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THE EFFECT OF LARGE-SCALE AFFORESTATION ON TARAWERA RIVER FLOWS

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ABSTRACT

Over 250 km^2 of the Tarawera catchment (906 km^2) in the central North Island, New Zealand, was planted in pine forest between 1964 and 1981. This change has affected flow of the River Tarawera. Between 1964-81 annual, summer and winter Tarawera flows showed significant reductions of 10.9 m^3/s, 11.4 m^3/s and 9.6 m^3/s respectively. Simple flow models for the Tarawera, and two neighbouring catchments that had undergone little landuse change, showed that about 4.5 m^3/s of these reductions, 13% of the mean flow over the calibration period, could be attributed to afforestation, while the remainder was due to decreased rainfall. The reduction attributed to afforestation was in accord with the results of small catchment studies.

INTRODUCTION

The Tarawera River (Fig. 1) is presently being investigated to determine its ability to assimilate effluent, mainly from the local pulp and paper industry. River water quality depends on both the type of effluent discharged and river flow, so the maximum permissible effluent discharge should reflect both effluent oxygen demand and the likely range of river flows. If 30-40 years of river flow data are available from a stable catchment then an acceptable estimate of the long-term flow distribution can be obtained. However, if changes have occurred in the catchment (e.g. afforestation, hydro-electric power development) then some of the record may not reflect present catchment conditions. The objective of this study was to determine if, and by how much, afforestation in the Tarawera catchment has reduced river flows.

The effect of afforestation on the hydrology of small catchments in New Zealand has been examined by Herald (1979), Pearce and Rowe (1979), Duncan (1980) and Dons (1981). These studies have shown that afforestation of areas of pasture, gorse and regenerating indigenous scrub have generally reduced

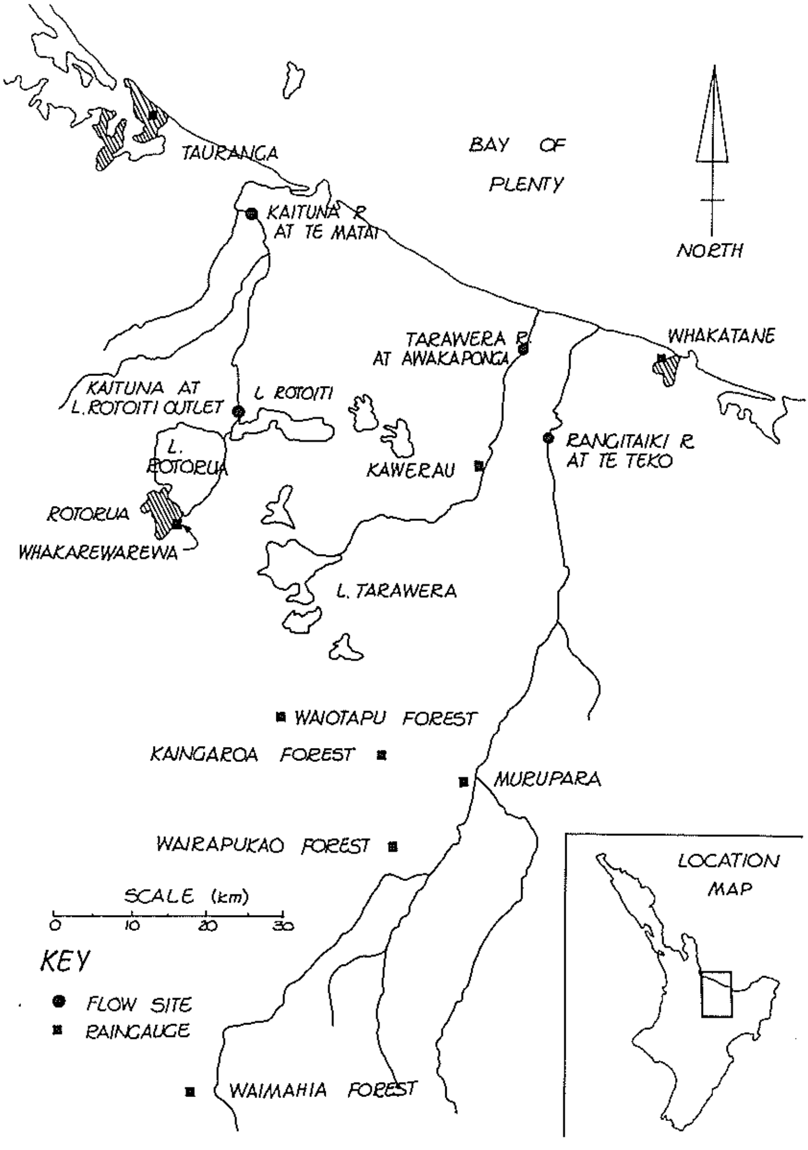

Figure 1: Rainfall and flow measurement sites — Kaituna, Tarawera and Rangitaiki catchments.

stream flow. These reductions have been attributed to the increased evaporation of water intercepted by the forest canopy during rainfall. However, the effect of forest cover on large catchments has not been demonstrated; the little information available tends to contradict the conclusions reached from small-basin studies (Morton, 1984). The Tarawera River (catchment area 906 km²) offers a rare opportunity to test the effect of large-scale afforestation on river flows. Pines have been planted over 250 km² (28% of the total catchment) and flow and rainfall data are available for the periods before and during the landuse change.

AFFORESTATION OF THE TARAWERA

Since large-scale afforestation in the Tarawera catchment started in the early 1960's, about 12 km²/yr has been planted in pines (Fig. 2). Because less than 3% of the catchment was afforested by 1963, and most of these trees were less than 3 years old, the period from 1949 to 1963 is used as the calibration period. During this time, afforestation is assumed to have had no effect on flow of the Tarawera River. The period from 1964 to 1981 is termed the afforestation period. By 1985 most of the plantable area within the catchment had been utilised, and therefore the hydrological effect of afforestation was near its maximum by 1981. Clearing the replanting after 1985 will only affect 3% of the catchment at any one time, and thus will have little impact on Tarawera River flow measured at Awakaponga (Fig. 1). Of the area planted, 60% was originally scattered light scrub and 40% native bush (Fig. 3) (Department of Lands and Survey, 1952). Photographs taken before afforestation showed that the original scrub vegetation was poor and sparse while the original native bush was of low stature. Much of the afforested land occupies the high rainfall areas of the catchment (Fig. 3).

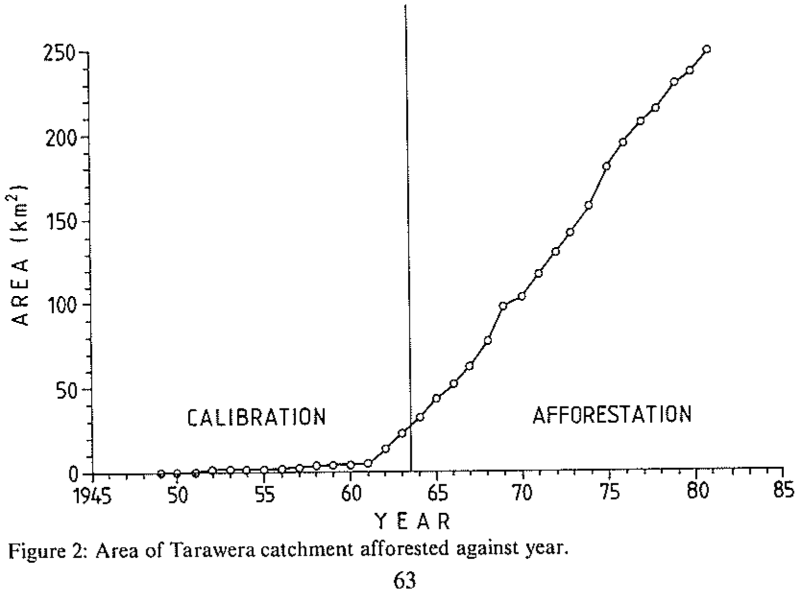

Figure 2: Area of Tarawera catchment afforested against year.

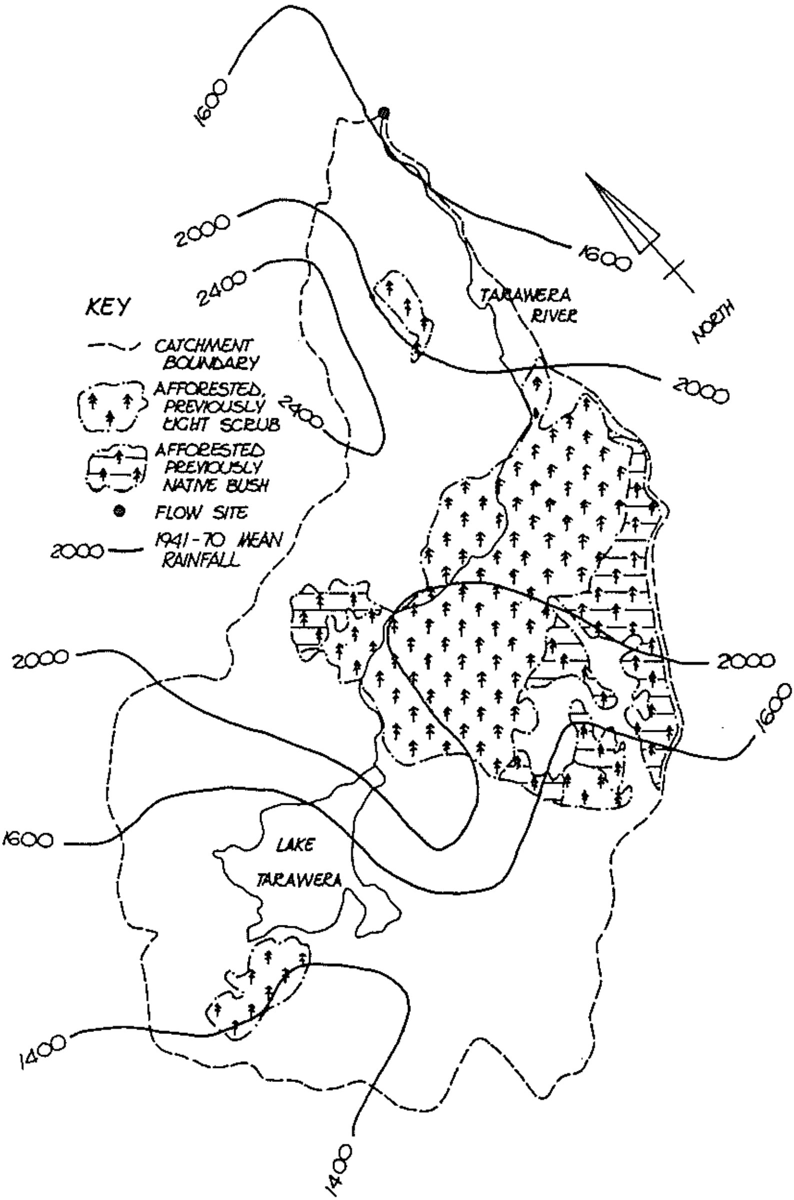

Figure 3: Map of Tarawera catchment afforestation.

Apart from afforestation the author knows of no other significant consumptive water use in the catchment above Awakaponga. The pulp and paper industry at Kawerau takes about 2.7 m^3/s from the Tarawera River, but discharges effluent at about the same rate and therefore does not "consume" water (Bay of Plenty Catchment Commission, pers. com.).

STUDY METHODS

Data

Flow data for the periods before and during Tarawera afforestation was available for the Tarawera catchment and for two large "control" catchments nearby (Kaituna and Rangitaiki) whose landuse had changed little during the study period (Fig. 1). The Kaituna and Rangitaiki were examined to compare flow changes for the Tarawera with those of other "stable" rivers in the region. Their catchment areas are 948 km^2 and 2893 km^2 respectively. The Kaituna and Tarawera Rivers have large lake systems which contribute about half of their flow while the Rangitaiki has no major lakes. Data from a flow recorder site at the outlet from Lake Tarawera could not be used to determine the effect of lake storage on Tarawera River flow because of unmeasured flow from the lake underneath the channel bed at the outlet. There are 8 years of data from within the calibration period (1956-63) for the Kaituna River, and 15 years (1949-63) for the Tarawera and Rangitaiki Rivers.

Rainfall was also used as a control variable. Tarawera and Kaituna flows were compared to Whakarewarewa rainfall while Rangitaiki flow was compared to Wairapukao Forest rainfall. This rainfall data, chosen from data from 9 gauges in the study area (Fig. 1), correlated best with flow during the calibration period. The ratio between Tarawera catchment rainfall and Whakarewarewa rainfall (1.22) was determined by dividing the catchment rainfall, estimated from a 1941-70 mean rainfall isohyetal map, by the 1941-70 Whakarewarewa mean rainfall (NZ Meteorological Service, 1973). Annual, summer and winter average flows and rainfall totals were used to test for seasonal variation. The start of summer was defined as the beginning of the last week in November, and each season was allocated 13 weeks with the summer season being extended by one week when necessary. All flow and rainfall data were accessed from the Ministry of Works and Development TIDEDA databank.

Recent data from these gauging sites and all the rainfall data should be relatively error-free, but both the early water-level data and water level-flow relationships (ratings) required confirmation. Tarawera water-level recording was by staff gauge, read weekly from 28 May 1948 to 17 December 1954, by 8-day chart recorder until 23 August 1965, and by a 15-min digital recorder since then. Water-level data from both the chart and digital recorder provide an almost continuous record. The accuracy of weekly recording of the Tarawera was assessed by comparing annual mean flows derived from the original chart and digital record with annual mean flows calculated using a subset of instantaneous weekly observations. The 27 annual means tested gave small (+2.2% to -1.5%) random differences with the mean difference being practically zero (+0.09%). The accuracy of early ratings cannot be confirmed easily. Infrequent flow gaugings of the Tarawera during the calibration period did little to decrease the uncertainty of the early flow records. However, eight gaugings between 1949 and 1962 show that the channel geometry during this period was stable and similar to that during 1962-69 when the river was gauged 84 times. Also, there was no consistent change in the relationship between Whakarewarewa rainfall and Tarawera flow during the period 1949-63 when land use was stable.

Kaituna water-level recording began with a 7-day chart recorder on 24 January 1955, which was converted to a 15-min digital recorder on 12 August 1965. Gauging of the Kaituna during the early years was more frequent than the Tarawera with 12 gaugings during 1956 and 1957 and an average of 10 gaugings per year from 1961.

Rangitaiki water level recording began with staff gauge readings weekly at Edgecumbe Bridge (12 km downstream from the present flow site) from 1 June 1948. These readings were increased to daily from 1 January 1950 to 16 August 1951 and twice daily from then to 9 August 1952. Water-level recording then began at its present site (Te Teko) with the establishment of a 32-day chart recorder which was subsequently converted to a 15-min digital recorder on 25 August 1965. As with the two other flow sites, gaugings were less frequent during the calibration period. The first rating was based on 20 gaugings at Te Teko (and water-level measurements at Edgecumbe Bridge) during 1944, 1945, 1950 and 1952. All subsequent ratings were based on water-level and flow measurements at Te Teko. In addition to the 20 early gaugings there were 11 from 1954-58, before regular gauging started in 1962 at an average rate of 12 per year.

Analysis Methods

Two questions were posed in this study to assess the effect of afforestation on Tarawera flows. Firstly, have river flows and/or rainfalls changed, for any reason, during the calibration or afforestation period? Secondly, were changes in river flow related to the area of afforestation in the Tarawera catchment? The first question was answered by testing for trends in flow and rainfall during both periods. The magnitude of the associated change in flow (or rainfall) was estimated by subtracting the flow (or rainfall) predicted for the end of the period (i.e. year = 81) from that predicted for the start of the period (i.e. year =64) using the estimated trend equation. The second question was answered by testing if the variable FOREST (area of Tarawera catchment afforested in km^2) was significant in explaining some variation in Tarawera flows, once the effect of rainfall variation was accounted for. If Tarawera flows were reduced in direct proportion to the area of afforestation then FOREST would significantly improve Tarawera flow models but not improve Kaituna or Rangitaiki flow models. A variable significantly improves a flow model if (Chatterjee and Price, 1977);

$$[(RSS(RM) - RSS(FM))/(p-k)]/[RSS(FM)/(n-p)] > F(p-k, n-p, a)$$

where RSS = Residual sum of squares.
FM = Full model (i.e. with FOREST)
RM = Reduced model (i.e. without FOREST)
p = Number of parameters of FM
k = Number of parameters of RM

n = Number of observations
F ( ) = F statistic at chosen level of confidence (a).

Least squares regression was used to detect trend and estimate flow models with and without FOREST.

The simple least squares regression model is:

$$Y = a + bX + e$$

where Y is the response variable,
X is the predictor variable,
a, b are the fitted intercept and slope parameters, and
e is the error term.

For reliable hypothesis testing the errors need to be independently normally distributed with constant variance and zero mean. The least squares procedure guarantees errors with zero mean, and the normality of the errors was tested using the Shapiro-Wilk statistic (Shapiro and Wilk, 1965). If the test rejected the hypothesis of normally distributed errors, a logarithmic transformation (to base e) was sufficient to normalise the errors. The Durbin-Watson statistic (Durbin and Watson, 1951) was used to test for auto-correlated (i.e. dependent) errors. If this test was significant the least squares regression was transformed using the error autocorrelation coefficient, as described by Cochrane and Orcutt (1949). Constant error variance was checked by plotting regression errors against the predictor variable. When testing the significance of FOREST the condition indices (Montgomery and Peck, 1982) were inspected to ensure independent (i.e. non-collinear) predictor variables. The Shapiro-Wilk, Durbin-Watson and the condition index tests, as well as the transformation to correct the autocorrelated errors, were available in standard statistical computer programmes (SAS, 1982a, b, c).

RESULTS AND DISCUSSION

Trends in Flow and Rainfall

Figure 4 shows the annual, summer and winter flow and rainfall data available for analysis. All Tarawera River flows (i.e. annual, summer and winter) showed highly significant ($p<0.01$) reductions during the afforestation period (Table 1). The decrease in flow between 1964 and 1981 was 10.9 m^3/s, 11.4 m/s and 9.6 m^3/s for annual, summer and winter mean flows respectively. Summer Kaituna flows also showed a significant ($p<0.01$) decrease of 13.6 m^3/s during the afforestation period. This was attributed to summer control of Lake Rotorua outflow and decreased summer rainfall. In addition to the above highly significant trends, annual Kaituna flow, summer Rangitaiki flow and summer Whakarewarewa rainfall showed marginally significant ($p<0.10$) decreases. Furthermore, all slopes (except winter Whakarewarewa rainfall) were negative during the afforestation period. During the calibration period only summer flow of the Tarawera showed a marginal increase although high rainfall in 1962 did cause mostly positive regression slopes during this period.

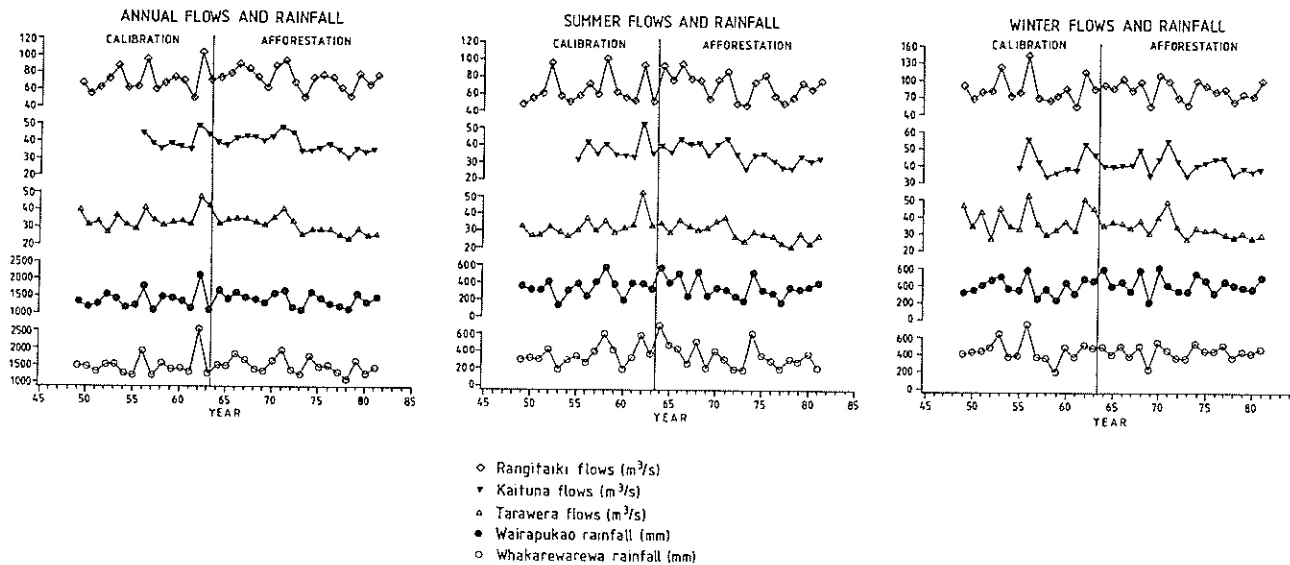

Figure 4: Annual, summer and winter flows and rainfalls.

TABLE 1—Regression of flow and rainfall against time.

		Calibration Period (1949-63)			Afforestation Period (1964-81)		
		Intercept	Slope	t(slope)	Intercept	Slope	t(slope)
Flow							
Tarawera	annual	2.9	0.012	1.36	4.9	-0.020	4.42***
	summer	2.4	0.019	2.10*	5.0	-0.023	3.93***D
	winter	3.5	0.0017	0.13	4.7	-0.017	3.00***
Kaituna	annual	3.1	0.011	0.62	4.6	-0.011	1.93*
	summer	2.5	0.018	1.19D	5.2	-0.022	4.21***
	winter	3.1	0.011	0.50	4.2	-0.0073	1.37
Rangitaiki	annual	3.7	0.010	1.19D	5.1	-0.010	1.56
	summer	3.6	0.0090	0.60	5.5	-0.017	1.78*
	winter	4.7	-0.0050	0.38D	5.1	-0.0093	0.97
Rainfall							
Whakarewarewa	annual	6.7	0.010	1.34D	8.0	-0.0096	1.51
	summer	4.7	0.021	1.05	8.2	-0.033	1.92*
	winter	606	2.95†	0.37	375	0.68†	0.31D
Wairapukao Forest	annual	6.8	0.0072	1.16D	7.9	-0.0089	1.47
	summer	5.2	0.011	0.54	7.3	-0.021	1.39
	winter	381	0.10†	0.017	620	-2.98†	1.04D

* Slope significant at 0.10 level
** Slope significant at 0.05 level
*** Slope significant at 0.01 level
D Significant ($p<0.05$) autocorrelation in least-squares regression errors
† Regression estimated from untransformed data (remaining flow and rainfall data $\log_e$ transformed)
Units: Flow — m^3/s, Rainfall — mm, time — year (i.e. 49, 50...)

If the afforestation period trend in annual Tarawera flows is converted to rainfall units then Tarawera flows decreased by 379 mm between 1964 and 1981. This decrease was greater than the decrease in Tarawera catchment rainfall over the same period of 296 mm. Under stable catchment conditions it is very unlikely that annual average flow could decrease faster than catchment rainfall. This strongly suggests that some factor other than rainfall has caused at least 83 mm (2.5 m^3/s) of the decrease in Tarawera River flow during the afforestation period.

Flow Models

Annual rainfall-flow models estimated from the total data set (1949-81)

TABLE 2—Annual rainfall-flow models

Flow variable (m^3/s)	Predictor variable	Parameter Estimates Full Model	Reduced Model	Residual SS Full Model	Reduced Model	F	n	R^2
$Tarawera_t$	Wh_t	0.014	0.014	149	224	9.7***	33	0.82
	Wh_{t-1}	0.0088	0.0094		D			
	$Forest_t$	-0.025	—					
	intercept	0.64	-2.94					
$Kaituna_t$	Wh_t	0.011	0.011	82	89	1.7	26	0.80
	Wh_{t-1}	0.0073	0.0075	D	D			
	$Forest_t$	-0.013	—					
	intercept	12.62	10.60					
$Rangitaiki_t$	Wa_t	0.058	0.057	556	587	1.5	33	0.88
	Wa_{t-1}	0.024	0.023					
	$Forest_t$	0.011	—					
	intercept	-42.33	-39.87					

F Sample F statistic (see text)
*** Model improvement significant at 0.01 level
R^2 Correlation coefficient of full model
Wh Whakarewarewa rainfall (mm)
Wa Wairapukao Forest rainfall (mm)
Forest Area of Tarawera catchment afforestation (km^2)
D Significant ($p<0.05$) autocorrelation in least-squares regression errors.

showed that FOREST significantly ($p<0.01$) improved the Tarawera flow model but not the Kaituna or Rangitaiki models (Table 2). The Tarawera model suggests that afforestation in the Tarawera catchment reduced annual flows by 6.3 m^3/s by 1981 when 250 km^2 of the catchment was afforested. The full model for the Tarawera explained a high proportion (82%) of the variation in Tarawera River flow and hence could be used to estimate the effect of future afforestation, and conversely, the effect of converting previously afforested land to pasture. This assumes that the effect of deforestation is equal and opposite to afforestation and that the effect is independent of the location of the landuse change.

The flow-flow models also showed that FOREST was important in explaining Tarawera River flow (Table 3). Annual Tarawera flow appears to be significantly reduced by afforestation in relation to Kaituna flow ($p<0.05$) and Rangitaiki flow ($p<0.01$) by 4.5 m^3/s and 8.5 m^3/s respectively. Because the Tarawera-Kaituna model explained 23% more of the variation in Tarawera flow than the Tarawera—Rangitaiki model, the former model is more reliable for estimating the decrease in Tarawera River flow due to factors other than rainfall, during catchment afforestation. The Rangitaiki catchment, however, provided an independent confirmation of the decrease in Tarawera River flow. As Kaituna

TABLE 3—Flow-flow models

Response variable	Regressor variable	Parameter Estimates: Full Model	Parameter Estimates: Reduced Model	Residual SS: Full Model	Residual SS: Reduced Model	F	n	R^2
Tarawera$_a$	Kaituna$_a$	1.01	1.10	73	87	4.4**	26	0.89
	Forest	-0.018	—	D	D			
	intercept	-4.78	-10.10					
Tarawera$_a$	Rangitaiki$_a$	0.26	0.26	274	362	9.6***	33	0.66
	Forest	-0.034	—	D	D			
	intercept	16.81	14.16					
Kaituna$_a$	Rangitaiki$_a$	0.20	0.21	153	178	3.8*	26	0.63
	Forest	-0.021	—	D	D			
	intercept	25.97	23.61					
Tarawera$_s$	Kaituna$_s$	0.88	0.92	111	121	2.2	27	0.88
	Forest	-0.012	—	D	D			
	intercept	0.12	-2.59					
Tarawera$_s$	Rangitaiki$_s$	0.22	0.23	400	469	5.2**	33	0.60
	Forest	-0.032	—	D	D			
	intercept	18.01	15.12					
Kaituna$_s$	Rangitaiki$_s$	0.28	0.28	264	309	4.1*	27	0.72
	Forest	0.028	—	D	D			
	intercept	20.0	16.78					
Tarawera$_w$	Kaituna$_w$	0.99	1.05	152	223	7.6**	27	0.87
	Forest	-0.024	—		D			
	intercept	-3.91	-8.95					
Tarawera$_w$	Rangitaiki$_w$	0.24	0.25	554	725	7.1**	33	0.63
	Forest	-0.32	—					
	Intercept	17.99	14.61		D			
Kaituna$_w$	Rangitaiki$_w$	0.19	0.20	381	394	0.79	27	0.57
	Forest	-0.011	—	D	D			
	intercept	26.26	25.04					

***, **, * 0.01, 0.05, 0.10 significance levels respectively
a, s, w Annual, summer, winter data respectively,
For full explanation of abbreviations see Table 2.

flow appeared to decrease in relation to Rangitaiki flow (Table 3) by 5.25 m^3/s, the 8.5 m^3/s decrease estimated from the Tarawera-Rangitaiki model appears to be an overestimate. Summer Tarawera flow has not decreased significantly in relation to summer Kaituna flow (Table 3) although this was expected because summer Rotorua outlet flow has been controlled since the early 1970's. Because of this, summer Tarawera and Kaituna flows both decreased in relation to the Rangitaiki, although the FOREST variable was more important in the Tarawera model. The winter flow models reinforced the annual results, with Tarawera flow showing a significant ($p<0.05$) reduction due to FOREST in relation to both Kaituna (6.0 m^3/s) and Rangitaiki (8.0 m^3/s) flows. Winter Kaituna flow was not significantly reduced by FOREST in relation to Rangitaiki flow.

These analyses demonstrate that Tarawera River flow has decreased in relation to rainfall and the flow of two other local rivers with the most reliable model (annual Tarawera-Kaituna) indicating a 4.5 m^3/s decrease or 13% of mean flow for the calibration period. Although regression methods cannot establish the cause for the decrease in flow, the only reasonable cause for this decrease is afforestation of 250 km^2 of the Tarawera catchment.

Comparison With Other Studies

Study of a small catchment (Purukohukohu), about 50 km southwest of the area afforested in the Tarawera, showed that seven year old pine trees caused a 47% reduction in the annual yield of a catchment previously in pasture (Dons, 1981). If the Purukohukohu decrease is proportional to the area of the Tarawera catchment afforested, then the decrease in yield for the Tarawera would be 13%. Bosch and Hewlett (1982) in a review of 94 international catchment experiments, showed that afforestation by conifers (in catchments of 0.01-24 km^2) caused 40 mm change in water yield per 10% change in forest cover. Applying this to the Tarawera, a 3.2 m^3/s decrease in flow would be predicted. Calder and Newson (1979), in assessing the effect of upland afforestation of Britain's water resources, presented a nomograph for estimating the percentage reduction in flow due to afforestation of grassland. Applying their procedure to the Tarawera a 10% decrease in flow would be predicted. These estimates agree with the contention that afforestation has decreased Tarawera flows by about 4.5 m^3/s or 13%. Although some areas of initially taller vegetation were afforested in the Tarawera this effect was offset by the afforestation of wetter areas of the Tarawera catchment (Fig. 3).

CONCLUSIONS

Flow of the Tarawera River has decreased significantly between 1964 and 1981. Annual, summer and winter flows have shown similar reductions of 10.9 m^3/s, 11.4 m^3/s and 9.6 m^3/s, despite varying seasonal rainfall. Afforestation of 250 km^2 within the 906 km^2 catchment could account for 4.5 m^3/s of the decrease (or 13% of mean flow during the calibration period) with lower rainfall accounting for the remainder. The decrease is of a similar magnitude to results of a study of a nearby small catchment and international reviews. The decrease in flow has water management implications, not only for effluent assimilation in the lower Tarawera River, but also for any future afforestation of potentially water-short catchments.

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