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The relationship between throughfall, stemflow, and rainfall in a northern New Zealand native forest headwater catchment

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Abstract

Results are presented for a 14-month multi-site throughfall study at Huapai Experimental Catchment, a small native forest headwater catchment near Auckland, New Zealand. Six sites under different vegetation types were instrumented with throughfall troughs and the results empirically related to gross rainfall recorded outside the forest. Relationships between throughfall and gross rainfall, derived for daily data, explain 87-98% of the variance, and are even stronger using non-linear regression on rainfall-event data. Relationships are clearly non-linear in most cases, with evident potential for systematic bias in the derived relationship if a linear model is used for predictive purposes. The throughfall results were combined with an earlier stemflow study at the same location and an additional small stemflow study at one of the six throughfall sites in order to derive non-linear empirical relationships between effective and gross rainfall at each of the six throughfall sites, plus a composite catchment relationship. The key finding is that, although the basic form of the relationship is consistent across vegetation types, there is substantial variability in the magnitude of effective rainfall over distances of a few tens of metres.

Keywords

throughfall; stemflow; interception; catchment hydrology

Introduction

Interception is a significant component of the water balance of most vegetated surfaces, especially in the case of forests, where it can account for 35-75% of total evaporation (McNaughton and Jarvis, 1983). Rutter (1975) reported annual interception losses in the range 15-40% and 10-25% of gross annual rainfall for coniferous and deciduous forests, respectively, while results tabulated by Levia and Frost (2006) for more diverse wooded ecosystems have an even wider spread (<10% - >70%).

A multitude of vegetation and climatic factors interact to determine forest interception 'loss' (Chang, 2006; Muzylo *et al.*, 2009). Vegetation factors include albedo, aerodynamic roughness, leaf area index, leaf architecture, and canopy structure. Climate factors relate to water availability and evaporative demand. The former includes the type of precipitation (e.g., fog, snow, rain), its seasonality, and the frequency and intensity of precipitation events. Evaporative demand includes seasonally-varying evaporative conditions (e.g., windiness, air temperature, humidity, radiation), both between and within storms. However, despite the number of factors affecting interception, there is usually a close relationship between rainfall and interception, to the extent that, for many practical applications, local interception loss can reasonably be empirically derived from local rainfall data alone (Zinke, 1967). Some authors have gone further, suggesting that generalised relationships can be derived based on forest type – such as the composite envelopes for hardwood and coniferous forests presented by Dunne and Leopold (1978). Others (e.g., Muzylo *et al*., 2009) have cautioned that transferring empirical relationships is fraught.

Empirical results for 12 New Zealand forest/scrub interception studies were reviewed by Blake (1975). Half of the studies were for scrub (mostly gorse and manuka) and three of the six forest studies were for radiata pine. Linear relationships between daily gross rainfall and interception, throughfall, and stemflow mostly yielded correlation coefficients larger than 0.9, with more than 90% of the variance explained for 15 of the 25 regression equations cited, although the author acknowledged that a curvilinear model may be more appropriate. A more recent review by Rowe *et al.* (2002) summarised empirical results for throughfall studies under radiata pine (17 experiments), Douglas fir (five), native forest (nine, including seven under beech), manuka/kanuka scrub (three), and gorse scrub (four). They also reported results for ten New Zealand stemflow studies. Similarly to Blake (1975), Rowe *et al.* (2002) summarised the empirical throughfall and stemflow results using linear regression equations.

The Rowe *et al.* (2002) review suggests there has been a focus on understanding the water balance implications of exotic plantation forestry (radiata pine, Douglas fir) in New Zealand. Native forest has received rather less research attention, and the limited work completed has focused on beech forests. Also apparent from the Rowe *et al.* (2002) study is a second research gap related to comparative studies, where measurements are made in different stands at the same time (i.e., holding climate constant). They report only one such New Zealand throughfall study – the Canterbury Plains radiata pine vs. Douglas fir study of Fahey *et al.* (2001).

A previously unpublished study that contributes to both of the research gaps noted above was undertaken in 1987-88, as part of a climate change impact assessment on water resources in the Auckland region (Fowler, 1992; 1999). Throughfall was monitored over a 14-month period at multiple sites under diverse native forest vegetation, in order to develop and parameterise an empirical interception function in a daily water balance model, which was then used to undertake multi-decadal modelling of a native forest catchment. Here the Fowler (1992) data are revisited to investigate the linearity (or otherwise) of empirical relationships between rainfall and throughfall, and the variability of those relationships over spatial scales of tens of metres.

Study site

The study area is located within Huapai Scientific Reserve (Fig. 1) in Auckland, New Zealand. The southwest side of the reserve, bounded by Hinau Road, follows the crest of a spur. The northwest boundary is within native forest and the northeast and southeast boundaries are against open farm land. Both southern boundaries follow the crest of the spur. Gentle slopes extend to the northeast and north about 50 m into the forest. Ridges and gullies descend north and east from this plateau, descending about 40 m over a distance of 150 m. Ridge tops are rounded but valley sides exceed 30 degrees in places. The soil is Orthic granular (Hewitt, 1993).

The most easterly of the three headwater catchments shown in Figure 1 is the 13,020 m^2 'Huapai Experimental Catchment'. Reed (1984) described the vegetation and examined the cycling of nutrients within the catchment and Sangster (1986) examined throughfall and stemflow. Figure 2 is a composite of Sangster's (1986) survey of

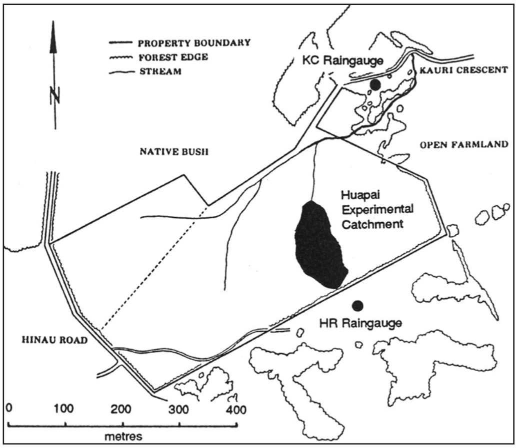

Figure 1 – Huapai Scientific Reserve, showing the immediate surroundings, Huapai Experimental Catchment, and two automatic raingauge sites: Kauri Crescent (KC) and Hinau Road (HR). Adapted from Thomas and Ogden (1983).

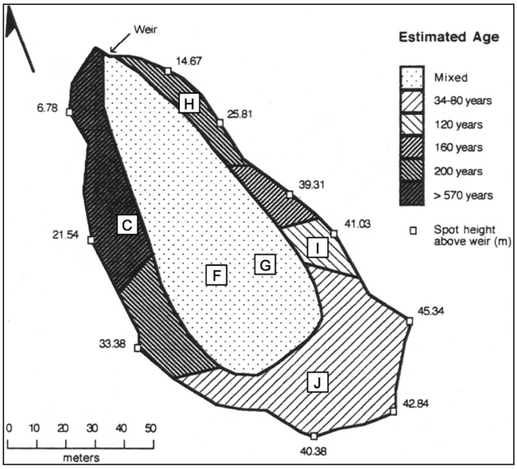

Figure 2 – Huapai Experimental Catchment. Catchment boundaries with selected spot heights are from Sangster (1986) and tree-ring-derived vegetation age classes are from Reed (1984). Large squares show the six throughfall monitoring sites (sites labels relate to the nearest neutron probe access tube, not used here).

the catchment and the vegetation age classes identified by Reed (1984). All areas identified with a vegetation age of 120 years and older are dominated by kauri (*Agathis australis*).

The kauri-dominated western ridge of the experimental catchment has several large kauri (greater than one metre diameter at breast height (DBH)), some with ages over 500 years (Fowler and Boswijk, 2001). The eastern ridge is also kauri-dominated. There are five trees larger than 1 m DBH, but most are within the range 0.3–0.7 m. There is also a stand of juvenile kauri undergoing density-dependent thinning. Away from the kauri-dominated areas, canopy trees are diverse, with puriri (*Vitex lucens*), taraire (*Beilschmiedia tarairi*), rewarewa (*Knightia excelsa*), tanekaha (*Phyllocladus trichomanoides*), totara (*Podocarpus totara*), and rimu (*Dacrydium cupressinum*) most common (Thomas and Ogden, 1983). The lower slopes and gully have a valley-bottom vegetation, dominated by tree ferns, nikau palms (*Rhopalostylis sapida*), and cabbage trees (*Cordyline australis*), with dense tangles of supple-jack (*Rhipogonum scandens*) in places and a few large canopy trees, including puriri and kahikatea (*Dacrycarpus dacrydioides*). The original kauri-dominated forest was not logged and remains relatively undisturbed, apart from edge effects, possum browsing impacts, and ephemeral rooting damage caused by escaped domestic pigs on at least two occasions. The exception is the kanuka (*Leptospermum ericoides*) scrub-dominated south-eastern margin of the catchment, where a fire in 1950 destroyed most of the original vegetation. The under-storey in this area is diverse, containing most of the canopy trees present elsewhere in the catchment, with mamangi (*Coprosma arborea*), tanekaha, rimu, and kauri most common.

Data and methods

Rainfall

A 200 mm diameter Stevens tipping-bucket raingauge (Model TB100-01), attached to a punched tape recorder and solid-state timer, was installed at the end of Kauri Crescent (Fig. 1) on 1 May 1986. The design capacity of the tipping bucket was 0.2 mm and the time increment on the punched tape recorder was set to five minutes. A four-inch (101.6 mm) diameter Nylex-1000 volumetric raingauge was installed adjacent to the automatic raingauge. Both raingauges were positioned with collecting rims 450 mm above a grass surface and were operational continuously until 27 February 1989. A similarly instrumented rainfall recording site was installed in open pasture at the southeast end of the catchment (Fig. 1), as a backup to the Kauri Crescent raingauge and to test for a possible rainfall gradient across the catchment. An unbroken 49-week record was obtained at this site (11 June 1987 to 23 May 1988). The Nylex-1000 raingauge catches were recorded and the gauges emptied on each site visit (usually weekly or twice-weekly during the study period).

Hourly and daily (midnight-midnight) rainfall time series were derived from the punched tapes by summing bucket tips within each hour and multiplying by the rainfall amount per tip. Using the design 0.2 mm per tip resulted in under-measurement of low-intensity and intermittent events, due to evaporation of water from the tipping buckets. The rainfall amount per bucket tip was therefore derived from the Nylex-1000 check raingauges by dividing the total catch by the number of bucket tips between site visits.

Figure 3 shows the strong correlation (R^2 = 0.989) between daily rainfall recorded at the two raingauge sites (KC, HR). Rainfall summed over all 304 common days (excluding 33 days of missing data at Site KC) totalled 1195.2 and 1204.7 mm for sites KC and HR, respectively; a difference of 0.8%.

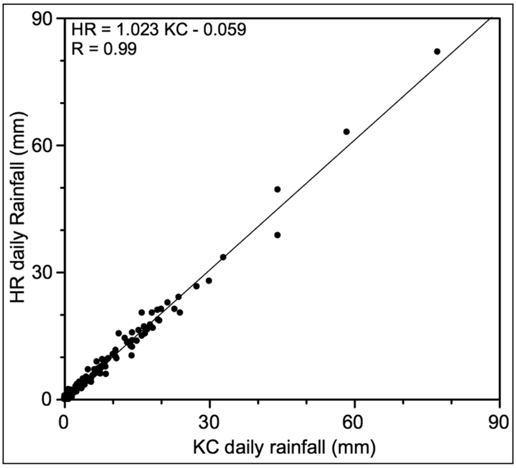

Figure 3 – Inter-comparison of Kauri Crescent (KC) and Hinau Road (HR) daily rainfall. The linear regression line and equation are shown.

Throughfall

Each throughfall site consisted of three 5 m lengths of 110 mm wide PVC guttering attached to wooden posts and radiating out from a levelled 200 litre drum (Fig. 4). A Stevens F-type chart recorder was positioned over the drum to continuously monitor water level. Eight-day gearing on the chart recorder gave a pen speed of approximately 1.2 mm per hour. One-to-one vertical gearing, the dimensions of the 200 litre drum, and a total collecting area of approximately 1.65 m^2, gave a recording sensitivity of about 6.3 mm chart-pen movement for each millimetre of throughfall.

Figure 4 – Throughfall Site C, viewed from the south.

To characterise the rainfall-throughfall relationship for the catchment as a whole, six throughfall measurement sites were scattered through the catchment (Fig. 2), following the vegetation typing of Reed (1984). Site topographic and vegetation details are summarised in Table 1. Throughfall Sites F and J were installed on 6 April 1987 and all six sets of instrumentation were in place by 28 May 1987.

Throughfall data collection was at least weekly for the duration of the throughfall experiment, with more frequent visits following major rainfall events (to empty collection drums). The data collection programme continued until 23 May 1988, except for Site I, which was disabled by a tree fall on 9 March 1988.

Figure 5 shows operational periods for each throughfall site. Apart from the variable installation dates, missing data were primarily due to failure of the chart recorders. One recorder was out of action for extended periods, necessitating rotation of the remaining five to ensure reasonable coverage. Other missing data periods relate to missing or incomplete traces caused by: collection drum overflow; the pen running off the end of the chart; other equipment failures; site interference; and possums drowning in the drums (three occurrences).

Figure 6 shows a typical chart of three weekly throughfall traces for Site C over the period 18 February to 9 March 1988. Steps in the traces represent recorded throughfall and the steepness of the rise indicates intensity. Flat trace sections separate events and rounded corners represent water drainage from the canopy (and instrumental inertia). The larger step in Trace C0218 is

Table 1 – Topographic position and vegetation characteristics of the six throughfall monitoring sites. 'DBH' refers to tree diameter at breast height. Age estimates are for the time of the interception study in 1987-88.

Site	Position	Vegetation
C	West ridge crest	Mature kauri canopy (ca. 600 years). Site completely covered by the crown of one tree. Forest open under the kauri crown with no trees above 0.2 m DBH over the site.
F	Valley bottom	Mixed broadleaf gully vegetation. Some large nikau palms, tree ferns, and dense supplejack.
G	Eastern mid-slope	Nikau palm and tree fern canopy. Fern and supplejack undergrowth.
H	East ridge crest	Even-aged mature kauri canopy (ca. 200 years). Tree fern sub-canopy. Minimal undergrowth.
I	East ridge crest	Even-aged juvenile kauri canopy (ca. 120 years). Mostly under 0.3 m DBH. Clear evidence of density-dependent thinning. Few other species present except for isolated kanuka, probably remnants of the original 'nursery' vegetation. No undergrowth.
J	Southern plateau	Regenerating forest after a fire in 1950. Mixed juvenile broadleaf species mostly under 0.2 m DBH. A few large kanuka, but none are over the throughfall instrumentation.

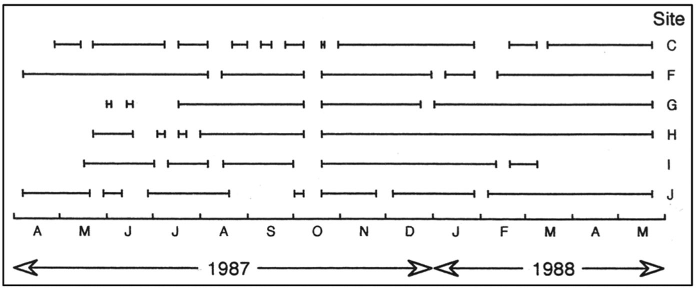

Figure 5 – Operational periods by site for the throughfall study.

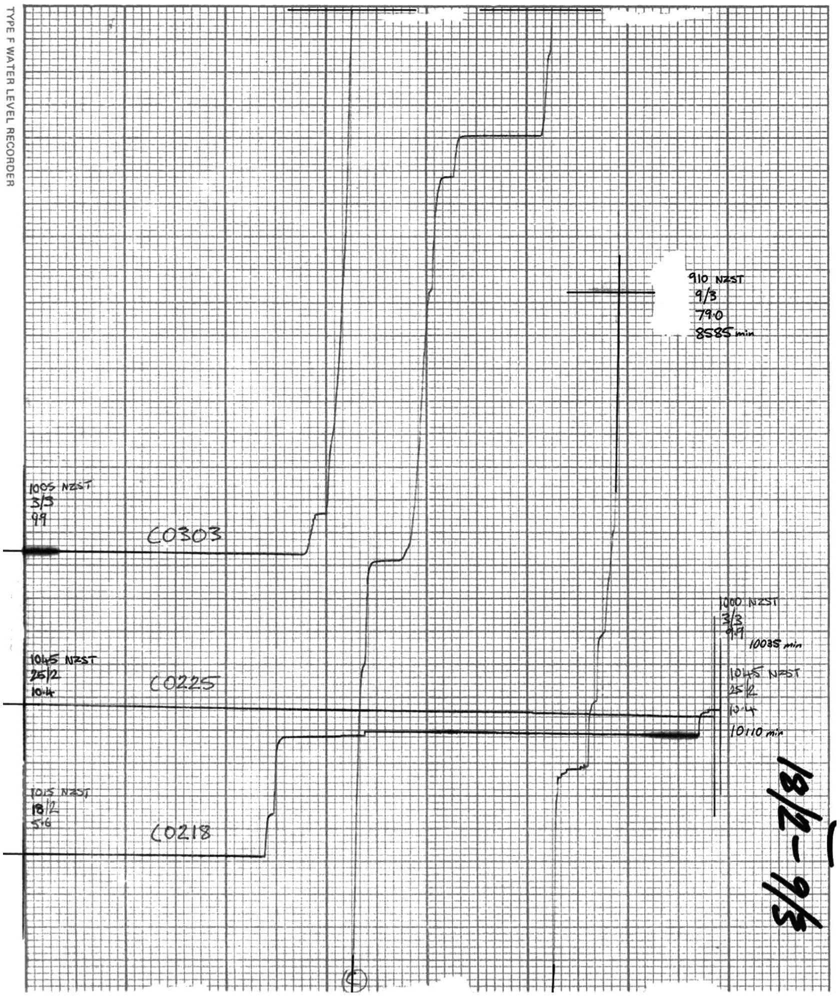

Figure 6 – Example throughfall chart (Site C, 18 February 1988 to 9 March 1988). Trace labels (e.g., 'C0218') give the site and the start date (MMDD). Trace start and end dates and time (NZST) are given at the respective ends of each trace, along with the water level in the drum (cm).

a 6 mm throughfall response to 16 mm of rainfall over six hours on 20 February 1988. The smaller step at the end of the same trace is a 1.2 mm throughfall response to 6 mm of rainfall over two hours on 25 February 1988. Trace C0225 is for a period of no rainfall. The negative slope of this trace is due to 5 mm evaporation from the drum. Trace C0303 shows the throughfall response to a series of major rainfall events. Approximately 160 mm of rainfall was recorded over the period of this trace, sending the chart recorder completely round twice and nearly filling the collection drum.

A total of 264 usable throughfall traces were obtained over the 14-month throughfall data collection period. Each of the 215 traces recording some throughfall were digitised, then processed, to derive hourly and daily time series of throughfall by site.[1] Hourly data were further processed to produce an event-based data set, with a 'new' event being triggered after at least one rainless clock hour.

Stemflow

Sangster (1986) monitored stemflow on a rainfall event basis at Huapai Scientific Reserve, obtaining volumetric measurements from 18 trees of five species (kauri, mamangi, tanekaha, nikau, puriri) for 25 rainfall events ranging from 3 to 98 mm. His focus, though, was on kauri trees on the eastern and western ridges of the catchment, with negligible coverage of the mixed-age shoulder slope and valley bottom vegetation (stippled area in Fig. 2), or of the scrubby vegetation at the southern end of the catchment (crosshatched 34-80 years age area in Fig. 2). Sangster derived a composite catchment relationship between rainfall and stemflow by weighting results according to species dominance in the catchment (from Reed, 1984). He reported rainfall-event stemflow accounting for 1.0-4.7% of rainfall, with an overall relationship tending to an upper limit of about 4.0%. Linear regression of catchment stemflow on event rainfall gave the equation (Sangster, 1986):

$$\text{Stemflow} = 0.042\ \text{KC} - 0.108; \quad \text{KC} \geq 2.6\ \text{mm} \quad (1)$$

where KC is rainfall recorded at Kauri Crescent. According to Sangster, the equation explains 98.9% of the variance and the data are well defined by a linear relationship.

Figure 7 shows Sangster's composite catchment results (his Figure 4.10). The linear regression line for all 25 points (solid line) differs from that reported by Sangster.

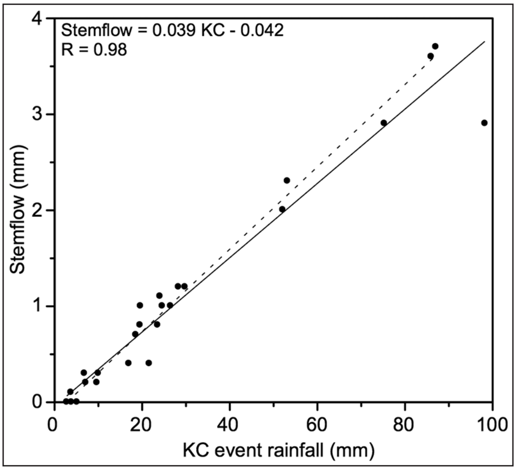

Figure 7 – Composite catchment relationship between Kauri Crescent (KC) rainfall and stemflow at Huapai Scientific Reserve. Data from Sangster (1986, his Figure 4.10). The solid regression line and equation are for all data points. The dashed line is the regression line with the right-most data point excluded.

1 The raw automatic raingauge and throughfall trough data were assumed to be directly comparable, based on the results of an open-field experiment undertaken to compare respective catches. Over a seven week period (15 October 1988 to 8 November 1988), the Stevens tipping-bucket raingauge recorded 175.4 mm of rainfall from 28 events, compared to 170.6 mm recorded by a throughfall trough setup. This 3% under-measurement by the trough setup seems likely to be an upper limit given the lower evaporative environment under the forest canopy.

His relationship is almost identical to the dashed line, suggesting that the far-right point was incorrectly plotted, or was treated as an outlier. However, the difference is relatively small and Sangster's equation was accepted as reasonable. Equation 1 gives negligible stemflow (<0.1 mm, 2%) for rainfall events up to 4.9 mm, rising to 3% at 9 mm, then to a 4% asymptote for larger storms, which is broadly consistent with results published for New Zealand forests by Blake (1975).

Throughfall results (see Results section of this paper) gave broadly similar relationships across sites, but with somewhat anomalous totals for Site J. Because the vegetation at this site is uncharacteristic (juvenile) and was not included in the Sangster (1986) study, a stemflow monitoring experiment was undertaken to test whether a complementary relationship exists between throughfall and stemflow, as suggested by the results presented by Blake (1975). Stemflow collection collars were installed on all 22 stems within a radius of 2.5 m of a point central to the throughfall calibration area at Site J. Stemflow was routed through plastic tubing to the same collection drum and chart recorder setup used for the (completed) throughfall experiment. The small surface area of the collecting drum (0.27 m^2) relative to the stemflow collection area (19.64 m^2) gave a very sensitive chart pen response of 71.8 mm per mm of stemflow. The experiment was operational from 13 October 1988 to 13 January 1989, with no missing data. Over this period, rainfall was recorded on 48 days at the Kauri Crescent raingauge, in the range 0.2 to 31.1 mm/day.

Empirical analysis

The empirical analysis examines the relationship between effective rainfall (throughfall + stemflow) and gross rainfall, primarily using visualisation and regression. However, although the derived relationships are data driven, they are constrained within a simple conceptualisation of relationships, which imposes four limitations. First, there is a minimum gross rainfall amount, below which there will be no effective rainfall. Second, once this minimum is satisfied, additional rainfall (larger storms) will contribute to effective rainfall at least as effectively as smaller storms. Therefore, an empirical relationship across multiple observations must have a constant or increasing slope as rainfall increases. Third, an incremental increase in effective rainfall cannot exceed the associated gross rainfall increment, which means that the local slope of an empirical relationship cannot exceed one. Fourth, there will be some level of gross rainfall above which all storage capacity is satisfied and all potential for in-storm evaporation is exhausted. It follows that any additional rainfall can reasonably be assumed to be completely effective (i.e., a 1:1 relationship from this threshold), although it is possible that the threshold may be beyond the bounds of the available data. These four rules are empirical and pragmatic in nature and individual storms may well deviate from the norm, depending on factors such as rainfall intensity/duration and within-storm evaporative potential. Such differences are expected to be responsible for relationship residuals, along with measurement errors.

The empirical throughfall data is used to establish empirical relationships, independently for each of the six sites. These are supplemented by the available stemflow data to derive site-specific relationships between effective and gross rainfall. The relationships are then adjusted, if necessary, to conform to the limits noted above. The six site plots are then compared to assess spatial variability in relationships, before they are finally combined to produce a single catchment-scale relationship that accounts for vegetation coverage. At each step the focus is on daily data, reflecting the daily modelling application of the original Fowler (1992) study, but selected event-based analyses are reported where they provide additional insight.

Results

Throughfall

Figure 8 shows daily throughfall data for each throughfall site plotted against mean daily rainfall for the two Huapai raingauges. Four features are immediately apparent from inspection of the six scatter plots. First, most of the variance in daily throughfall can be explained by gross rainfall alone at all sites. Second, the strength of the relationships varies between sites, with Site C notable in terms of a less clearly defined relationship (i.e., more scatter). Third, the relationships are close to, but not quite, linear. Fourth, there are substantial inter-site differences in throughfall. For example, peak recorded throughfall ranges from 43.2 to 77.2 mm in response to a 79.6 mm storm. Similar percentage differences are also evident for smaller daily rainfall totals (Fig. 9). For example, throughfall response to 20 mm daily rainfall ranges from about 8.5 mm at Sites F and J to about 14 mm at Site G.

Figure 8 shows linear and second order polynomial regressions and associated R^2 values. The latter are also given in Table 2, together with regression results for the two raingauges separately, and for an equivalent event-based analysis (in square brackets). Interestingly, relationships are weakest for the closer HR raingauge (Fig. 1) and using mean rainfall does not materially increase the variance explained (compared to KC alone). The rainfall-event analysis yields stronger relationships than the daily analysis, but the increase in variance explained is small (ca. 1%).

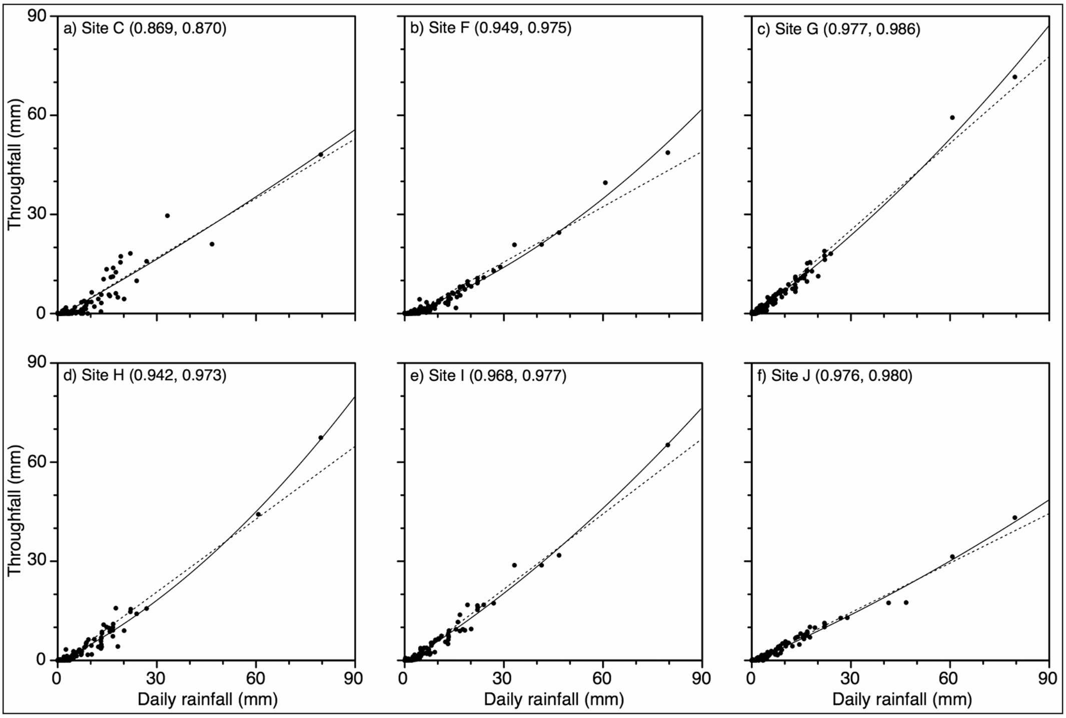

Figure 8 – Regression of daily throughfall against mean daily rainfall (KC, HR). Regression lines are linear (dashed) and second order polynomials (solid). Corresponding R^2 values are given in brackets against the site label.

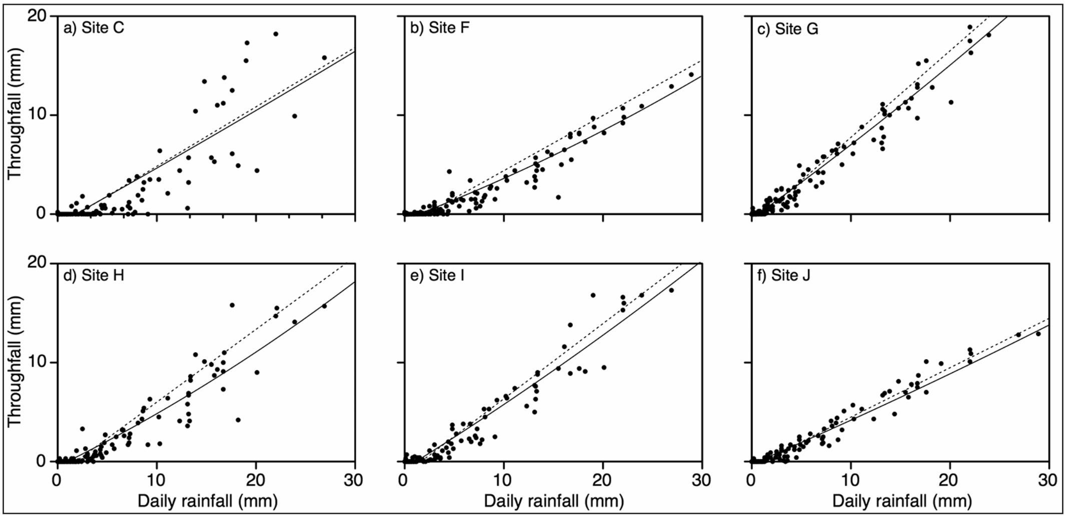

Figure 9 – Same as Figure 8, but showing data for daily rainfall less than 30 mm.

Compared to the linear regressions, the non-linear regression relationships (Fig. 8) only increase variance explained by about 1%. However, inspection of the scatter plots shows that the data are generally characterised by a slight upwards curve, resulting in sometimes notable systematic bias in the case of linear regression. Specifically, the throughfall data tend to plot above the linear regression line on the heaviest rain days and below it on low rainfall days. The latter is most clearly apparent in Figure 9, where the polynomial curves, which generally follow the data spread more closely, systematically plot below the linear regression lines. However, bias is not ubiquitous – Sites F, G, H, and I clearly show

Table 2 – Variance explained (R^2) by linear and second order polynomial regression of daily throughfall against daily rainfall. R^2 values are tabulated for regressions against each of the two Huapai Scientific Reserve raingauges and for mean rainfall across both. Figures in square brackets are results for an equivalent analysis of rainfall-event data.

	Variance Explained (R^2)					
	Kauri Crescent Rainfall		**Hinau Road Rainfall**		**Mean Rainfall**	
Site	**Linear**	**Polynomial**	**Linear**	**Polynomial**	**Linear**	**Polynomial**
C	0.875 [0.903]	0.877 [0.905]	0.701 [0.701]	0.704 [0.736]	0.869 [0.898]	0.870 [0.898]
F	0.936 [0.957]	0.970 [0.983]	0.933 [0.954]	0.948 [0.974]	0.949 [0.966]	0.975 [0.985]
G	0.970 [0.975]	0.982 [0.986]	0.967 [0.976]	0.971 [0.979]	0.977 [0.982]	0.986 [0.990]
H	0.937 [0.953]	0.972 [0.978]	0.917 [0.941]	0.931 [0.947]	0.942 [0.959]	0.973 [0.979]
I	0.961 [0.970]	0.973 [0.980]	0.935 [0.947]	0.937 [0.948]	0.968 [0.976]	0.977 [0.983]
J	0.973 [0.976]	0.980 [0.980]	0.971 [0.973]	0.972 [0.973]	0.976 [0.978]	0.980 [0.980]
Mean	0.942 [0.956]	0.959 [0.969]	0.904 [0.915]	0.911 [0.926]	0.947 [0.960]	0.960 [0.969]

it, but the displacement is minor for Sites C and J – and the linear regression appears to be the better fit in the case of Site J over most of the data range. Nevertheless, it is clear that linear regression of the rainfall – throughfall relationship is potentially problematic.

Stemflow

Linear regression of Site J stemflow on rainfall (Fig. 10) gives the relationship:

$$\text{Stemflow} = 0.149\ \text{KC} - 0.260;\ \ \text{KC} \geq 1.7\ \text{mm} \quad (2)$$

where KC is daily rainfall recorded at the Kauri Crescent raingauge. This equation confirms field observations of a more substantial stemflow contribution to effective rainfall at Site J and explains, in part, the anomalously low recorded throughfall (Fig. 8f). For rainfall events greater than 10 mm, stemflow is estimated to be more than 12% of rainfall, three times larger than the 4% threshold derived by Sangster (1986) for the catchment as a whole. It seems likely that this difference would also apply for larger rainfall events.

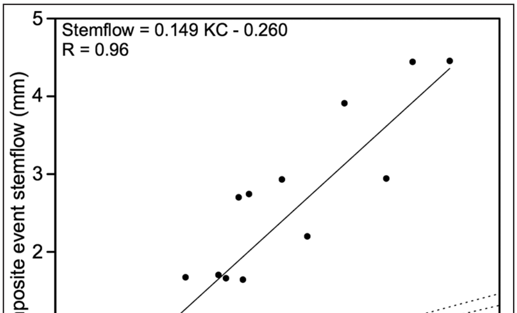

Figure 10 – Relationship between daily stemflow recorded at Site J and daily rainfall recorded at the Kauri Crescent raingauge (14 October 1988 to 10 January 1989). The solid line and equation are the linear regression. Thin dashed lines are the composite catchment relationship, from Figure 7.

Minimum effective rainfall for interception (Hinge Point 1: INT0P)

Figure 11 shows in detail the throughfall data for Site G. To determine the daily rainfall amount at which measureable throughfall is unequivocal (INT0P) is a simple matter of finding the rainfall amount above which throughfall was normally recorded. This could easily be objectively determined to a narrow range. For example, in the case of Site G, daily rainfall up to 1.0 mm/day mostly produced no throughfall, whereas throughfall was consistently recorded for 1.3 mm rain days, and therefore INT0P was taken to be 1.2 mm for Site G. Determining a specific value for INT0P sometimes required judgement, based on close inspection of the relevant plots. Table 3 shows INT0P ('Hinge Point 1') for each of the six throughfall sites. No adjustment is made for stemflow, which can reasonably be assumed to be zero for such low daily rainfall totals.

Effective rainfall on light to moderate rain days (Hinge Point 2: INT1P, INT1Peff)

As previously noted, linear regression over the full data set for each site results in under-estimation of throughfall on very heavy rain days and over-estimation on light to moderate rain days for four of the six throughfall sites (F, G, H, I). In relative terms, the latter bias is most pronounced in the vicinity of 10 mm daily rainfall. Because the apparent non-linear relationship is quite subtle, a simple practical solution is to treat the effective rainfall relationship for each site as three linear components, defined by three 'Hinge Points'. These are shown in Figure 11c for Site G, along with the corresponding three linear components. As required, the hinge points can be set to represent anything from a straight line (with maximum 1:1 slope) to something very similar to the polynomial plots shown in Figure 8.

The first of the three hinge points is INT0P. Based on inspection of the throughfall scatter

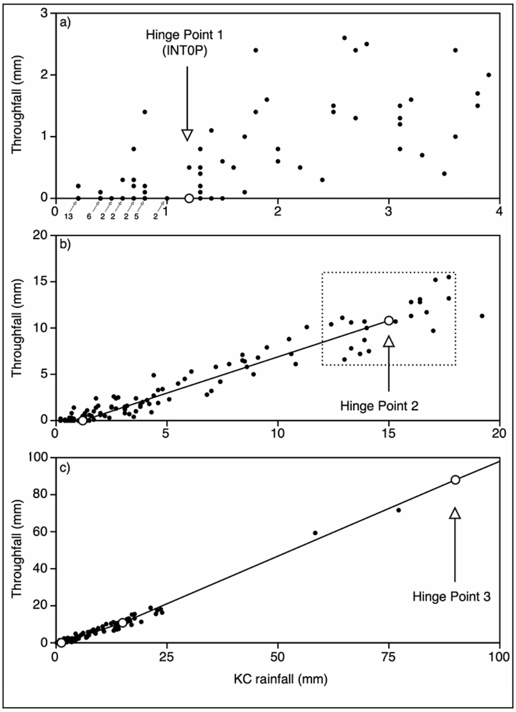

Figure 11 – Derivation of the three interception function ‘hinge points’ (excluding stemflow), for Site G.

a) Hinge Point 1 is the minimum daily rainfall for meaningful throughfall, defined as the rainfall amount above which throughfall is unambiguously more common than zero.
b) Hinge point 2 is throughfall for daily rainfall of 15 mm, computed as the mean recorded throughfall for rainfall in the range 12-18 mm (dashed box).
c) Hinge point 3 is throughfall for daily rainfall of 90 mm, derived by fitting a best-fit line, by eye, from Hinge Point 2 through the data for larger daily rainfall totals (15.0-79.6 mm here).

Note that there is considerable over-plotting in Panel a) for daily rainfall up to 1.0 mm (denoted by arrows and the number of observations).

plots (Figs. 8, 9), the second hinge point was set at 15 mm daily rainfall (INT1P) with the throughfall component (INT1Peff) set equal to the mean of all available data within 3 mm (dotted box in Fig. 11b). INT1Peff was then adjusted up by 0.5 mm to account for stemflow (Equation 1) or by 2.0 mm at Site J (Equation 2, Table 3).

Effective rainfall on moderate to very heavy rain days (Hinge Point 3: INT2P, INT2Peff)

The available data for heavy rain days (> 30 mm) are too limited to provide a convincing basis for objectively determining a daily rainfall amount above which all additional rainfall is likely to be effective. A pragmatic solution was therefore adopted where the daily rainfall amount for Hinge Point 3 (INT3P) was arbitrarily set beyond the data range (i.e., to 90 mm). A line anchored to Hinge Point 2 was then fitted by eye to the remainder of the data (to the right of Hinge Point 2) and extended to intersect the vertical line at KC = 90 mm (Fig. 11c) to determine INT3Peff, which was then adjusted up to account for stemflow, as above. The derived value for Site G (93.3 mm) was then reduced to 86.3 mm to ensure the maximum 1:1 relationship slope limit was adhered to.

Catchment-scale relationship

Inter-site variability of the effective rainfall relationships (Table 3) is shown in Figure 12. For completeness, ‘J*’ shows the relationship for Site J using the catchment relationship derived by Sangster (1986), a result that triggered the small stemflow experiment for this specific site, reported above. Also plotted on Figure 12 is a site-weighted composite relationship. The relationship was derived by weighting the hinge point values for each site according to an estimate of the proportion of the catchment the site represents (Table 3, second column). For example, Site C is taken to represent the most north-westerly area of the catchment, the mixed age shoulder and valley-bottom area is split equally between Sites F and G, and Site J wholly represents the regenerating southern area.

The relationships shown in Figure 12 were applied to the daily rainfall record for June 1987 to May 1988 – the 12-month period corresponding to the most complete throughfall data (Fig. 5). During this period, gross rainfall was 1368 mm and estimated effective rainfall ranged from 572 mm (Site F) to 1012 mm (Site G), equating to interception losses of 58% and 26%, respectively. Estimated site-weighted catchment interception loss was 44%.

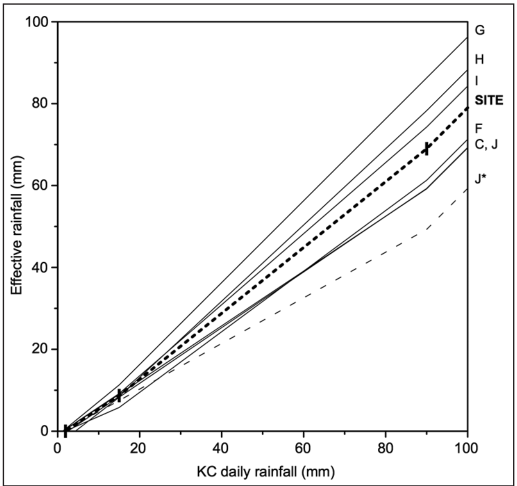

Figure 12 – Composite of relationships (Table 3) between daily effective rainfall and KC daily rainfall. Thin black lines are individual site relationships, labelled at right. The thin dashed line (J*) is the original relationship for Site J, before being adjusted up based on a stemflow experiment at the site. The heavy dashed line is the site-weighted composite relationship, with the three hinge points marked by vertical lines.

Table 3 – Effective rainfall function 'Hinge Point' parameters in mm (INT0P, INT1P, INT1Peff, INT2P, INT2Peff), derived as shown schematically in Figure 11. INT1Peff and INT2Peff are adjusted up to account for stemflow, using Equation 1. Figures in brackets for Site J, and against the summary statistics, are derived using Equation 2, to account for higher estimated stemflow at the site. The tabulated INT2Peff value of 86.3 mm for Site G was reduced from a calculated value of 91.3 mm to ensure a maximum 1:1 slope of the line between hinge points. Site-weighted summary values are derived using the estimated area weights for each throughfall site (second column). These combine the relative size of the vegetation areas mapped in Figure 2 with the throughfall sites that best represent them. For example, Sites F and G conjointly represent 45.4% of the catchment (stippled in Figure 2), so each has a whole of catchment area weighting of 22.7%.

		Hinge Point 1	**Hinge Point 2**		**Hinge Point 3**	
Site	**Weight (%)**	**INT0P**	**INT1P**	**INT1Peff**	**INT2P**	**INT2Peff**
C	12.3	4.3	15	8.3	90	59.3
F	22.7	1.8	15	5.8	90	61.3
G	22.7	1.2	15	11.3	90	86.3
H	12.8	2.5	15	8.5	90	78.3
I	4.7	1.2	15	9.2	90	74.3
J	24.9	1.3	15	(9.0) 7.5	90	(59.2) 49.3
	Mean:	2.1		(8.7) 8.4		(69.8) 68.1
	Median:	1.6		(8.8) 8.4		(67.8) 67.8
	Site-weighted:	1.9		(8.7) 8.3		(69.0) 66.5

Discussion

The results presented here show that, for the Auckland region's climate regime, most of the variance in throughfall beneath native forest can be explained by gross rainfall alone. Indeed, with the exception of Site C, simple linear regression of daily throughfall on daily rainfall explains 94-98% of the variance (Table 2). Non-linear regression and event-based analyses each increase the variance explained by about 1% and conjointly to 98-99% (but to only 90% in the case of Site C), leaving only relatively weak residuals to be explored for the effects of different storm characteristics and evaporative conditions (seasonal and within-storm). However, it should be noted that the small increase in predictive power associated with event-based analysis may partly be due to the fact that several of the larger recorded events were bursts of rainfall associated with ex-tropical cyclone Bola (6-10 March 1988), which coincidentally fitted neatly into 24-hour day blocks. Therefore, the expected decrease in performance using daily data – because daily data artificially splits or combines events spread over midnight (e.g., a single large event may be represented as two moderate daily falls) – may be reduced in this study.

The noticeably lower (but still high) 87% of variance explained in the case of Site C is interesting. Because both the experimental setup and the climatology are identical (apart from variable missing events across sites, Fig. 5), it follows that the explanation must relate to the characteristics of the canopy. In this context, Site C is unusual in two ways: it has limited secondary canopy and undergrowth (Fig. 4), and the kauri tree above it is a huge canopy emergent (i.e., the crown is well clear of the surrounding vegetation). The latter probably makes rainfall interception by the crown more dependent on wind direction than at other sites, perhaps explaining the greater scatter about the empirical relationship at this site.

Linear regression of throughfall on rainfall yields similar R^2 values to non-linear regression at two of the six throughfall sites and values that are not much reduced at the other four. Moreover, the linear regression intercepts with the rainfall axis (Fig. 8, median = 1.8 mm) are very similar to the INT0P values calculated here (Table 3, median = 1.6 mm). However, although this may suggest that linear regression may be a useful approximation for comparison purposes (see below), it is clear from the analyses presented here that problems may arise related to possible significant and systematic predictive bias: positive in the case of daily rainfall amounts of about 5-30 mm; and negative for >60 mm rain days. This is an unequivocal finding for four sites, but is debatable for two (C, J). Fortunately, the curvature of the non-linear fits is so shallow that it is a simple matter to correct for it (or not) using a set of three line segments, defined by three data-adaptive hinge points. This proved to be a pragmatic and flexible solution.

To the extent that comparisons are feasible, the linear regression results presented here are broadly comparable with those reported by Blake (1975) and Rowe et al. (2002). Taking the site-weighted estimate of the minimum rainfall for throughfall (INT0P, 1.9 mm) as an estimate of interception storage capacity gives a comparable result to the '… about 2 mm…' figure for native evergreen forest given by Rowe et al. (2002, p. 17). For the three throughfall sites under variable-age kauri canopies (I, H, C, in increasing age order), decreasing linear regression line slopes with age (0.76, 0.73, 0.60) compare to a value of 0.6 for mature kauri forest at Trounson Kauri Park, reported by Blake (1975). The throughfall regression slope for Site J (0.50) is marginally higher than four non-gorse scrub results (0.44-0.47) given in Rowe et al. (2002), but the stemflow regression slope (Fig. 10, 0.15) is much lower than their

0.30-0.43, giving Site J relatively low effective rainfall.

An important result emerging from this study is the pronounced spatial variability of the relationship between effective and gross rainfall (Fig. 12). Some of the variability may be caused by unknown sampling-related artefacts (Levia and Frost, 2006), such as troughs under preferential canopy drip points, so attributing differences solely to vegetation is not reasonable. Nevertheless, it is clear that, over distances of a few tens of metres, effective rainfall can vary by more than 100% on light rain days (<10 mm) and by more than 40% on heavy rain days (> 30 mm). For rare daily rainfall more than 80 mm, this amounts to absolute inter-site differences in effective rainfall of > 20 mm. Huapai Experimental Catchment is somewhat unusual in having a diverse range of vegetation types (Table 1) over such a small area (1.3 ha), but this vegetation diversity is characteristic of native forest in northern New Zealand. This poses a daunting challenge for distributed hydrological modelling where this diversity in the interception process may need to be encapsulated within individual model cells. On the positive side, however, the functional form of the empirical relationship does appear to be consistent across different vegetation types.

Conclusions

This study contributes to the sparse database of New Zealand native forest interception studies, particularly related to throughfall. It is also a rare comparative study, where multiple vegetation 'types' are investigated under essentially the same meteorological conditions and over the full seasonal cycle. Three specific conclusions can be drawn. First, although linear regression between gross and effective rainfall may be a suitable model in some circumstances, and is likely to be useful for comparative purposes, clear systematic bias is apparent in some cases. It follows that applying the linear model for predictive purposes should be treated cautiously. Second, it is a relatively simple task to derive a non-linear empirical function that effectively deals with the linear through non-linear forms of the relationship between effective and gross rainfall. Third, for native forest characteristic of northern New Zealand, significant spatial variability is apparent in the relationship, over distances of just tens of metres, although the basic form of the relationship appears to be similar across vegetation types.

References

Blake, G.J. 1975: The interception process. *In*: Chapman, T.G; Dunin, F.X. (*eds.*) *Prediction in catchment hydrology*. Australian Academy of Science, Canberra.

Chang, M. 2006: *Forest Hydrology: an Introduction to Water and Forests, 2nd ed*. Taylor & Francis, Boca Raton, 474p.

Dunne, T.; Leopold, L.B. 1978: *Water in Environmental Planning*. Freeman, San Francisco, 818p.

Fahey, B.; Watson, A.; Payne, J. 2001: Water loss from plantations of Douglas fir and radiata pine on the Canterbury Plains, South Island, New Zealand. *Journal of Hydrology (NZ) 40*: 77-96.

Fowler, A. 1992: Climate change and water resources in the Auckland region. PhD thesis, The University of Auckland.

Fowler, A.M. 1999: Potential climate change impacts on water resources in the Auckland Region (New Zealand). *Climate Research 11*: 221–245.

Fowler, A.; Boswijk, G. 2001: Tree-ring analysis of kauri (Agathis australis) from Huapai Scientific Reserve, Huapai, Auckland. New Zealand Tree-Ring Site Report No. 6. University of Auckland, *Department of Geography Working Paper No. 13* (ISBN 0-908672-91-8).

Hewitt, A.E. 1993: *Methods and rationale of the New Zealand soil classification*. Landcare Research Science Series No. 2. Manaaki Whenua Press.

Levia, D.F.L. Jr.; Frost, E.E. 2006: Variability of throughfall volume and solute inputs in wooded ecosystems. *Progress in Physical Geography 30*: 605-632.

McNaughton, K.G.; Jarvis, P.G. 1983: Predicting effects of vegetation changes on transpiration and evaporation. *In*: Kozlowski, T.T. (*ed.*) *Water Deficits and Plant Growth, Vol. VII: Additional Woody Plant Crops*. Academic Press, New York.

Muzylo, A.; Llorens, P; Valante, F.; Keizer, J.J.; Domingo, F.; Gash, J.H.C. 2009: A review of rainfall interception modelling. *Journal of Hydrology 370*: 191-206.

Reed, D.G. 1984: The nutrient cycle of a kauri forest watershed, Huapai, New Zealand. MSc thesis, University of Auckland.

Rowe, L.; Jackson, R.; Fahey B. 2002: *Land use and water resources: hydrological effects of different vegetation covers*. SMF2167: Report No. 5. Landcare Research Contract Report LC0203/027.

Rutter, A.J. 1975: The hydrological cycle in vegetation. *In*: Monteith, J.L. (*ed.*) *Vegetation and the Atmosphere Volume I: Principles*. Academic Press, London.

Sangster, K.B. 1986: Throughfall and stemflow in New Zealand kauri (*Agathis australis (D. Don) Lindl.*). M.Sc. thesis, University of Auckland.

Thomas, G.M.; Ogden, J. 1983: The scientific reserves of Auckland University, I. General introduction to their history, vegetation, climate and soils. *Tane 29*: 143–161.

Zinke, P.L. 1967: Forest interception studies in the United States. *In*: Sopper, W.A.; Lull, M.W. (*eds.*) *International Symposium on Forest Hydrology*. Pergamon Press, Oxford.

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