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Simple estimation of the effects on runoff of afforestation under different rainfall regimes

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Abstract

The hydrological effects of changing catchment vegetation cover are well known, and rainfall to runoff models have been used to predict those effects. However, use of these models may be constrained by data availability and expertise. There is thus a need for planners to have access to simple, science-based models that can be used confidently to indicate the degree of hydrological change caused by conversions between forest and grassland. Published relationships between rainfall parameters and flow changes accompanying afforestation of grassland or forest clearance have normally provided relationships with large uncertainties. In this study we critically examine the data from New Zealand paired catchment afforestation studies, details of the degree of forest cover, control catchment conditions, and catchment similarity. This process resulted in some studies being discarded, and allowed the adjustment of runoff from studies with partial forest cover to provide a data set for estimating runoff differences from fully forested catchments. The relationship compares well with an existing empirical model developed using a global dataset implying that this model may be more generally used across New Zealand as there are so few local studies. This suggests that both approaches may be useful for planning in New Zealand.

Keywords

vegetation change, hydrological change, land cover

Introduction

Changing the vegetation cover of catchments has long been known (Bosch and Hewlett, 1982) to cause changes in the hydrological response of catchments. In catchments with summer soil water deficits in particular, there is often concern that increases in forest cover could reduce reliability of supply to abstractors or reduce the life supporting capacity of rivers and streams. Alternatively, reductions in forest cover could increase flows. Water yield changes are greatest in absolute value in high rainfall areas, but in percentage terms the greatest changes occur in low rainfall areas, where runoff can cease after afforestation (Scott and Lesch, 1997; Scott and Smith, 1997).

The methods for estimating these flow changes range from sophisticated process-based and semi-distributed hydrological models such as TopNet (Bandaragoda *et al.*, 2004) or MIKE SHE (Graham and Butts, 2005), through intermediate-complexity models such as WATYIELD (Fahey *et al.*, 2010), to simple percentage reductions (Duncan *et al.*, 2008). The more complex models require specialised knowledge to operate and access to data and databases, but can take into account spatial variations in climatic, geological, vegetation cover and soil parameters, whereas percentage reduction methods may not. Relationships between annual rainfall and runoff reduction appear too uncertain to be useful for predicting the hydrological effects of land-use change (Adams and Fowler, 2006). However, there is a need, for the purposes of planning, for a simple and defensible method for predicting the hydrological effects of land-use change, and in particular the effect of afforestation of short grassland or of forest removal.

Reviews of research about the effects of land-use change on hydrology have been carried out by Bosch and Hewlett (1982), Stednick (1996), Scott and Lesch (1997), Scott and Smith (1997), Fahey and Rowe (1992), Fahey (1994), Smakhtin (2001), Zhang *et al.* (2001), Farley *et al.* (2005), Adams and Fowler (2006), Brown *et al.* (2005), Lane *et al.* (2005), and others. These reviews support the conclusions of Bosch and Hewlett (1982) that reduction in forest cover increases annual water yield, and establishment of forest cover on short grassland and sparsely vegetated scrubland decreases annual water yield. When eucalyptus and coniferous forests, deciduous hardwoods, brush, tall tussock and pasture are altered they have, in that order, a decreasing influence on water yield.

Many authors (e.g., Farley *et al.* (2005), Adams and Fowler (2006)) have attempted to find simple relationships between rainfall statistics and absolute or percentage change in runoff. In most cases the relationships are too uncertain (Adams and Fowler, 2006) to be useful for the prediction of mean changes in flow statistics. Some of the uncertainly stems from using the data as published without taking into account the specifics of the studies, such as the amount of forest cover, as has been found in this study.

The first aim of this paper is to carefully examine predominantly paired catchment studies of afforestation of short grassland in New Zealand to see if accounting for the particular circumstances of the studies can yield relationships between rainfall and percentage changes in runoff that can be useful in predicting the hydrological effects of land-cover change. The second aim of the paper is to investigate the method of Zhang *et al.* (2001) to determine if it could be used to predict runoff change in New Zealand.

Table 1 – Catchment characteristics. Where there is more than one catchment in a study with the same cover, a range of areas is shown and the number of catchments is in parentheses.

Catchment	Catchment area (grassland) (km^2)	Catchment area (forest) (km^2)	Rainfall (mm/y)	Penman PET (mm/y)	Data source
Ashley	0.154	0.229	910	855	Jackson (1995)
Berwick	1.63-2.92 (2)	1.15-1.92 (2)	978/1040	787	Smith (1987)
Glendhu	2.18	3.10	1309	594	Fahey, Jackson (1997) Fahey pers.com.
Kakahu	4.55	2.75	874	605	Duncan (2000)
Moutere	0.04-0.07 (2)	0.043-0.077 (3)	1012	948	Duncan (1995)
Pakuratahi	7.95	3.45	1363	1018	Wood and Fahey (2006)
Purukohukohu	0.1	0.34	1357	907	Dons (1987)
Tarawera	906	906	1990	933	Dons (1986)

Examination of data sets for New Zealand paired catchments

Eight catchment experiments were considered for the present analysis (Fig. 1, Table 1). Each is examined to determine if the rainfall and runoff data are reliable, if the assumptions about the nature of the cover and its extent are correct, and whether the catchments in the pair are sufficiently alike to provide useful data for assessing the hydrological effects of land-use change. Runoff data from reliable data sets were then pro-rata adjusted to provide mean flow changes for a cover change from grassland to fully forested cover, as described in Hewlett and Hibbert (1961) and Rowe and Pearce (1994). Table 1 provides climate and cover characteristics of the catchment pairs. A range of areas is given for some data suites, as there is more than one catchment with that vegetation type. Annual rainfall data were estimated from catchment records for the periods of the studies. There are rainfall totals for both the pasture and forest catchments respectively for Berwick, as the catchments are about 5 km apart. The mean annual potential evapotranspiration (PET) was interpolated from NIWA's virtual climate network (Tait and Woods, 2006) for which PET is calculated using Penman (1963). The rainfall and Penman PET data are given to indicate the range of climatic conditions used for the study as an indication of the climates to which the study might apply.

Ashley

The Ashley forest catchment has ~100% forest cover, and each catchment of the pair has similar catchment characteristics (Jackson and Rowe, 1997). Annual runoff data are listed in Appendix A.

Berwick[1]

The Berwick catchment characteristics are similar, however the forested Jura and Storm catchments (F1 and F2 in Smith, 1987) had 88% and 79% forest cover respectively (NIWA National Hydrometric Database site initial comments[1]). Hence adjustments have to be made to the flows from the forested catchments for a valid comparison with other studies. There are two pasture and two forested catchments in this study. The annual data are from Smith (1987).

Glendhu

The Glendhu catchments characteristics are similar (Fahey and Jackson, 1997), but the Glendhu forested catchment is only 67% forest. Adjustments thus have to be made to the flows from the forest for a valid comparison with other studies. The other catchment of the pair has a cover of tall tussock. The annual data are listed in Appendix A.

Kakahu

Analyses of historical aerial photographs suggest a significant portion of the Kakahu grassland catchment is covered in scrub. The accuracy of the flow ratings, data gaps and weir maintenance issues for the Kakahu catchments raise questions about data quality (Duncan, 2000). From a hydrological perspective, both catchments have anomalously high runoff ratios. Consequently it was decided not to use this data set in this study to assess the effects of land-use change. Annual data are listed in Appendix A.

Moutere

The Moutere forest-covered catchments are fully forested and all the catchment characteristics are comparable (Duncan, 1995). The runoff data used here is the mean from two pasture and the mean from three forested catchments, which leads to reduced variability in the data set for this site as used in this study. The data are from Duncan (1995).

1 Data and comments available from NIWA on request: Kathy.Walter@niwa.co.nz

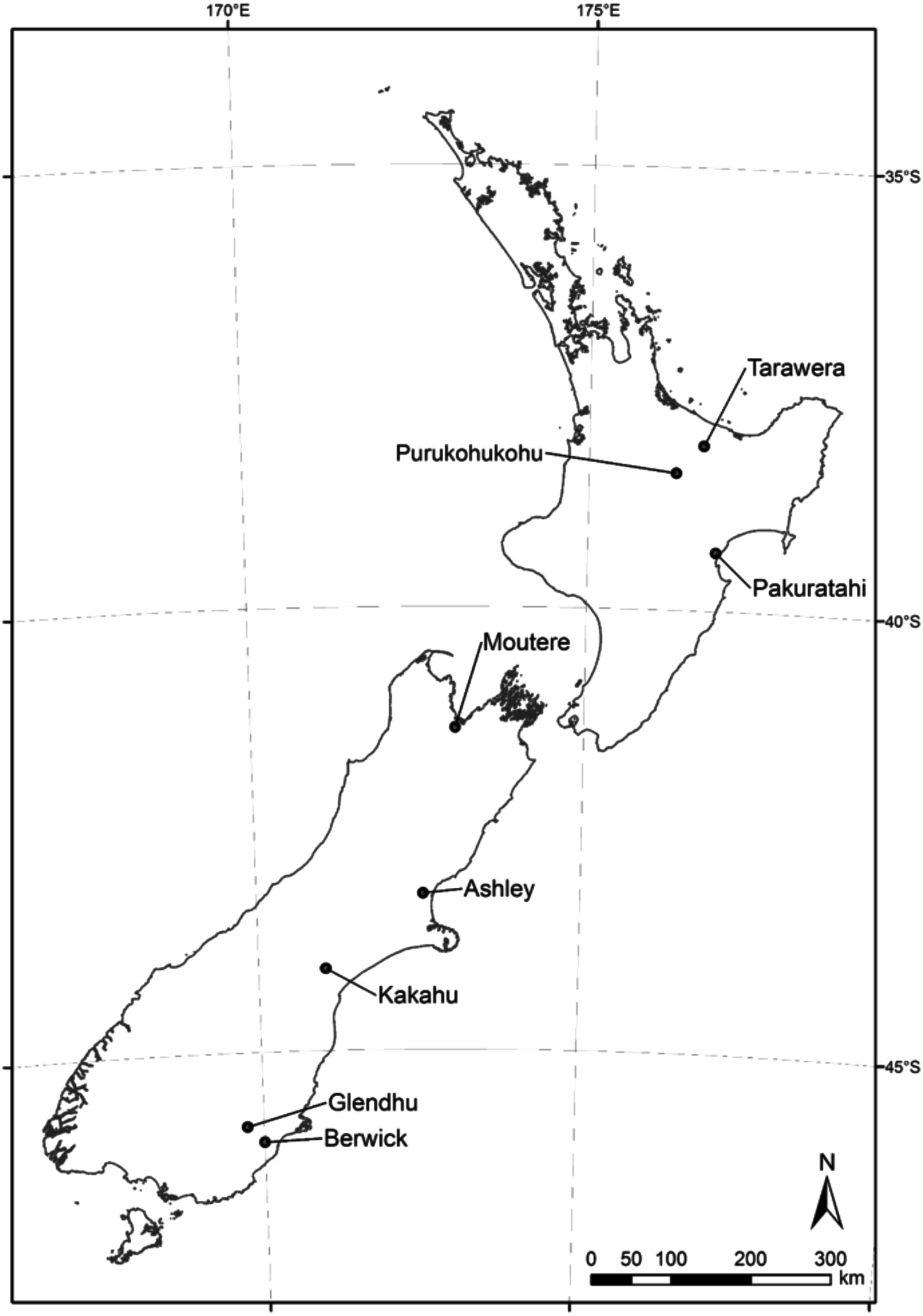

Figure 1 – Study site locations.

Pakuratahi and Tamingimingi

The forested Pakuratahi catchment has a consistently higher specific yield than the pasture-covered Tamingimingi catchment (Wood and Fahey, 2006), which is counter-intuitive. The higher specific yield from the Pakuratahi catchment is most apparent at lower flows and is probably caused by the presence of an area of high-yielding Kawaka Formation limestone in the upper catchment. While the Pakuratahi is fully forested, the data set as a whole should not be used to assess the effects of land-use change in this study because of the differences in geology between the catchments and its effect on water yield. Annual data are listed in Appendix A.

Purukohukohu

The Purukohukohu forest catchment is fully forested. While the pumice lithology may mean that the hydrological catchment boundary is not equivalent to the topographical catchment boundary (Dons, 1987), the data set is acceptable for land-cover hydrological analysis (Rowe, 2003). Annual data are listed in Appendix A.

Tarawera

The Tarawera study (Dons, 1986) did not use paired catchments, but instead examined catchment hydrology of the 906 km^2 Tarawera catchment before and after afforestation. The results are consistent with those from small paired catchment studies elsewhere in New Zealand, even though some hydrological processes may be different at this scale. In addition, it allows the New Zealand data set to be extended to a higher rainfall climate and to catchments with larger areas. Catchment rainfall of 1990 mm yr^{-1} was obtained from Water Resources Explorer New Zealand (http://wrenz.niwa.co.nz/webmodel) and is consistent with isohyetal values in Dons (1986).

Data analysis

The data used in the present analysis are the annual averages from each study (Table 2) for a period when there is full forest canopy cover, and in some cases those annual values are also averages from catchments with the same cover (e.g., Moutere has two pasture and three forest catchments and the Berwick study has two catchments of each cover type). Where possible, data has been taken from journal publications; data from informal publications, analysed from the NIWA Hydrometric Data Base or obtained from individuals is listed in APPENDIX A and source cited. Runoff change is simply the difference between runoff from a pasture and a nearby forest catchment. This assumes the catchments are otherwise hydrologically similar. Paired catchments are rarely identical, and commonly pre-treatment calibration equations are used to derive flow changes. There is uncertainty associated with this calibration approach and so for this study, which proposes simple methods, the simple difference between runoff from pasture and forest was used. The lower portion of Table 2 has runoff from the partially forested catchments scaled according to forest cover, so that each value corresponds to an effective coverage of 100%, thus allowing direct comparison across sites. For example:

(Forest runoff for 100% forest cover) =
(Forest runoff for x% cover) * (x/100).

Pasture and forest evapotranspiration (ET) in Table 2 are unknowns and were obtained using a simple water balance equation ($P = Q + ET$). As the data are long-term averages, net changes in soil water are assumed to be zero, as is drainage to deep groundwater. The latter assumption is close to reality, except for Purukohukohu, where losses to deep ground water in the pumice regolith might be expected.

Dons (1986) demonstrates that discharge is reduced by 4.5 m^3s^{-1} as a result of 28%

Table 2 – Water balance data for the New Zealand paired catchment data sets.

Catchment	Rainfall mm/y	Pasture runoff (mm/y)	Pasture ET (mm/y)	Forest runoff (mm/y)	Forest ET (mm/y)	Reduction (mm/y)	Reduction %	Forest fraction
Ashley	910	146	764	60	850	86	59	1
Berwick	1,009†	365	644	212	797	153	42	0.83
Glendhu	1,329	831	498	558	771	273	33	0.67
Kakahu	874	314	560	198	676	116	37	1
Moutere	1,012	211	801	71	941	140	66	1
Pakuratahi	1,363	504	859	451	912	53	11	1
Purukohukohu	1,357	468	889	224	1,133	245	52	1
Tarawera	1,990	1,205	785	1,048	942	157	13	0.28
With 100% forest								
Berwick	1,009	365	644	181	828	184	51	1
Glendhu	1,329	831	498	424	905	407	54	1
Tarawera	1,990	1,205	785	639	1,351	566	47	1

† The average rainfall for the two catchment groups is used here and in Figures 2-4

afforestation with pines. This corresponds to a flow reduction of 16.1 m^3s^{-1} (i.e., 46.4% of mean annual flow) for 100% afforestation (Table 2).

Figure 2 shows mean runoff reduction percentages when mature forest replaces grassland for all New Zealand paired catchments, irrespective of the percentage cover. Kakahu and Pukuratahi appear to behave differently for reasons outlined above and are plotted separately. Analysis of the change in water yield indicates a general

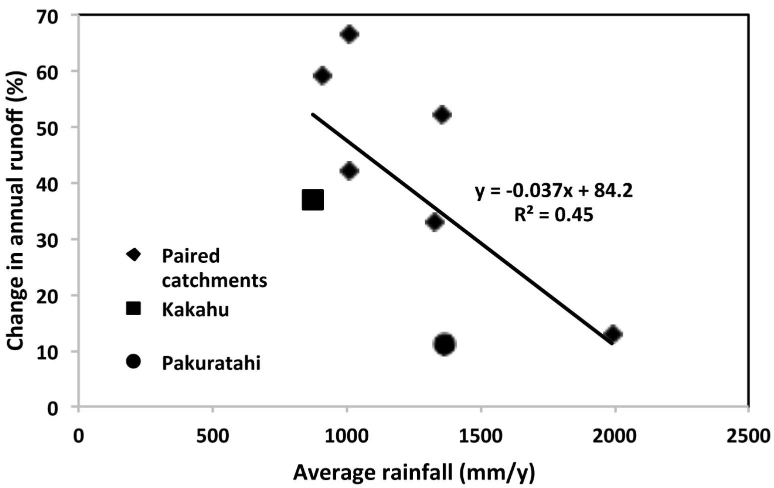

Figure 2 – Mean flow runoff reduction percentage for New Zealand paired land-use change catchments as published. The linear relationship is for all data.

decline in percent runoff change with increasing annual rainfall, though the data as presented do not suggest a close relationship.

A censored dataset can be obtained by discounting paired catchments that are not hydrologically similar or where the cover or data quality is in doubt, and normalising percentage change in runoff to full afforestation land cover (Fig. 3). Analysis of the censored dataset indicates the scatter of the data has been largely reduced. This relationship more readily provides guidance on the effect on mean flow of afforestation or deforestation across rainfall zones and spatial scales. The relationship is based on data from studies with mean annual rainfalls from 910 to 1990 mm and is applicable over this range. When annual rainfall reduces to less than about 700 mm, annual evapotranspiration and rainfall are similar regardless of vegetation cover and runoff will be minimal. This was the case in the Ashley catchment in 1982, when there was an annual rainfall of 630 mm and no annual runoff from the pasture catchment and only 2 mm from the pines catchment (Appendix 1). Thus the relationship developed here should not be used where the annual rainfall is less than 900 mm.

A comparison of Figures 2 and 3 shows that attention to the details of degree of forest cover, control catchment condition and catchment similarity can provide a much more useful data set. The exclusion of the Kakahu data set on the basis of water balance alone is arguable, but the doubt over the nature of the catchment cover of the 'pasture' catchment and record quality provide further reasons to exclude the set.

In addition to developing a censored data set for land-cover hydrological change, we can also compare the results to empirical modelling based on a worldwide data set. Following analysis of 250 catchments located across the world, Zhang *et al.* (2001) demonstrated a relationship between the long-term precipitation and evapotranspiration for both forest and short grass. These relationships were used to develop a simple model using only mean annual rainfall to assess the long-term average effect of vegetation changes on catchment evapotranspiration.

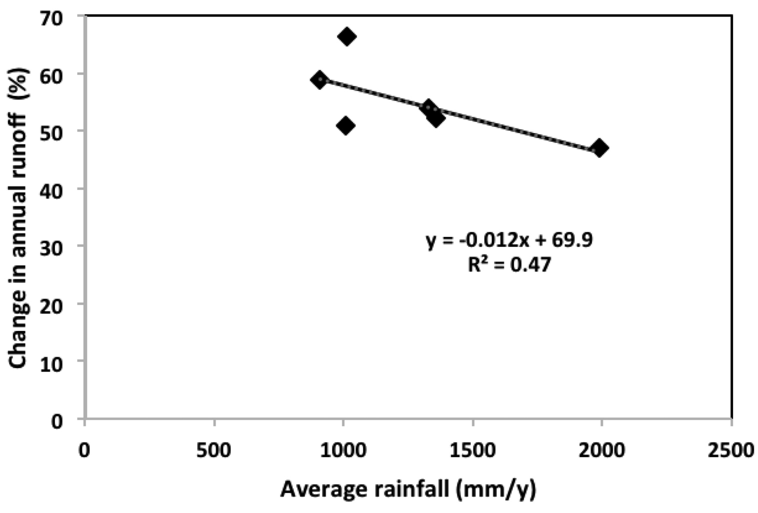

Figure 3 – Mean flow runoff reduction percentage for New Zealand paired land-use change catchments for the censored data set where water yield has been adjusted for 100% forest coverage.

$$ET = \left(f \frac{1 + w\frac{E_z}{P}}{1 + w\frac{E_z}{P} + \frac{P}{E_z}} + (1-f)\frac{1 + w\frac{E_z}{P}}{1 + w\frac{E_z}{P} + \frac{P}{E_z}} \right) P$$

where ET = annual average evapotranspiration,
E_z = potential evapotranspiration (1410 mm for forest, 1100 mm for grassland),
P = annual average rainfall,
f = the fraction of forest cover,
w = plant available water coefficient (2 for forest, 0.5 for grassland).

The model is a function of the fraction of forest cover *(f)* and of the plant available water coefficient *(w)* that represents the relative difference in the way plants use soil water for transpiration. Zhang *et al.* (2001) interpret this as mainly taking into account differences in root zone depth. There is no guidance in Zhang *et al.* (2001) for the values of E_z and w that might be used for tall tussock grassland, but they note that differences in albedo and aerodynamic resistance between grassland and forest might be responsible for the differences in E_z. A comparison with the censored dataset is provided in Figure 4.

Given mean annual observed precipitation and the evaporation estimates from Zhang *et al.* (2001), average annual runoff can be calculated by simple water balance, as was done for the data in Table 2, assuming no change in soil water or drainage losses to deep groundwater. By using different proportions of forest cover, the hydrological effect of cover changes (expressed as change of annual runoff) can be estimated. If there is reliable information about mean catchment rainfall and runoff for

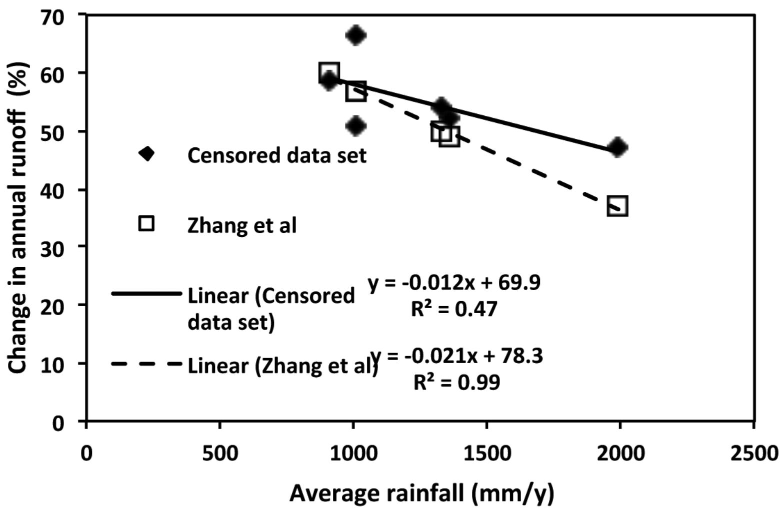

Figure 4 – Mean flow runoff reduction percentage for New Zealand paired land-use change catchments for the censored data set normalised for full afforestation and using water balance where evapotranspiration has been estimated using Zhang *et al.* (2001).

Table 3 – Water balance data for the New Zealand catchment data sets estimated using annual rainfall and the method of Zhang *et al.* (2001).

Catchment	Rainfall mm/y	Pasture runoff (mm/y)	Pasture ET (mm/y)	Forest runoff (mm/y)	Forest ET (mm/y)	Reduction (mm/y)	Reduction %	Forest fraction
Ashley	910	310	600	124	786	186	60	1
Berwick	1,009†	376	633	197	812	179	48	0.83
Glendhu	1,329	612	717	409	920	203	33	0.67
Kakahu	874	287	587	112	762	175	61	1
Moutere	1,012	378	634	161	851	217	57	1
Pakuratahi	1,363	639	724	326	1,037	313	49	1
Purukohukohu	1,357	634	723	323	1,034	311	49	1
Tarawera	1,990	1,167	823	1,045	945	122	10	0.28
With 100% forest								
Berwick	1,009	376	633	160	849	216	57	1
Glendhu	1,329	612	717	308	1,021	304	50	1
Tarawera	1,990	1,167	823	734	1,256	433	37	1

† The average rainfall from the two catchment groups is used in this table and Figures 2-4.

a catchment with a known proportion of forest cover, the plant available water coefficient can be manipulated to achieve a water balance to give more reliable estimates of the effect of land-use change for that catchment, rather than relying on the general relationship.

The Zhang *et al.* (2001) method was tested using mean annual rainfall data from the censored data set (Table 1) and standard values of E_Z and w. The results are shown in Table 3 and depicted in Figure 4.

Applying the general relationship from Zhang *et al.* (2001) to the New Zealand data set gives similar results, as percentage changes in runoff, to the limited censored data set. This lends confidence to results from the censored data set. If there are catchments in the region of interest for which annual rainfall and runoff and fraction of forest cover are known, the Zhang *et al.* (2001) method may be used to adapt the results to local climate and soil conditions.

Discussion

The results of this analysis illustrate the role of rainfall regimes in regulating the effect of land-cover change on catchment hydrology, but also of the benefit in censoring the experimental data in order to better isolate the direct effects of land cover. The close correspondence with the Zhang *et al.* (2001) model, and hence with the worldwide data on which it is based, further supports the analysis of New Zealand data. However, it is also important to appreciate the uncertainties and limitations associated with these results.

When studies of land-cover hydrology are conducted, a common challenge is often in isolating the direct effects of land cover from confounding effects of geology, soil, climate and other factors. The analysis here has endeavoured to achieve this as far as possible based on information presented in the original studies, by producing a censored data set. In this limited study of New Zealand data, we have attempted to take into account the degree of afforestation, the nature of the land cover on the control catchment, and similarity of the catchment pair. In small (< 2 km^2) catchments, a pro-rata increase to the flow reduction to estimate flows from 100% forest cover, when there is already a predominant forest cover, is unlikely to result in unacceptable errors in the resulting runoff. However, in a large catchment such as the Tarawera River catchment, the issue is more problematic as the remainder of the catchment may have different climate, soil and morphology from the forested area. Nevertheless, to allow a valid comparison of the catchments, a uniform degree of catchment cover is required. We recognise that often catchments will not be fully forested, but that could be taken into account by a pro-rata reduction in the forest effect once the effect of a full catchment cover is predicted, or by using the Zhang *et al.* (2001) approach where the fraction of forest cover can be specified.

There are only a few New Zealand studies where pasture or pasture-like vegetation has been replaced by plantation forest. This small sample size decreases the reliance than can be placed on the validity of the percentage change in runoff relationship, and the removal of one case can have a significant effect of the relationship. It is because of this sensitivity that the method of Zhang *et al.* (2001) has been applied to introduce more credibility to the annual rainfall vs. percentage change in runoff relationship.

The grassland at Glendhu is not pasture, but tall tussock grassland; it has a higher aerodynamic roughness than pasture and might be expected on that basis to have a higher evaporative loss than pasture. However, the stomata are on the inside of the leaves, which are rolled to prevent water loss by transpiration. The climate there also has many rain days (Fahey and Jackson, 1997) that tend to reduce evaporative losses. The overall effect is for both the tussock and forest to have lower evaporative losses than might be expected (Table 2) and the percentage change in flow associated with the afforestation of the tall tussock grassland does not appear to be anomalous; this has allowed the data to be included in the study.

The area of the Tarawera catchment that was afforested was originally 60%, poor, scattered light scrub and 40% low-stature native bush (Dons, 1986) that would have had a low interception capacity compared to mature pines and probably a low transpiration rate. In this study we are assuming that the combined interception and transpiration of the original vegetation would have been similar to the more vigorous pasture cover of the other experiments.

Comparing the empirical model proposed above to more physically based models already in use in New Zealand, a range of strengths and weaknesses can be seen. The present model uses minimal data and is quick and easy to use. However, physically based models such as WATYIELD (Fahey *et al.*, 2010) and TopNet (Bandaragoda *et al.*, 2004) are expensive to set up and require a large amount of climatic, pedological and geomorphological information and associated parameterised characteristics (e.g., digital elevation model, rainfall at daily or sub-daily time steps, rainfall interception, evapotranspiration, crop transpiration coefficient, total and readily available water in the root zone, base-flow index, base-flow recession coefficient, and a flow record, if the model is to be calibrated). However, the empirical model is incapable of modelling the effects of land-cover change on flow variability, including floods and low flows, for which physically-based, time-stepping models are better suited. Furthermore, the present model considers only mean annual precipitation as the climate driver, and not the complexities of seasonality, inter-annual variability, and potential evapotranspiration, which are again better represented with physically based models. The present model is thus most useful for indicative assessments of catchment water yield where data are limited, or where more complex modelling is either technically or financially unattainable. In New Zealand, rainfall is well distributed throughout the year, with a tendency for higher monthly totals in summer in the south and higher winter totals in central to northern New Zealand, without there being a strong seasonal component. However, potential evapotranspiration has a very seasonal signal that commonly results in a seasonal soil moisture deficit. Most of the sites in this study have a summer soil moisture deficit, and the effect of this is reflected in the data and is one of the reasons that there is a greater effect of afforestation on runoff from sites with lower rainfall.

Comparing the proposed relationship to the established model by Zhang *et al.* (2001) the method of Zhang *et al.* (2001) appears to offer a more sophisticated and more scientifically justifiable method of estimating the effect of afforestation of grassland for planning purposes than using a simple percentage reduction. The method takes into account average annual rainfall, the different evaporative loses from grassland and forest, plant available water (mainly the different rooting depths of grassland and forest), and current amounts of afforestation, and it can be adjusted to the specific soil and climate conditions of a catchment.

However, the relationships between annual rainfall and proportional runoff change when forest replaces short grassland derived from the censored data set and using the approach of Zhang *et al.* (2001) are very similar and are not substantially different. Both relationships appear suitable for use for planning by those with limited hydrological expertise. Both require an estimate of mean annual rainfall that can be obtained from suitably located rain gauges or by using Water Resources Explorer New Zealand (http://wrenz.niwa.co.nz/webmodel). The advantage of Zhang *et al.* (2001) is that the plant available water coefficient of the cover can be adjusted to achieve a water balance where catchment annual rainfall, runoff and proportion of forest cover are known. This allows the relationship to be adjusted for local soil depths, climate and other conditions. If those factors are known for the catchment in question, then the Zhang *et al.* (2001) method should be used because it is more scientifically based than the empirical relationship.

Adams and Fowler (2006) concluded, based on their analysis of New Zealand land-use change experiments, that the relative effects of afforestation and deforestation were statistically indistinguishable. So while the New Zealand data analysed here are from afforestation experiments, the methods could also be used to determine the effects of deforestation.

Both analyses give similar percentage changes in flow, and provided there are measurements of flow from nearby forest or pasture catchments, estimations of the effects of cover change should be sufficiently accurate for planning purposes. However, if the data are expressed as absolute changes in flow, then the flows and flow differences predicted by Zhang *et al.* (2001) can differ from measured values. This is primarily because Zhang is using a general relationship, modified by annual rainfall to estimate evapotranspiration, whereas the catchments are responding to the local climate, geology, aspect, slope and soils.

Conclusions

Published rainfall and runoff data from New Zealand paired catchments and land-use change experiments were critically examined to develop a relationship between mean annual rainfall and a reduction in catchment water yield associated with complete grass-forest conversion. Some data sets were discarded either because the catchment characteristics of each member of a 'pair' were too different or because of questionable data quality. Of the remaining studies, runoff measurements from partially forested catchments were scaled linearly to give estimates of runoff from fully forested catchments. The combined censoring and adjustments reduced the large scatter in the relationship between mean annual rainfall and percentage runoff change. This gives a relationship more amenable for planning and water management purposes, where the objective is to predict the effects of changes in forest cover on mean water yield, often with limited data or technical capacity. The results agreed well with the model of Zhang *et al.* (2001), based on 250 studies worldwide, lending support to the Zhang model for more general use across New Zealand, in light of the paucity of local studies.

Acknowledgements

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Appendix A

Table A1 – Annual rainfall and runoff for the Ashley catchments (Jackson and Rowe, 1997). Data for 1982 was not used as there was no runoff from the pasture catchment.

Year	Rainfall (mm/y)	Pasture runoff (mm/y)	Pines runoff (mm/y)
1981	770	122	32
1982	630	0	2
1983	930	157	79
1984	1110	180	89
1985	830	123	40
1986	1260	499	398

Table A2 – Annual rainfall and runoff data for the Glendhu Catchments for the period of full canopy cover (Dr B.D. Fahey, Landcare Research, 16-07-2013).

Year	Rainfall (mm/y)	Tussock runoff (mm/y)	Pines runoff (mm/y)
1991	1320	890	633
1992	1445	1054	800
1993	1401	919	689
1994	1322	959	686
1995	1388	927	656
1996	1304	839	588
1997	1413	953	677
1998	1116	600	431
1999	1088	583	385
2000	1462	851	585
2001	1190	709	461
2002	1316	907	568
2003	1020	628	392
2004	1546	946	535
2005	1274	808	639
2006	1571	913	604
2007	1180	847	480
2008	1311	761	471
2009	1175	695	414
2010	1511	814	474
2011	1431	871	565
2012	1448	817	552

Table A3 – Annual rainfall and runoff for the Kakahu catchments (Duncan, 2000).

Year	Rainfall (mm/y)	Pasture runoff (mm/y)	Pines runoff (mm/y)
1996	422	269	279
1997	620	360	266
1998	649	167	86
1999	700	414	243

Table A4 – Annual rainfall and runoff for the Pakuratahi catchments. Data from 1995-1997 is from Wood and Fahey (2006) and from 2008-2011 from Dr B.D. Fahey, Landcare Research (pers. comm.) The forest was harvested in 1998 and the canopy was closed by 2008 (Dr B.D. Fahey, Landcare Research, pers. comm.).

Year	Rainfall (mm/y)	Pasture runoff (mm/y)	Pines runoff (mm/y)
1995	1134	283	276
1996	1302	428	388
1997	1431	526	497
2008	1043	444	393
2009	1235	369	375
2010	1702	746	583
2011	1696	734	644

Table A5 – Annual rainfall and runoff for the Purukohukohu catchments. Data from the NIWA National Hydrometric Database.

Year	Rainfall (mm/y)	Pasture runoff (mm/y)	Pines runoff (mm/y)
1982	1254	394	153
1983	1394	571	275
1984	1414	426	223
1985	1245	372	187
1986	1372	631	293
1987	1462	416	211

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