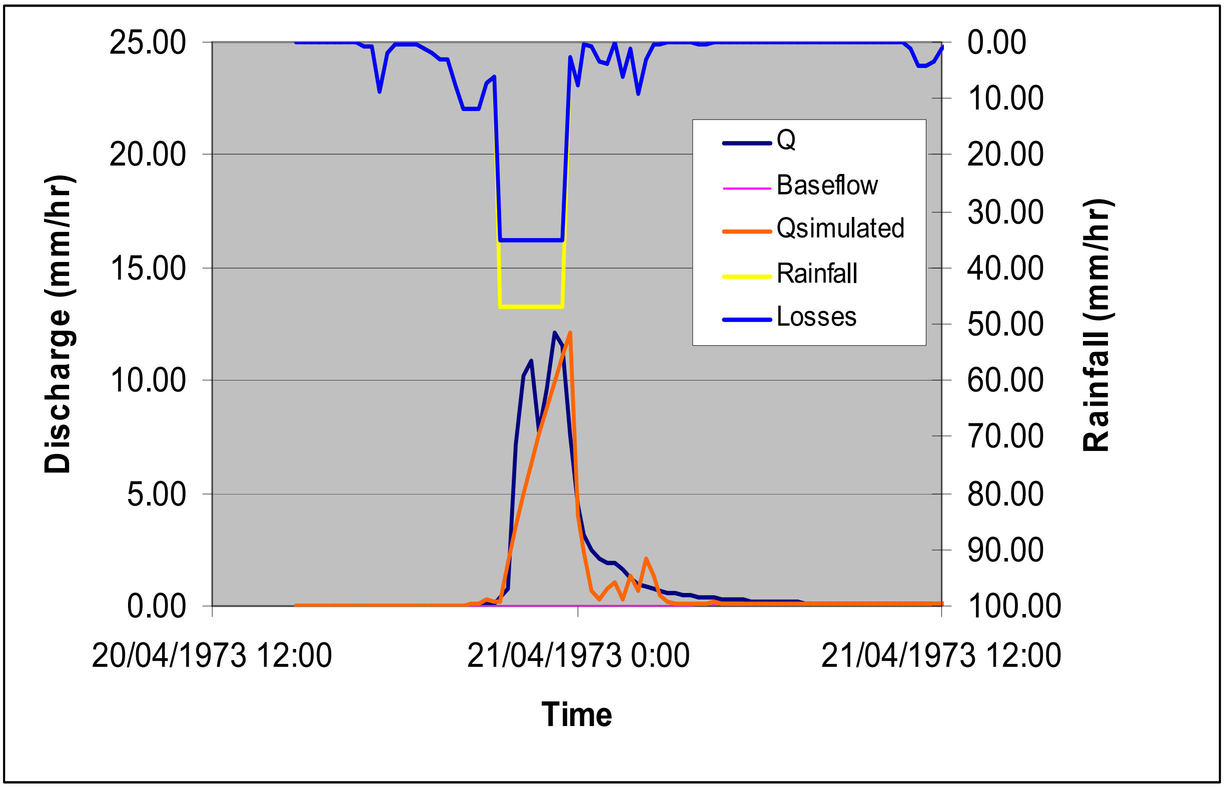
Discharge (mm/hr)
Rainfall (mm/hr)
Time
Q
Baseflow
Qsimulated
Rainfall
Losses
29/09/1970 0:00
30/09/1970 0:00
1/10/1970 0:00
2/10/1970 0:00
3/10/1970 0:00
4/10/1970 0:00



Discharge (mm/hr)
Rainfall (mm/hr)
Time
Q
Baseflow
Qsimulated
Rainfall
Losses
12/05/1971 18:00
13/05/1971 0:00
13/05/1971 6:00
13/05/1971 12:00
13/05/1971 18:00

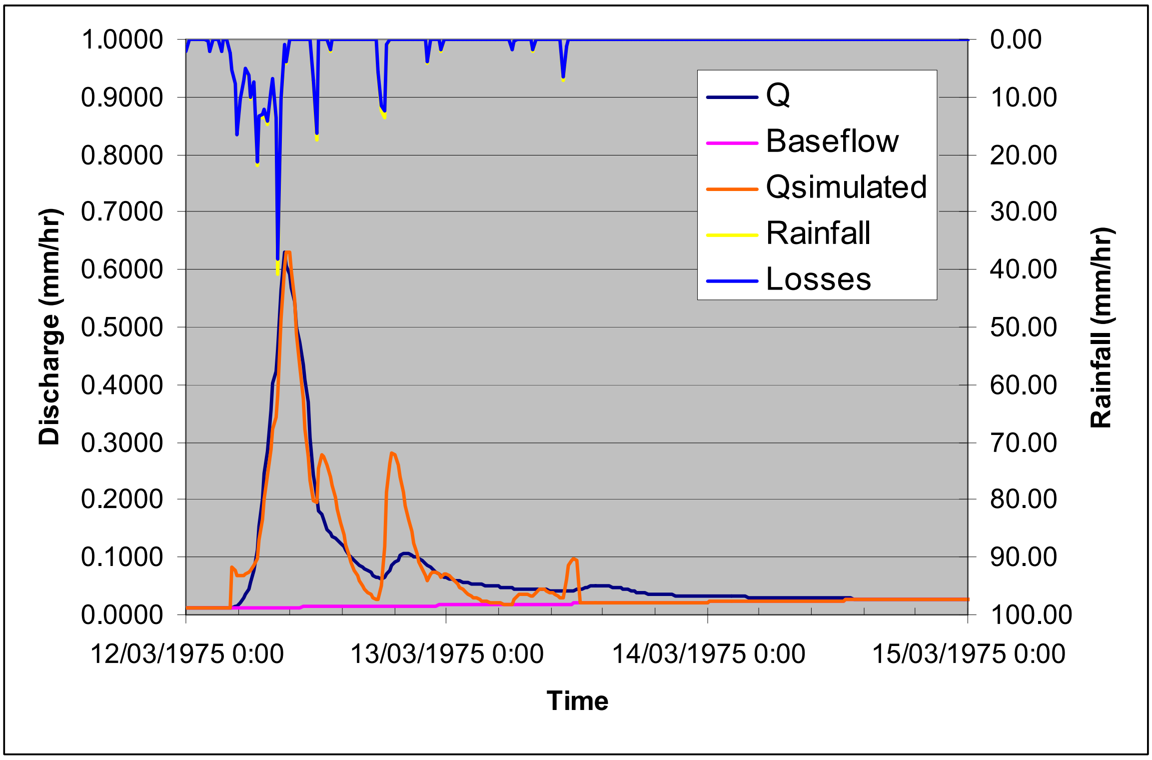

Discharge (mm/hr)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Rainfall (mm/hr)
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
Q
Baseflow
Qsimulated
Rainfall
Losses
1/01/1972 6:00
1/01/1972 12:00
Time

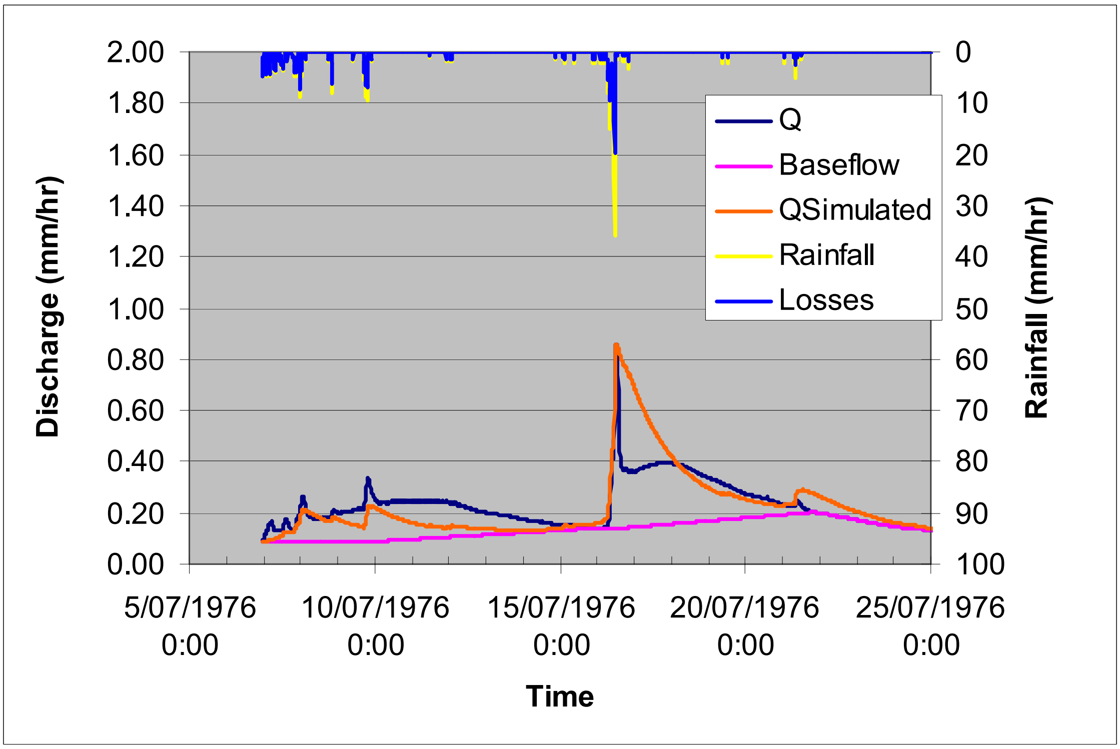

Discharge (mm/hr)
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Rainfall (mm/hr)
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
Q
Baseflow
Qsimulated
Rainfall
Losses
6/01/1973 18:00
6/01/1973 21:00
7/01/1973 0:00
7/01/1973 3:00
Time

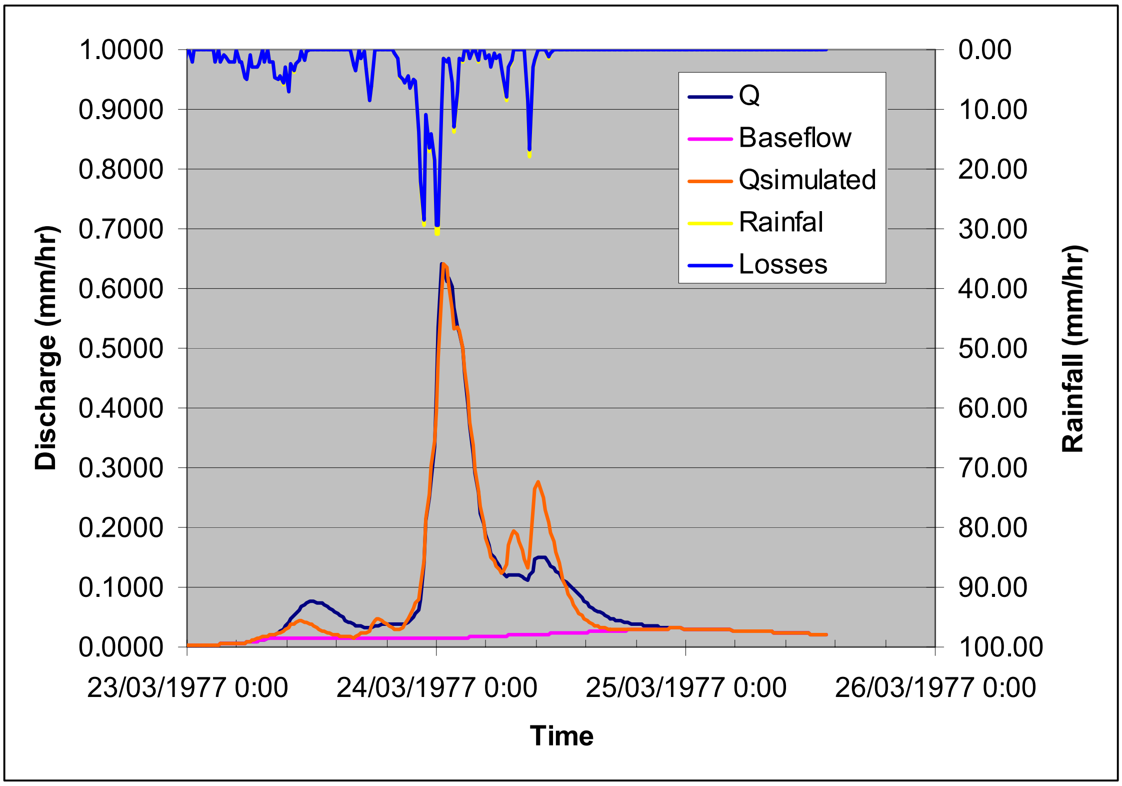


25.00
20.00
15.00
10.00
5.00
0.00
Discharge (mm/hr)
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
Rainfall (mm/hr)
Q
Baseflow
Qsimulated
Rainfall
Losses
20/04/1973 12:00
21/04/1973 0:00
21/04/1973 12:00
Time

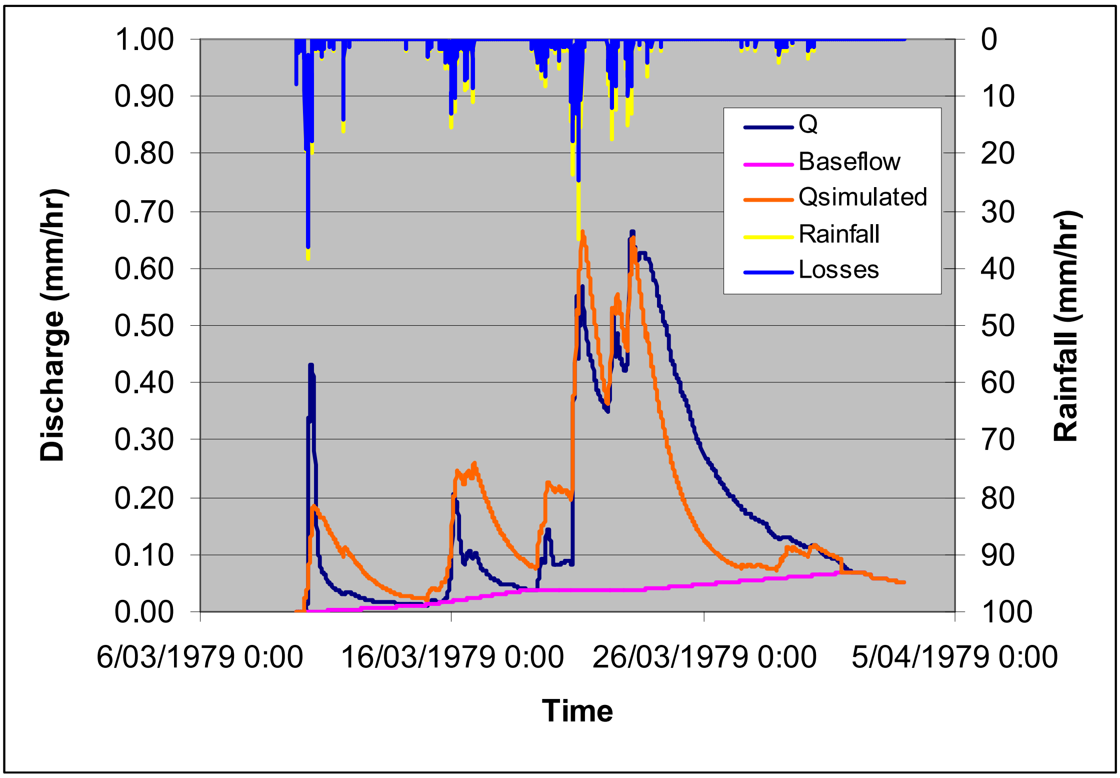
A.2 Purukohukohu at Puruki in Forest



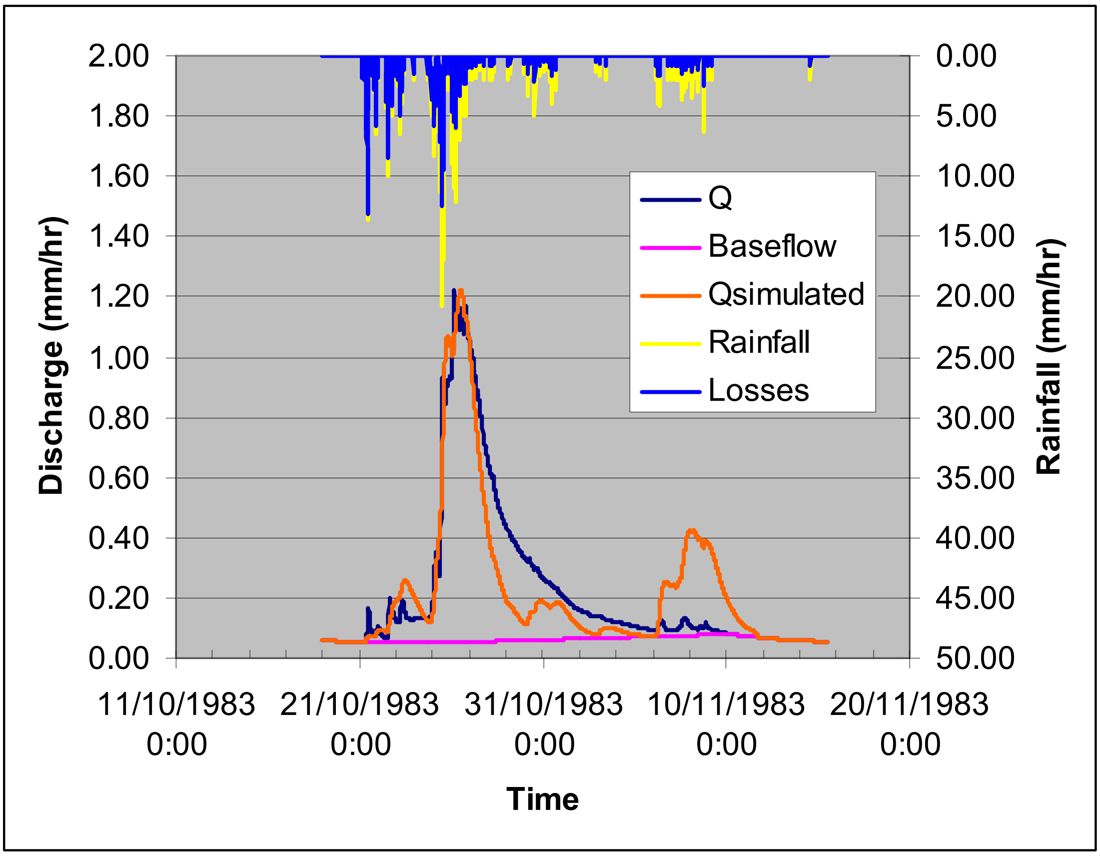


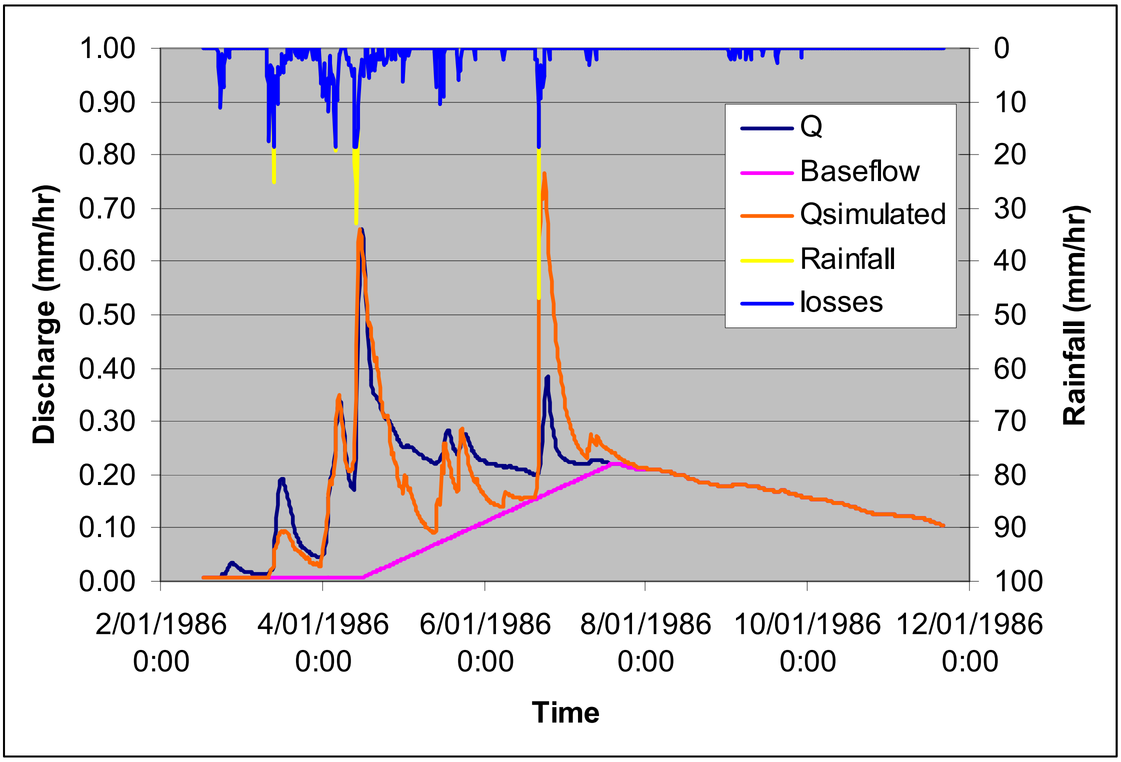


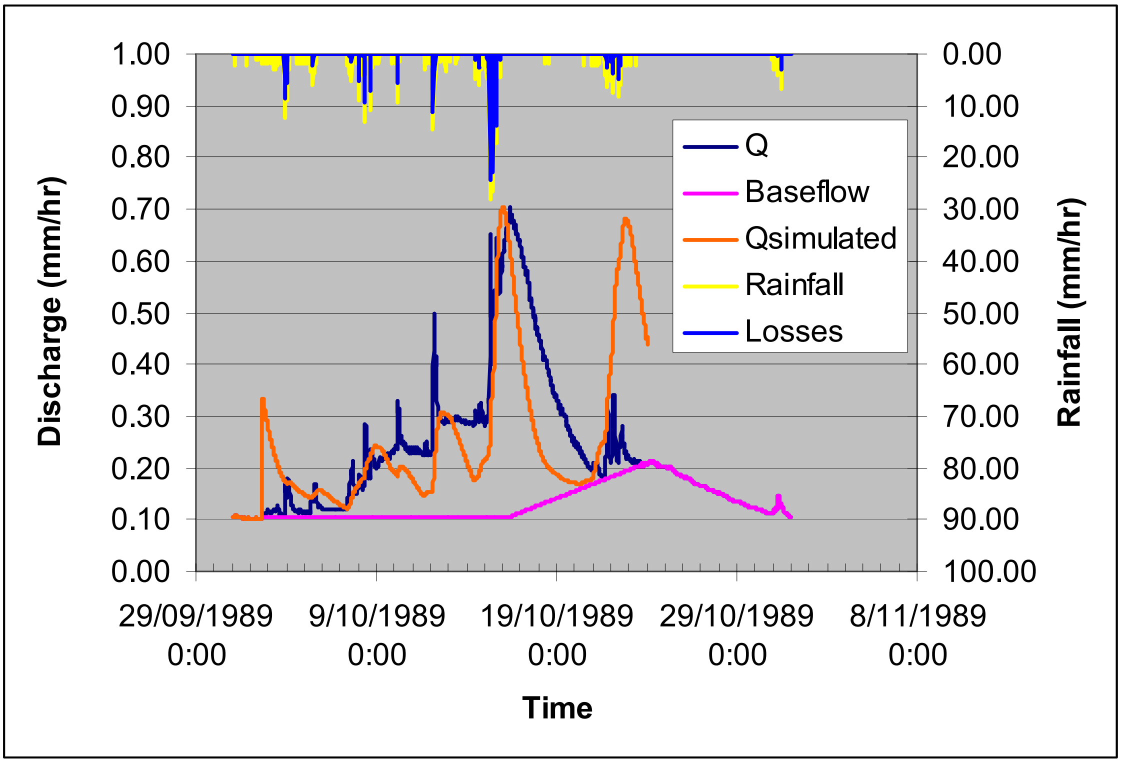
1.0000
0.9000
0.8000
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
Discharge (mm/hr)
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
Rainfall (mm/hr)
Q
Baseflow
Qsimulated
Rainfal
Losses
23/03/1977 0:00
24/03/1977 0:00
25/03/1977 0:00
26/03/1977 0:00
Time

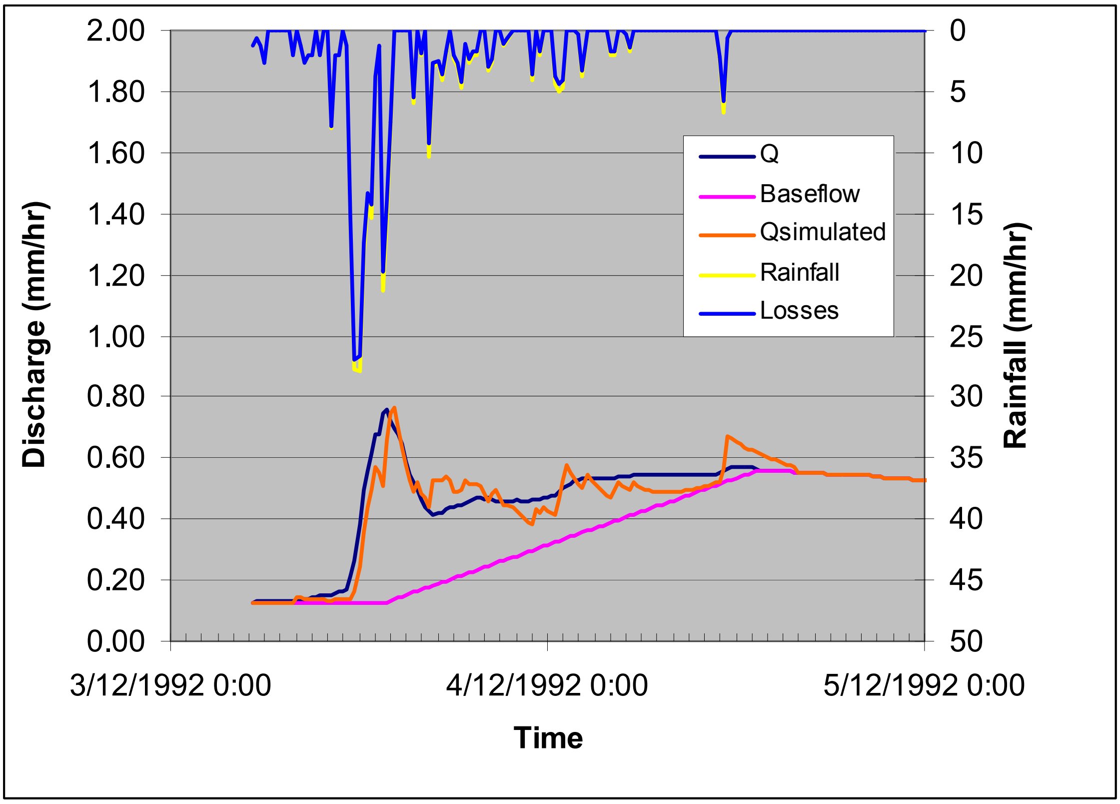


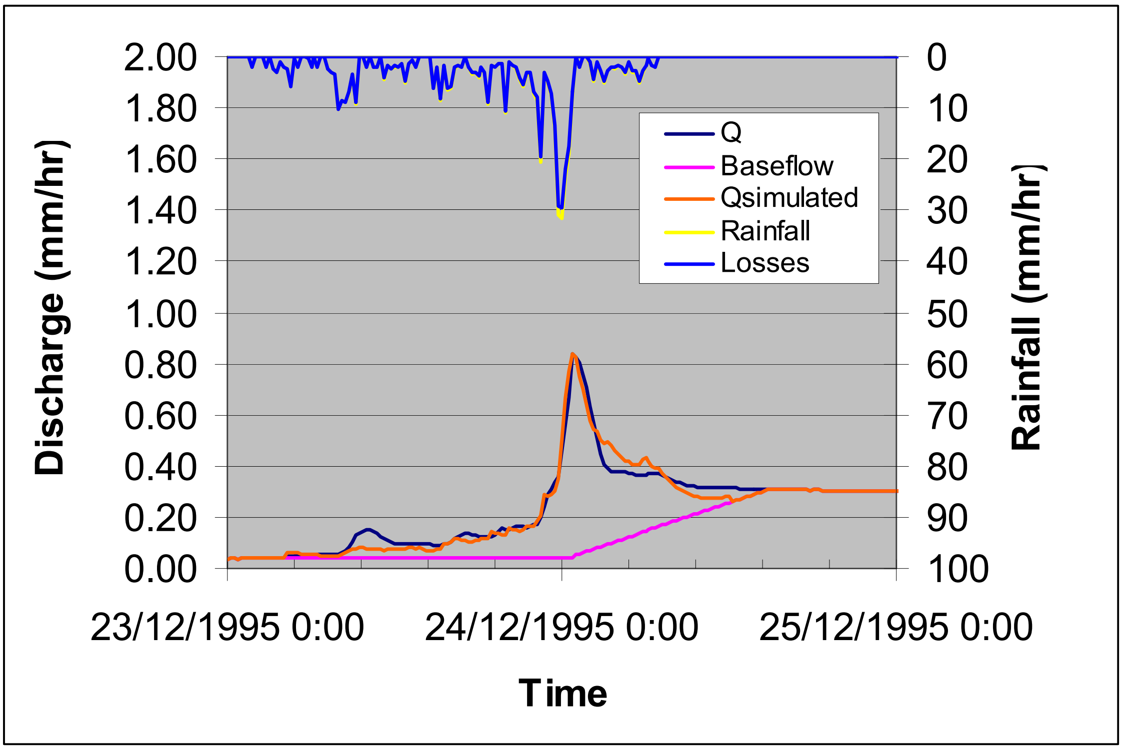
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Discharge (mm/hr)
0
10
20
30
40
50
60
70
80
90
100
Rainfall (mm/hr)
Q
Baseflow
Qsimulated
Rainfall
Losses
6/03/1979 0:00
16/03/1979 0:00
26/03/1979 0:00
5/04/1979 0:00
Time


Discharge (mm/hr)
Rainfall (mm/hr)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
Q
Baseflow
Qsimulated
Rainfall
Losses
11/10/1983 0:00
21/10/1983 0:00
31/10/1983 0:00
10/11/1983 0:00
20/11/1983 0:00
Time

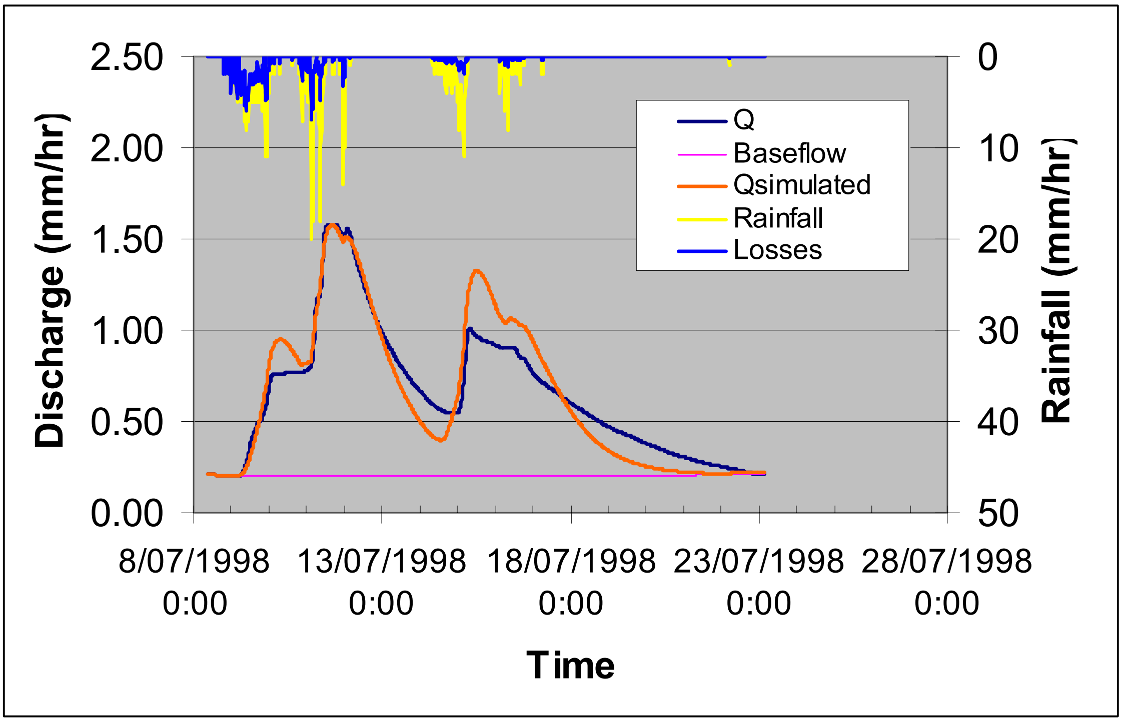

Discharge (mm/hr)
Rainfall (mm/hr)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
10
20
30
40
50
60
70
80
90
100
Q
Baseflow
Qsimulated
Rainfall
losses
2/01/1986 0:00
4/01/1986 0:00
6/01/1986 0:00
8/01/1986 0:00
10/01/1986 0:00
12/01/1986 0:00
Time


1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Discharge (mm/hr)
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
Rainfall (mm/hr)
29/09/1989 0:00
9/10/1989 0:00
19/10/1989 0:00
29/10/1989 0:00
8/11/1989 0:00
Time
Q
Baseflow
Qsimulated
Rainfall
Losses


2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Discharge (mm/hr)
0
5
10
15
20
25
30
35
40
45
50
Rainfall (mm/hr)
3/12/1992 0:00
4/12/1992 0:00
5/12/1992 0:00
Time
Q
Baseflow
Qsimulated
Rainfall
Losses

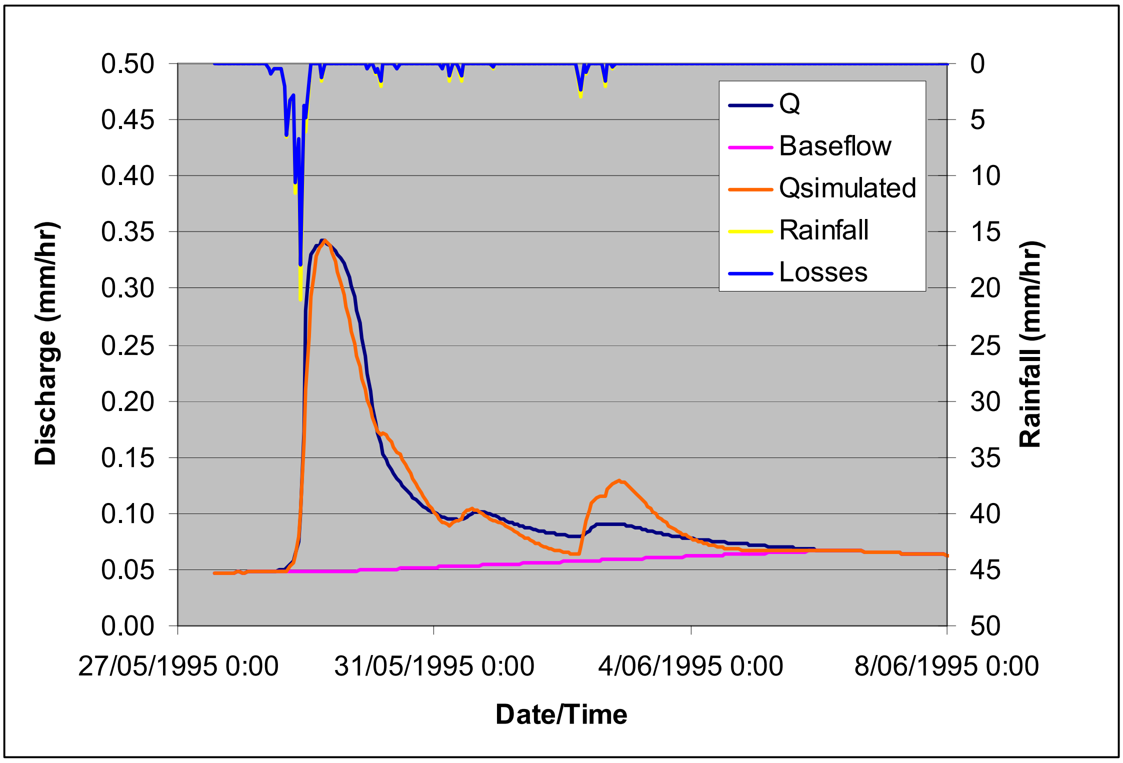


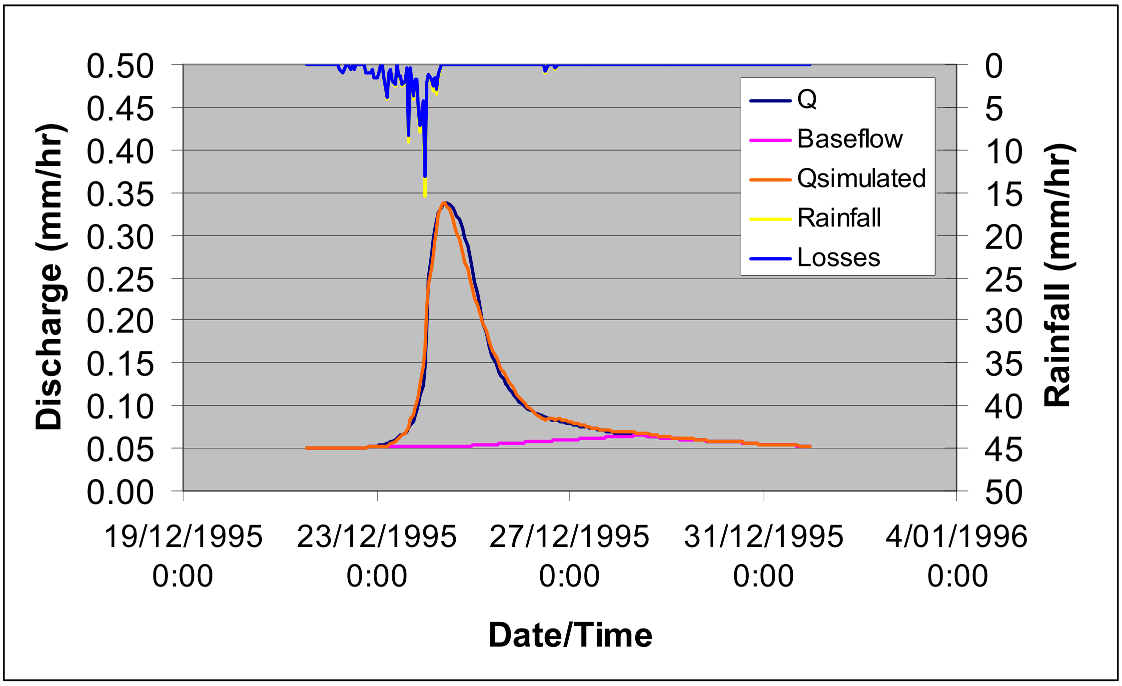
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Discharge (mm/hr)
0
10
20
30
40
50
60
70
80
90
100
Rainfall (mm/hr)
Q
Baseflow
Qsimulated
Rainfall
Losses
23/12/1995 0:00
24/12/1995 0:00
25/12/1995 0:00
Time

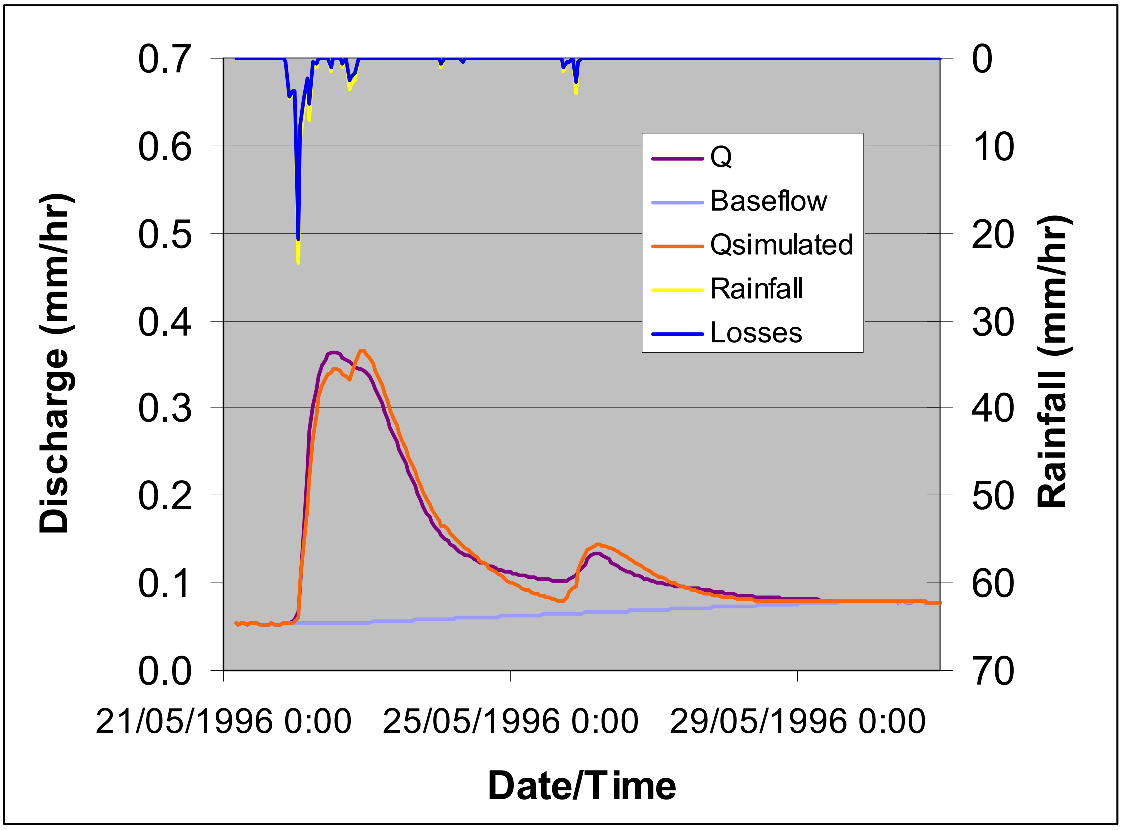


2.50
2.00
1.50
1.00
0.50
0.00
Discharge (mm/hr)
0
10
20
30
40
50
Rainfall (mm/hr)
Q
Baseflow
Qsimulated
Rainfall
Losses
8/07/1998 0:00
13/07/1998 0:00
18/07/1998 0:00
23/07/1998 0:00
28/07/1998 0:00
Time

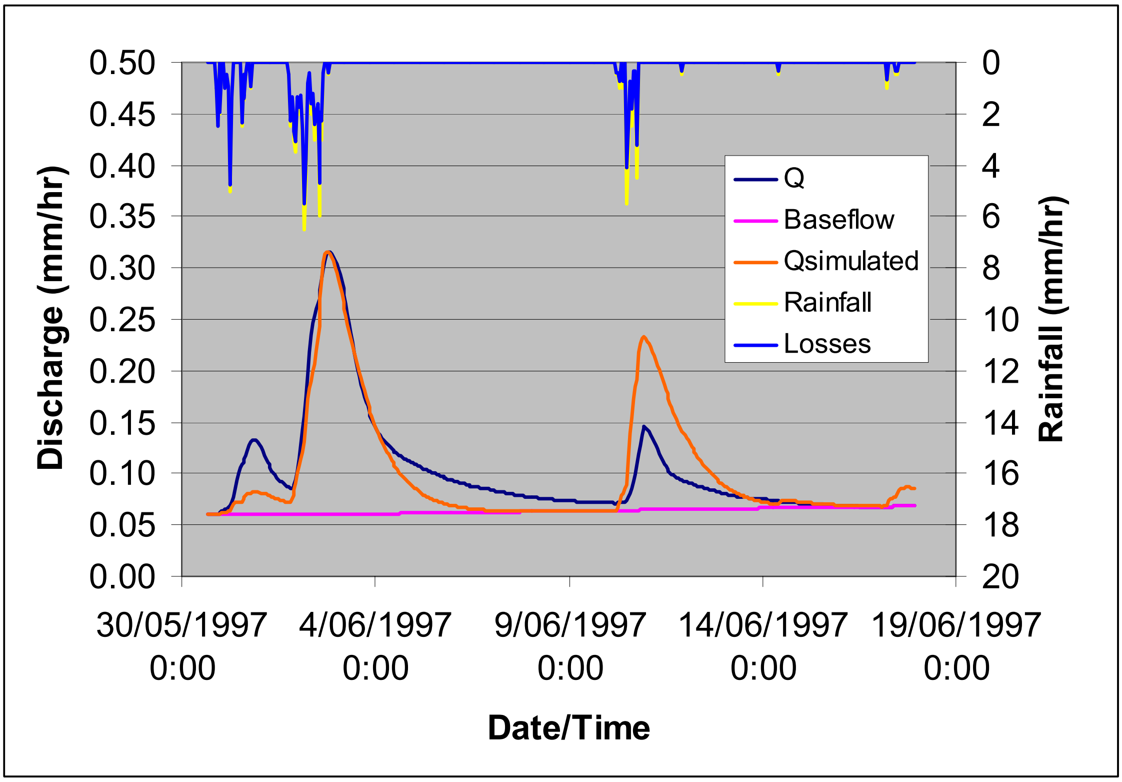
A.2 Waiotapu Stream at Reporoa



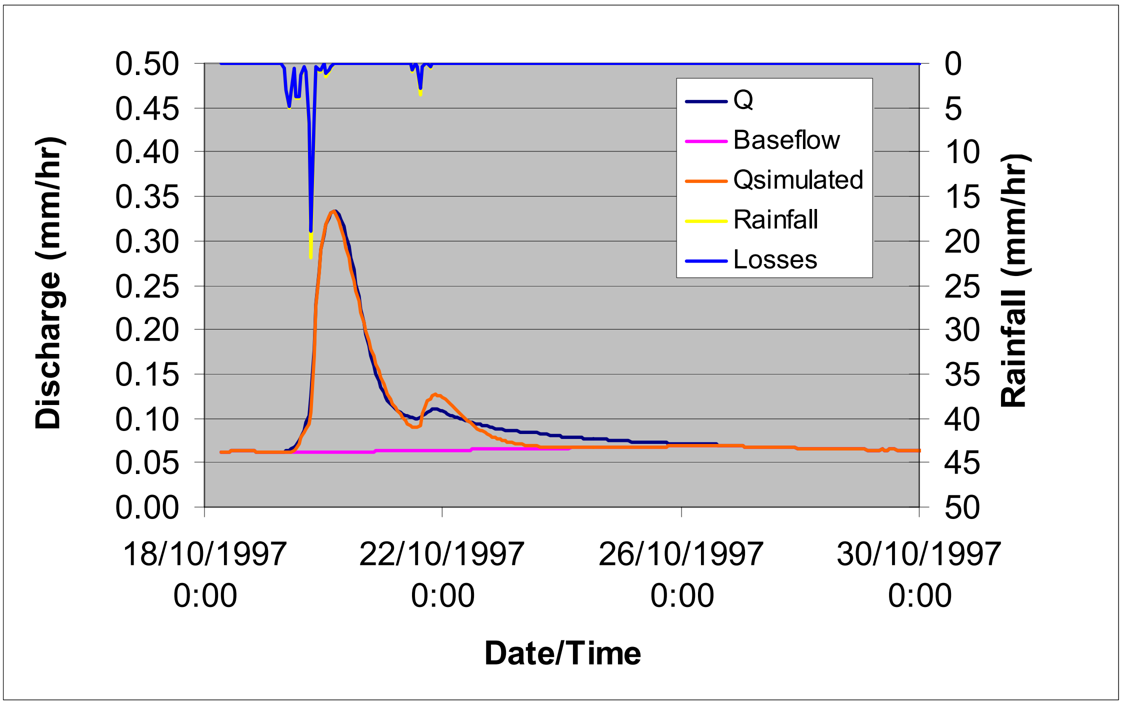


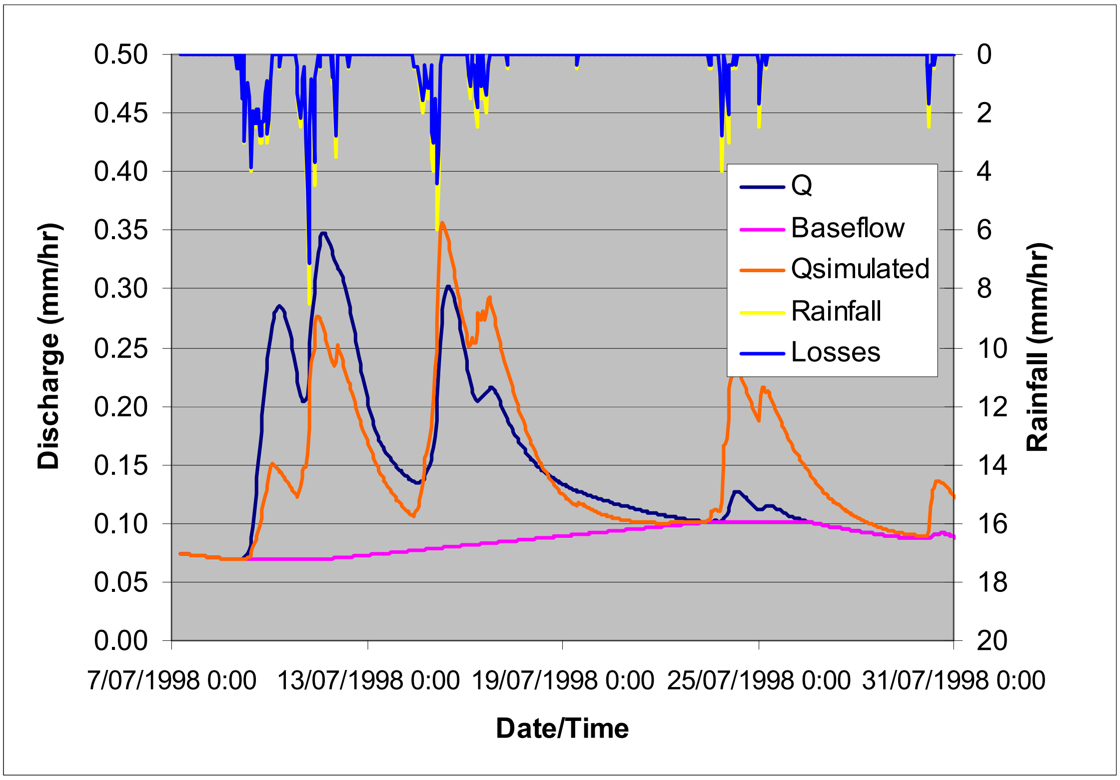


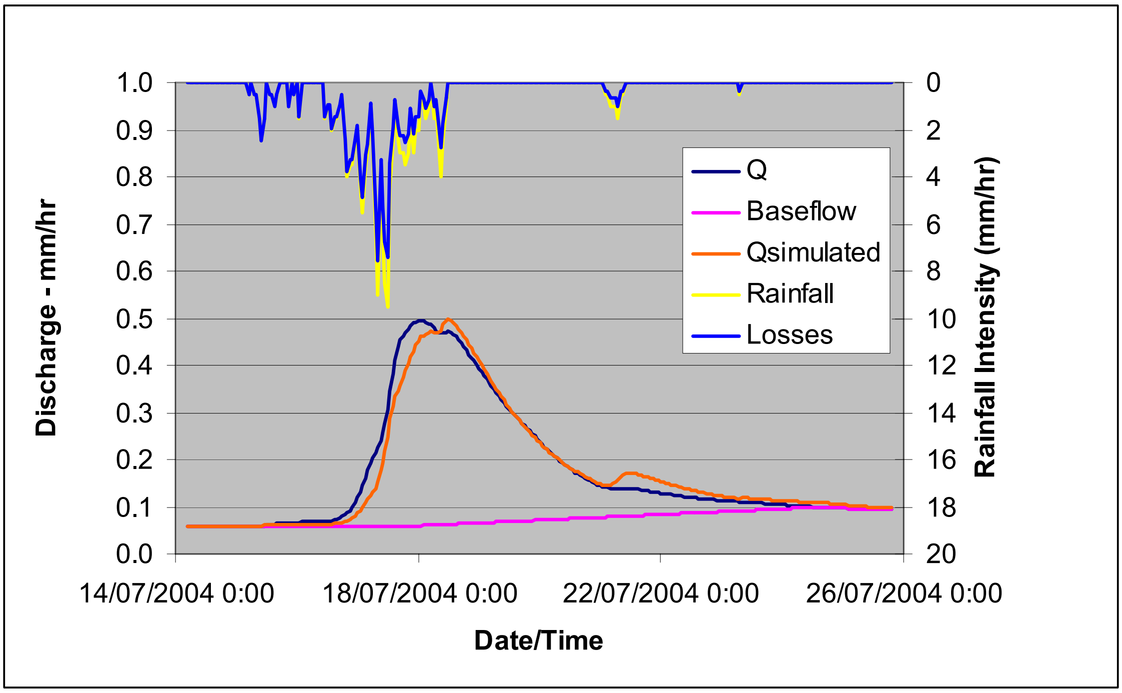
Discharge (mm/hr)
Rainfall (mm/hr)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
30
40
50
60
70
Q
Baseflow
Qsimulated
Rainfall
Losses
21/05/1996 0:00
25/05/1996 0:00
29/05/1996 0:00
Date/Time



Discharge (mm/hr)
Rainfall (mm/hr)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
2
4
6
8
10
12
14
16
18
20
Q
Baseflow
Qsimulated
Rainfall
Losses
30/05/1997 0:00
4/06/1997 0:00
9/06/1997 0:00
14/06/1997 0:00
19/06/1997 0:00
Date/Time


0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Discharge (mm/hr)
0
5
10
15
20
25
30
35
40
45
50
Rainfall (mm/hr)
Q
Baseflow
Qsimulated
Rainfall
Losses
18/10/1997 0:00
22/10/1997 0:00
26/10/1997 0:00
30/10/1997 0:00
Date/Time


0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Discharge (mm/hr)
0
2
4
6
8
10
12
14
16
18
20
Rainfall (mm/hr)
Q
Baseflow
Qsimulated
Rainfall
Losses
7/07/1998 0:00
13/07/1998 0:00
19/07/1998 0:00
25/07/1998 0:00
31/07/1998 0:00
Date/Time



Discharge - mm/hr
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Rainfall Intensity (mm/hr)
0
2
4
6
8
10
12
14
16
18
20
Q
Baseflow
Qsimulated
Rainfall
Losses
14/07/2004 0:00
18/07/2004 0:00
22/07/2004 0:00
26/07/2004 0:00
Date/Time