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# New data for water losses from mature Sitka spruce plantations in temperate upland catchments

**K.V.HEAL**

School of GeoSciences, University of Edinburgh, Darwin Building, Mayfield Road, Edinburgh EH9 3JU, UK, k.heal@ed.ac.uk

**R.T. STIDSON**

School of Chemistry, University of Edinburgh, West Mains Road, Edinburgh EH9 3JJ, UK

**C.A. DICKEY**

School of GeoSciences, University of Edinburgh, Darwin Building, Mayfield Road, Edinburgh EH9 3JU, UK

**J.N. CAPE**

Centre for Ecology and Hydrology, Bush Estate, Penicuik, Midlothian EH26 0QB, UK

**M.R. HEAL**

School of Chemistry, University of Edinburgh, West Mains Road, Edinburgh EH9 3JJ, UK

**Abstract** Accurate estimates of water losses from mature Sitka spruce (*Picea sitchensis*) plantations in the UK uplands are required to assess the sustainability of water supply in the event of land use change. Many investigations have demonstrated that afforestation increases water losses from temperate upland catchments, to up to 40% of annual site rainfall. In a 0.86 km$^2$ upland water supply catchment, southwest Scotland, interception loss in a Sitka spruce-dominated 37-year old plantation, was 52% of annual precipitation (2912 mm), considerably higher than reported in previous studies of similar catchments. From direct measurements of rainfall, cloudwater, discharge and soil evaporation, the catchment water balance was 96–

117% complete, within the limits of measurement error. The most probable explanation for the higher forest interception loss reported here is the inclusion of cloudwater measurements.

**Keywords** catchment water balance; cloudwater; conifer forest; evapotranspiration; interception; stemflow; throughfall; UK; upland catchment; water loss

## Nouvelles données pour des pertes d'eau des plantations mûres de sapins de Sitka en bassins tempérés versants d'altitude

**Résumé** Des évaluations précises des pertes d'eau des plantations mûres de sapins de Sitka (*Picea sitchensis*) dans les versants d'altitude Britanniques sont exigées pour évaluer un approvisionnement en eau soutenable en cas du changement d'utilisation de la terre. Beaucoup d'investigations ont démontré que le reboisement augmente des pertes d'eau des bassins tempérés versants d'altitude, à jusqu'à 40% de précipitations annuelles d'emplacement. Dans un bassin versant d'altitude d'approvisionnement en eau de 0.86 $km^2$, de l'ouest du sud Ecosse, perte d'interception dans une 37 ans de vieux plantation sapin-dominée par Sitka, était 52% de précipitation annuelle (2912 mm), considérablement plus haut que rapporté dans des etudes précédentes des catchments semblables. Des mesures directes de la pluie, d'eau de nuage, du débit et de l'évaporation de sol, le bassin d'équilibre de l'eau était 96-117% complets, dans les limites de l'erreur de mesure. L'explication la plus probable pour la perte d'interception de plus haute forêt rapportée ici est l'inclusion des mesures d'eau de nuage.

**Mot clefs** équilibre de l'eau de bassin; eau de nuage; forêt de conifère; évapotranspiration; interception; ruissellement le long des troncs; pluie au sol; Royaume-Uni; bassin versant d'altitude; perte d'eau

## INTRODUCTION

Assessments of the effect of land use changes on runoff from temperate upland catchments are important for water supply, flood prediction and maintaining ecologically acceptable flows. The UK uplands have experienced a substantial change in land use since the 1930s with the planting of conifer forests, dominated by Sitka spruce (*Picea sitchensis*), to reduce reliance on imported softwood timber and pulp. Planting has been concentrated in the UK uplands on land of marginal agricultural value, replacing the existing vegetation cover of heather (*Calluna vulgaris*) and grass-dominated moorland. In Great Britain the total area of Sitka spruce forest now stands at 6920 km$^2$ (Forestry Commission, 2002) and 85% of conifer plantation is in upland regions (Rowan, 1986). Initially water authorities favoured the afforestation of upland catchments that supply water to the major UK urban conurbations outside of London and southwest England. The dense forest cover reduced soil erosion and sedimentation in reservoirs and also restricted public access to reservoirs, thereby minimising the risk of water contamination from human activity. It was also believed (incorrectly) that the forest cover enhanced catchment rainfall resulting in increased water resource availability (McCulloch & Robinson, 1993). However, lysimeter studies in the 1950s of the hydrology of reservoir catchments in northwest England demonstrated that conversion of the land cover of temperate upland catchments from heather moorland or grass to conifer plantation caused an increase in water loss and a decrease in runoff (Law, 1956; 1958). This finding was of considerable concern to water authorities as the change in land cover of water supply catchments from moorland to forest reduced water resource availability. Law's results have been confirmed by subsequent detailed investigations in the UK, particularly by the former Institute of Hydrology in paired catchment experiments in the 1970s and 1980s at Plynlimon (mid Wales), Coalburn (northern England) and Balquhidder (southern Highlands, Scotland) (Institute of Hydrology 1991a, 1991b, 1998). From these studies it is now widely-accepted that conifer afforestation of upland catchments with annual precipitation in excess of 1000 mm causes increased water losses of approximately 35-40% of incident precipitation compared with heather moorland or grass (Calder & Newson, 1979). Departures from this figure may occur in catchments where snow forms a large proportion of the annual water input and/or shrubs with a high canopy storage capacity grow in exposed areas (e.g., Balquhidder – Institute of Hydrology, 1991b). The cause of increased water losses when upland catchments are afforested is increased interception losses arising from differences in canopy properties between coniferous trees, such as Sitka spruce, and heather and grasses. A higher proportion of incident precipitation is intercepted within the canopy of coniferous trees and is available for loss by evaporation. Evaporation rates from wetted forest canopies have been shown to be higher than from heather and grass due to the lower aerodynamic resistance of the wetted forest surface and the greater availability of energy within the forest as the result of advection and/or radiation balance modifications (Ward & Robinson, 1999).

The majority of field studies estimate water losses from forested catchments in one of two forms – evapotranspiration or interception. Interception (I) is incident precipitation stored in the canopy and lost to the atmosphere by evaporation. Evapotranspiration ($E_T$) is the sum of I plus forest transpiration (t) and evaporation from the forest soil and understorey vegetation (often assumed to be negligible in humid temperate forests). I is normally estimated in plot or lysimeter studies as the difference between incident wet precipitation to the forest canopy (P) and the sum of throughfall (T) and stemflow (S) below the canopy. $E_T$ has been estimated for whole catchments in numerous studies (e.g., Institute of Hydrology 1991a, 1991b) from application of the catchment water balance equation to measurements of precipitation inputs and discharge outputs (Q) over a minimum period of a year. Over this time it is widely assumed that the net change in groundwater and soil water storage is zero in upland catchments with steep gradients, thin soils and relatively impervious geologies. The two approaches of estimating catchment forest water losses are summarised in equations (1) and (2),

Whole catchment studies: $E_T = P - Q$ equation (1)

Plot/lysimeter studies: $E_T = I + t = [P - (T + S)] + t$ equation (2)

The majority of field studies reported have utilised only one approach of estimating forest water loss. In this paper forest water losses, derived from both approaches, are reported from a study of an upland water supply catchment in southwest Scotland, UK, that is dominated by mature Sitka spruce forest (37 years age). Explanations are discussed as to why the measured water loss in this study from mature Sitka spruce forest is considerably higher than reported in other studies, expressed as percentage of incident precipitation.

## STUDY SITE

The study site was the Ballochbeatties catchment, located in Ayrshire, southwest Scotland, UK (55° 13' N, 4° 29' W) (Fig. 1), and constituting part of the catchment of Loch Bradan, the seventh largest water supply source (by yield) in Scotland (Jowitt & Hay-Smith, 2002). The climate is humid, temperate, cool and windy. Summary climate data for the nearest weather station (4 km northeast of the catchment) at 250 m elevation at Loch Bradan Treatment Works are shown in Table 1. The catchment area (measured from a 1:5000 scale topographic map) is 0.86 $km^2$ and elevation ranges from 320 m to 480 m. Slope gradients vary from 2° in the lower part of the catchment to in excess of 25° in the upper part and the underlying geology is hard metamorphosed greywackes overlain with glacial drift. For these reasons the catchment is expected to be largely hydrologically self-contained, with a flashy runoff regime dominated by overland and near-surface throughflow and with minimal contribution from groundwater. A recent reservoir yield assessment estimated groundwater recharge in the wider Loch Bradan catchment to be < 100 mm $year^{-1}$ (Jowitt & Hay-Smith, 2002) and hydrological studies of nearby Loch Fleet showed that groundwater contributed only 5% of the mean loch outflow (Cook *et al.*, 1991).

Catchment land use and soil types are typical of the UK uplands. The upper catchment consists of unimproved moorland (NVC community type M15, *Scirpus cespitosis - Erica tetralix* wet heath) (0.45 $km^2$ area) underlain by peat, peaty gley and peaty podzols of the Dalbeattie and Ettrick soil associations (0.2-1.0 m depth), with occasional rock outcrops. The lower part of the catchment comprises forestry plantation (0.41 $km^2$ area), planted largely on basin peat (> 2 m depth in places) and dominated by Sitka spruce (*Picea sitchensis*) and hybrid larch (*Larix eurolepsis*) (67 and 16% of forested area, respectively). The forestry plantation has been managed in the standard manner with preparation of ground by ploughing and construction of drainage ditches prior to planting in 1964. In 2000, the mean tree density was 1 stem per 2.2 $m^2$ and the mean forest basal area was 53 $m^2$ $ha^{-1}$ (from diameter at breast height (DBH) measurements of 471 trees in ten plots of 10 m x 10 m, selected to represent the forest tree species and site conditions).

## METHODS

In 2001 the Ballochbeatties catchment was instrumented for a one year study of trichloroacetic acid (TCA) cycling, necessitating the measurement of rainfall, cloudwater, throughfall, stemflow, soil water behaviour in lysimeters and discharge at the catchment outlet (Fig. 1). Rainfall and discharge were recorded at 15-minute intervals and all other measurements were made as fortnightly totals on 26 occasions from 9 May 2001 to 15 May 2002. Rainfall was monitored by two ARG100 tipping bucket raingauges (rim 0.4 m above ground surface) in the moorland (430 m elevation) and forested (in a clearing at 330 m elevation) parts of the catchment, ensuring that the gauges were located the minimum distance of 2 times the height from the nearest tallest object (The Met. Office, 1997). Although aboveground raingauges are expected to systematically underestimate actual rainfall to the ground surface due to the effect of wind drift, rainfall data were not corrected since the loss of catch has been shown to vary seasonally, from storm to storm and also between sites (Rodda & Smith, 1986). Furthermore, the underestimate of rainfall catch by the ARG100 raingauges is expected to be less than documented in other studies due to the aerodynamic design of the gauges which minimises drag by presenting a reduced side area to the wind compared to standard cylindrical aboveground raingauges. Cloudwater was measured at 440 m in the upper reaches of the catchment using a passive harp-wire device strung with closely-spaced 0.6 mm diameter polypropylene filaments (as described by Crossley *et al.*, 1992) and mounted, at 1.5 m above the ground, on a funnel draining to a 2.5 l container. This container overflowed on four occasions and was replaced with a 10 l container which subsequently only overflowed on one occasion when 314 mm rain fell in a fortnight. The linear relationship between rainfall and water collected in the 10 l container ($r^2 = 0.875$, $n = 20$) was used to correct the cloud gauge data for the occasions when the 2.5 l container overflowed. Cloudwater volume was calculated as the difference in water volume collected by the cloud gauge and a nearby bulk precipitation collector (also mounted at 1.5 m above the ground) since the cloud gauge was exposed to driving rain. Cloud deposition was calculated as the cloudwater volume divided by the capture efficiency of the harp-wire collector (0.29) and multiplied by the average capture efficiency of Sitka spruce (~0.05). The estimates of the capture efficiencies of the gauge and vegetation are from field measurements in a Scottish upland Sitka spruce forest (Beswick *et al.*, 1991; Crossley *et al.*, 1992) and have been used to estimate cloudwater deposition in other UK upland catchments (Crossley *et al.*, 1992; Heal *et al.*, 2003). The effect of errors in rainfall and cloudwater measurement on catchment water balance are assessed in the Results.

*In-situ* lysimeters (volume 3800 $cm^3$, top diameter 20.2 cm) were constructed by placing intact soil cores (and attached vegetation for the moorland only) into plastic containers with a perforated base. The soil-filled containers were then replaced in the soil core holes in the field and soil drainage was collected in a polyethylene bag (volume c. 3 l) suspended below the container. Five lysimeters were located in the moorland part of the Ballochbeatties catchment and five in the forest (four under Sitka spruce and one under hybrid larch) (see Fig. 1) to assess TCA behaviour in soil and soil water. Fortnightly measurements ($n = 26$) of the water volume inputs and outputs from the forest and moorland lysimeters from May 2001 to May 2002 were used to estimate evaporation from forest soil and evapotranspiration from the moorland, respectively. The inputs were rainfall and cloudwater to the moorland lysimeters and throughfall only to the forest lysimeters, which were located away from tree trunks. Overflow of the output collection bag occurred on five occasions for the moorland lysimeters and on one occasion for the forest lysimeters. The output volumes on these occasions were estimated by applying linear relationships, fitted between output and input volumes for each lysimeter for the measurement periods when overflow did not occur, to the measured input volumes.

Forest stemflow and throughfall were measured in four of the 10 m x 10 m forest plots surveyed in 2000 (Table 2, Fig. 1), adhering to recommended methods (Puckett, 1991; Thimonier, 1998). The plots were selected to represent the relative proportions of tree species in the forest and included a forest edge site (Sitka Edge in Table 2) to take account of any edge effects on forest water loss. Three stemflow and three throughfall collectors were installed within each plot. The trees for stemflow measurements were selected to be representative of the distribution of measured DBHs in the forest, by choosing trees with DBHs corresponding to the median value of nine evenly spaced noniles for all ranked Sitka spruce DBH measurements (for Sitka spruce) and three evenly spaced terciles for all ranked larch DBH measurements (for larch). Stemflow collectors consisted of flexible plastic tubing (2 cm diameter), with a narrow slit opening, attached in a spiral around the tree trunk at approximately 1.5 m above the ground. Any gaps between the tubing and the tree trunk were filled with sealant. Stemflow collected in the tubing was directed in a closed tube to a 25 l lidded tank at the base of the tree.

Throughfall was collected in each plot in three below canopy inclined guttering systems, with a total area per plot of 0.92-0.95 $m^2$, that drained into a 25 l lidded tank. Every fortnight, water depths in the throughfall and stemflow tanks were measured in the field and converted to volumes from the calibration of an identical tank in the laboratory. Water loss from the tanks by evaporation between site visits is likely to be very small as the tanks are lidded and located beneath the forest canopy in a cool, temperate climate. Since throughfall is highly spatially variable beneath forest canopies additional throughfall tanks were deployed in each forest plot as a check on the validity of the throughfall measurements. The fortnightly throughfall depths measured in these tanks was always within the range of depths from the main throughfall collectors. The throughfall tanks overflowed on five occasions for which throughfall depths were calculated from the good linear relationship between fortnightly throughfall depth and mean catchment rainfall for all the throughfall collectors in the four forest plots ($r^2 = 0.941$, $n = 21$). The use of a linear function based on lower rainfall periods to estimate throughfall in high rainfall periods normally underestimates throughfall because in low rainfall periods repeated wetting and drying of the canopy will occur, enhancing interception loss and reducing throughfall. During higher rainfall the canopy storage will be full frequently, and the opposite effect will occur: interception losses will be limited and throughfall will be enhanced relative to rainfall. However, since the study catchment has a very high annual rainfall (2500 mm), this effect is expected to be negligible as the forest canopy is wet most of the time. Furthermore, even if throughfall was underestimated by 20%

during the wettest fortnight (in which 13% of the annual rainfall occurred) the annual throughfall total only increases by 2.6%.

Discharge was measured at 15-minute intervals, in a stabilised stream section at the catchment outlet, using a Doppler ultrasonic velocity gauge and pressure transducer (Isco 4150). The stream cross-sectional area was remeasured throughout the year and adjustments for any (small) changes in area made. On three occasions discharge was measured manually in the same section, using a Price type “mini” current meter (Scientific Instruments, Inc.), and demonstrated reasonable agreement (± 17%) with the automated discharge measurements, considering the uncertainties of both methods.

## RESULTS

### Field measurements

The depths of cloudwater, rainfall, discharge, throughfall and stemflow are shown for each measurement period in Fig. 2. Table 3 contains a summary of the hydrological data for the Ballochbeatties catchment for May 2001-May 2002. Rainfall was calculated as the mean depth measured by the two automatic raingauges to represent the range of elevations in the catchment. Fortnightly rainfall depths at the two gauges were strongly correlated ($r^2 = 0.979$) and 7% more annual rainfall was measured at the upper gauge, as expected. Estimated cloudwater inputs account for 14% of the total annual precipitation input to the Ballochbeatties catchment. Other measurements of cloudwater deposition as a proportion of total precipitation input at upland sites in southern Scotland support this figure (24% - Crossley *et al.*, 1992; 11% - Heal *et al.*, 2003). Fortnightly discharge depth was calculated by dividing the total fortnightly discharge volume by the catchment area (860 000 $m^2$). The fortnightly discharge depths were then summed to obtain the annual discharge depth. Fortnightly river discharge depths closely track rainfall depths (Fig. 2a), showing that discharge responds rapidly to rainfall inputs and that the effect of subsurface storage is negligible in the Ballochbeatties catchment.

There were no apparent differences in measured throughfall depths between the Sitka spruce and hybrid larch forest plots nor between Sitka Edge and the other Sitka plots (Fig. 2b). The fortnightly mean throughfall depth was calculated from the three throughfall samplers at each plot and then summed to obtain the annual throughfall depth in each plot. Annual forest throughfall in the catchment was calculated as the mean of the four annual plot values, since the averaging of contributions from three Sitka spruce plots and one hybrid larch plot reflects very closely the overall areal weighting in the forested part of the catchment of 67% Sitka spruce to 16% hybrid larch.

Fortnightly stemflow depths below Sitka spruce and hybrid larch in the catchment were calculated separately (Fig. 2c), to take account of any relationship between stemflow volume and tree basal area for individual tree species. For Sitka spruce, linear relationships were fitted for every fortnight between stemflow volume measured in each Sitka spruce collector and the $(\mathrm{DBH})^2$ of the collecting tree. There was generally a very good linear relationship between stemflow volume and $(\mathrm{DBH})^2$ and an example for one fortnight is shown in Fig. 3. Next, the relationship for each fortnight was applied to the root mean square DBH of deciles of the distribution of Sitka spruce DBHs, from the 2000 DBH survey, to calculate mean stemflow volume for each decile. This volume was multiplied by the number of trees in each decile (16 000) to calculate stemflow volume per decile. The stemflow volumes of all the deciles were then summed and divided by the area under Sitka spruce (328 000 $m^2$) to arrive at the fortnightly stemflow depth under Sitka spruce in the Ballochbeatties catchment. A similar approach, using basal area, was reported by Aboal *et al.* (1999) to be the most accurate method for scaling up stemflow values from individual trees to the whole stand. There was no apparent relationship between stemflow volume and $(\mathrm{DBH})^2$ for the three stemflow collectors in the hybrid larch plot in the Ballochbeatties catchment. The fortnightly larch stemflow depth was therefore calculated as the mean of these three stemflow collectors multiplied by the number of hybrid larch trees in the catchment (29 000) and divided by the area under larch (82 000 m$^2$).

Fortnightly stemflow depth under Sitka spruce was always greater than or equal to stemflow under hybrid larch in the Ballochbeatties catchment (Fig. 2c). This difference is probably caused by the differences in bark roughness between tree species, rather than tree spacing (Teklehaimanot *et al.*, 1991), as stem densities are similar in the Sitka spruce and hybrid larch plots (Table 2). The greater bark roughness of hybrid larch causes more absorption of water on the tree trunk before stemflow starts. Similar differences in stemflow production between tree species have also been observed by Aboal *et al.* (1999).

The mean fortnightly forest stemflow depth was calculated by summing the stemflow volumes under Sitka spruce and hybrid larch and dividing by the total area of forest (410 000 m$^2$). The mean annual stemflow depth was then obtained by summing the mean fortnightly forest stemflow depths.

The total annual water input and output volumes measured in the forest and moorland lysimeters provide annual estimates of evaporation from the forest floor and moorland evapotranspiration, respectively, in the Ballochbeatties catchment. Mean annual evaporation from the forest floor was 10% of throughfall. This figure is for soil evaporation only since there was no understorey vegetation below the dense forest canopy and the lysimeters did not contain any active tree roots. Mean annual evapotranspiration from the moorland was 29% of total annual precipitation, very similar to the evapotranspiration loss of 22% of annual precipitation from grass and heather measured in the Balquhidder upland catchment, Scotland (Institute of Hydrology, 1991b). It is probable that moorland evapotranspiration has been overestimated in this study because of the assumption, in the calculation of cloudwater deposition, that the vegetation capture efficiency of cloudwater is the same for moorland vegetation as for conifer trees. In practice it is expected that moorland grasses and shrubs will be less efficient at capturing cloudwater than conifer trees.

### Catchment water losses

Annual catchment water loss (evapotranspiration) was calculated, using the field hydrological data (Table 3) and literature values for transpiration as,

$E_{T,C} = A_F (E_{Tr,F} + E_{S,F} + I_F) + (1 - A_F) E_{T,M}$ equation (3)

where, $E_{T,C}$ is the catchment-average water loss (mm), $A_F$ is the fraction of catchment covered by forest, $E_{Tr,F}$ is the estimated forest transpiration (mm), $E_{S,F}$ is the measured soil evaporation below the forest (mm), $I_F$ is the measured interception loss for the forest (mm) and $E_{T,M}$ is the measured total water loss for the moorland (mm)

Forest interception loss was calculated as the difference between total precipitation (2912 mm) and throughfall (1331 mm) plus stemflow (76 mm) penetrating the canopy, giving a fraction of total precipitation lost by interception of 0.52, higher than the typical figure of 0.35-0.40 measured in many other upland UK Sitka spruce forests. From very consistent measurements of transpiration in similar UK upland forests (Table 4), annual forest transpiration was taken to be 320 mm. From the soil lysimeter measurements, soil evaporation below the forest was 133 mm and the total water loss from the moorland was 844 mm. Inserting these values in equation (3), and assuming that total precipitation is uniform across the catchment, the calculated total annual water loss from the Ballochbeatties catchment is 1375 mm, or 47% of the annual precipitation input. This figure is of similar magnitude to the total annual reference evapotranspiration (the potential evapotranspiration from a well-watered short green grass surface) of 1191 mm estimated for the Ballochbeatties catchment for 1995 in a separate study (Hardie, 2002) from daily evapotranspiration calculated using the Penman-Monteith method within the Reference Evapotranspiration Program (Hess, 1998).

## Catchment water balance

As a check on the accuracy of the field hydrological measurements, and assuming that there is no long-term change in soil water and groundwater storage, the annual water balance of the Ballochbeatties catchment was calculated as,

$$P = Q + E_{T.C} \qquad \text{equation (4)}$$

For the Ballochbeatties catchment, P = 2912 mm p.a. and Q = 1726 mm p.a., both obtained from direct field measurement, and $E_{T.c}$ = 1375 mm p.a., derived entirely from direct field measurement apart from a literature value for transpiration as described above. Since the estimated annual water outputs only exceeded the inputs by 6%, the water balance for the Ballochbeatties catchment for May 2001–May 2002 can be considered complete, demonstrating that all water fluxes in the catchment have been accounted for satisfactorily. A sensitivity analysis was conducted of the effect on the catchment water balance of varying the estimates of forest transpiration, moorland evapotranspiration, rainfall, cloudwater and discharge within the limits of measurement error (Table 5). The analysis showed that the catchment water balance is 96-117% complete and that the accuracy of discharge measurement is the major source of uncertainty. Indeed the catchment water balance is probably closer to 100% complete since the cloudwater inputs to the moorland area of the catchment have probably been overestimated, because of the assumption that the moorland vegetation capture efficiency is the same as conifer trees. Therefore all water fluxes in the Ballochbeatties catchment have been accounted for satisfactorily, almost entirely from the field measurements, validating the assumption that changes in soil and groundwater storage during the study period are negligible and also demonstrating that the large interception losses observed from the forest canopy are real and not a measurement artefact.

## DISCUSSION

Although the calculated annual water balance for the Ballochbeatties catchment is complete, within reasonable uncertainty, the measured annual forest interception loss (0.52), expressed as a fraction of the annual precipitation input, is considerably higher than interception losses reported in other studies of UK upland catchments dominated by Sitka spruce plantation (Table 6). In these studies reported annual forest fractional interception losses were typically 0.35 - 0.40 of annual rainfall input (although it is often not clear whether annual precipitation includes cloudwater or not). Excluding cloudwater, the forest interception loss from the Ballochbeatties catchment, expressed as a fraction of annual rainfall, reduces slightly to 0.44 (Table 3). Although forest interception loss varies spatially and temporally due to the interaction between local climate and forest canopy factors, it is important to use realistic values in assessments of the effects of upland land use change on water resource availability.

Despite the higher observed forest interception loss, the fractions of stemflow and throughfall of net precipitation below the forest canopy in the Ballochbeatties catchment are similar to measurements conducted in Sitka spruce stands in other UK upland catchments. Indeed the mean stemflow and throughfall results for Sitka spruce in the Ballochbeatties catchment, expressed as a fraction of net precipitation, provide further support for the relationship proposed by Johnson (1990) between Sitka spruce tree age and the fractions of net precipitation occurring as stemflow and throughfall (Fig. 4). From measurements in a number of UK upland forests, the maximum fraction of net precipitation occurs as stemflow when trees are 10-15 years old and decreases in older stands, probably due to an increase in leaf area index causing a higher proportion of precipitation to be intercepted by the canopy foliage.

A number of explanations may account for the higher forest interception loss measured in the Ballochbeatties catchment compared with other UK upland catchments, including: measurement uncertainty, tree age, stem density, differences in methodology, and climate change. The main sources of measurement uncertainty in this study are for discharge and cloudwater. Because cloudwater only accounts for 14% of the annual precipitation input the overall effect of even large uncertainties in its value on the overall catchment water balance are small, as has been already demonstrated. Other sources of error in the cloudwater measurement have already been discussed. Rainfall, throughfall and stemflow were measured in the Ballochbeatties catchment using standard methods and measurements at replicate sites showed close agreement. Evaporation loss from the inclined troughs of the throughfall samplers prior to storage in lidded tanks is likely to be negligible as the trough angles followed the recommendations of Thimonier (1998). Furthermore the cool, humid microclimate below the forest canopy is not conducive to evaporation. The strong relationship observed in the Ballochbeatties catchment between stemflow volume and $(\mathrm{DBH})^2$ for the Sitka spruce stemflow collectors indicate that systematic errors in these measurements are small. The greatest source of uncertainty in this study is the measurement of discharge which has measurement errors of ± 17%.

Differences in tree age and stem density between the Ballochbeatties catchment and other UK upland catchments could account for the observed differences in forest interception loss. Tree leaf area index, and hence canopy interception characteristics, change with tree age. However, tree age in the Ballochbeatties catchment at the time of this study (37 years) lies within the range of tree ages in other studies (14–63 years). Stem density in the Ballochbeatties catchment (4775 stems $\mathrm{ha}^{-1}$) is at the high end of reported stem densities in other Sitka spruce stands studied (Table 7), although this may be due partly to the widespread occurrence of forked stems in the Ballochbeatties plantation. Ideally, basal area data should be compared between Sitka spruce stands but these figures are not available for other studies.

Differences in methodology, in particular the inclusion of cloudwater in precipitation measurements in this study, could also account for the higher forest interception loss measured in the Ballochbeatties catchment compared to other UK upland catchments. Because interception loss is calculated as the difference between precipitation onto the forest canopy and throughfall and stemflow measured below the canopy, if cloudwater is not taken into account then interception loss may be underestimated. When data from other interception studies in Sitka spruce and European larch stands in the UK uplands at similar elevations are plotted as annual interception expressed as a fraction of annual rainfall (not including cloudwater), the Ballochbeatties result (which includes cloudwater) appears as an outlier (Fig. 5a). However if the data from other studies are recalculated, assuming the same proportion of cloudwater to annual rainfall as in the Ballochbeatties catchment (although in reality this proportion will vary between sites), the Ballochbeatties result is less of an anomaly (Fig. 5b) and the mean annual forest interception loss of other studies increases from 0.32 to 0.41 of total annual precipitation. The importance of including cloudwater for calculating catchment water budgets, particularly in temperate upland forested catchments, has been reported elsewhere. For example, for a small headwater catchment in southern Germany, the underestimate of annual evapotranspiration calculated by the catchment water budget method, compared with the eddy covariance energy budget method, was attributed to fog deposition (Zimmermann & Zimmermann, 2002). Consideration of cloudwater is also essential for catchment planning and management in assessing the effect of land use and vegetation changes on interception losses and, hence, water resource availability.

A final possible explanation for the higher forest interception loss measured in the Ballochbeatties catchment compared to other studies in UK upland forests is recent climate change. Decadal climate change, particularly increased cloudiness and decreased atmospheric specific humidity deficit, was suggested as a partial explanation for declining water loss observed in the forested Severn catchment, mid-Wales from 1969 to 1988 (Hudson & Gilman, 1993). The majority of other studies of interception losses in UK upland forests were conducted in the 1970s and 1980s. The higher forest interception loss measured in the Ballochbeatties catchment in 2001-2002 could be due to higher air temperatures, particularly in winter, causing an increased rate of evaporation of water intercepted in the forest canopy. This hypothesis cannot be tested from the data currently available and would require a further modelling study to hindcast forest interception losses from the Ballochbeatties catchment from 1970s and 1980s weather records.

## CONCLUSIONS

The complete annual water budget of the Ballochbeatties catchment, a small UK headwater catchment with 48% forest cover, has been well-characterised and completed, within the limits of measurement uncertainty. The proportions of throughfall and stemflow of net precipitation through the forest canopy are similar to other forested UK upland catchments and follow the trend of increasing significance of throughfall in net precipitation as tree age increases. However forest interception loss in the Ballochbeatties catchment, 52% of total annual precipitation, was considerably higher than interception losses of 35-40% measured in similar catchments. The most probable explanation for this difference is that cloudwater inputs have not been included in calculations of interception loss in other studies, resulting in an underestimate of catchment water loss as the result of vegetation change in upland catchments. It is important that the effects of vegetation change on the catchment water losses, are fully understood and quantified in order to inform the sustainable management of catchment water resources.

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## TABLES

Table 1. Summary climate data from Loch Bradan Treatment Works weather station located at 250 m elevation.

| | | |
|---|---|---|
| Mean annual rainfall (mm) | 1824[1] | 1988-1999 |
| Mean daily minimum air temperature ($^{o}$C) | 4.7 | 1993-1998 |
| Mean daily maximum air temperature ($^{o}$C) | 11.4 | 1993-1998 |
| Mean daily windspeed (m $s^{-1}$) | 3.7 | 1993-1998 |
| Mean daily maximum windspeed (m $s^{-1}$) | 16.7 | 1993-1998 |

[1] Missing daily values interpolated from six weather stations within a 20 km radius (Poole, 2001)

Table 2. Characteristics of the forest throughfall and stemflow measurement plots, Ballochbeatties catchment. DBH = diameter at breast height.

| | *Sitka Edge* | *Sitka North* | *Sitka South* | *Larch* |
|---|---|---|---|---|
| No. of stems in 100 $m^2$ | 42 | 64 | 45 | 40 |
| Mean DBH (cm) | 9.9 | 9.5 | 13.0 | 13.5 |

Table 3. Summary of hydrological data measured in the Ballochbeatties catchment, 9 May 2001-15 May 2002.

| | |
|---|---|
| Mean rainfall depth | 2500 mm |
| Cloudwater depth | 412 mm |
| Total precipitation depth | 2912 mm |
| Cloudwater as % of total precipitation | 14% |
| Mean forest throughfall depth | 1331 mm |
| Mean forest stemflow depth | 76 mm |
| Discharge depth | 1726 mm |
| Forest interception loss (of total precipitation) [Total precipitation – (throughfall + stemflow)] | 1505 mm |
| Forest interception loss (of mean rainfall) [Mean rainfall – (throughfall + stemflow)] | 1093 mm |
| Forest interception loss as % of total precipitation | 52% |
| Forest interception loss as % of mean rainfall | 44% |
| Mean forest soil evaporation loss (± 1 SD of 5 forest soil lysimeters) | 10 ± 26% of throughfall |
| Mean moorland evapotranspiration loss (± 1 SD of 5 moorland soil lysimeters) | 29 ± 7% of total precipitation |

Table 4. Measurements of annual forest transpiration in forested UK upland catchments (from Roberts, 1983).

| *Reference* | *Location* | *Study years* | *Tree species* | *Tree age (years)* | *Transpiration (mm p.a.)* | *Method* |
|---|---|---|---|---|---|---|
| Law (1956, 1958) | Stocks Reservoir, Lancashire | 1954-55 | Sitka spruce | 25-26 | 340 | Large lysimeter |
| Calder *et al.* (1982) | Severn, Plynlimon | 1974-76 | Norway spruce | 29-31 | 290-340 (Same stand, 3 separate years) | Large lysimeter + soil moisture measurements |

Table 5. Sensitivity analysis of Ballochbeatties catchment water balance to hydrological parameters.

| *Scenario* | *Rainfall (mm)* | *Cloud water (mm)* | *Forest transpiration (mm)* | *Discharge (mm)* | *Moorland evapotranspiration (mm)* | *Catchment water out / water in (%)* |
|---|---|---|---|---|---|---|
| Mean[1] | 2500 | 412 | 320 | 1726 | 844 | 106 |
| Max forest transpiration value[2] | 2500 | 412 | 340 | 1726 | 844 | 107 |
| Min forest transpiration value[2] | 2500 | 412 | 290 | 1726 | 844 | 106 |
| Rainfall + 10%[3] | 2750 | 412 | 320 | 1726 | 844 | 101 |
| Rainfall - 10% | 2250 | 412 | 320 | 1726 | 844 | 113 |
| Cloudwater + 10 % | 2500 | 453 | 320 | 1726 | 844 | 106 |
| Cloudwater - 10 % | 2500 | 371 | 320 | 1726 | 844 | 107 |
| Discharge + 17 %[2] | 2500 | 412 | 320 | 2020 | 844 | 117 |
| Discharge - 17 %[4] | 2500 | 412 | 320 | 1433 | 844 | 96 |
| Moorland evapotranspiration mean literature value[5] | 2500 | 412 | 320 | 1726 | 582 | 102 |

[1] Calculated using mean field measurements and mean transpiration from literature.

[2] From literature cited in Table 4.

[3] Estimated loss of catch for a standard aboveground raingauge compared to a ground level raingauge in this part of the UK (Rodda & Smith, 1986).

[4] Mean % difference between logger and manual measurements of river discharge.

[5] Mean literature value for moorland evapotranspiration = 0.2 of annual precipitation from whole catchment studies of UK upland catchments with grass and heather vegetation cover (Calder & Newson, 1979; Institute of Hydrology, 1976; Institute of Hydrology, 1991b; Shuttleworth & Calder, 1979).

Table 6. Mean interception losses measured in Sitka spruce stands in other UK upland catchments. All measurements were made using standard raingauges, throughfall and stemflow collectors, except where stated.

| Reference | Location | Altitude (m a.s.l.) | Tree age (years) | Study years | Mean annual rainfall (mm) | Mean annual interception/ mean annual rainfall |
|---|---|---|---|---|---|---|
| *This study* | *Ballochbeatties, SW Scotland* | *350* | *37-38* | *2001-02* | *2912*[1] | *0.52*[1] |
| Law (1956, 1958) | Stocks Reservoir, NW England | ~ 200 | 25-26 | 1954-55 | 984 | 0.38 |
| Calder (1990) | Stocks Reservoir, NW England | ~ 200 | 26-40 | 1956-70 | 1496 | 0.38 |
| Ford & Deans (1978) | Greskine Forest, S Scotland | 355 | 14-16 | 1975-77 | 1639 | 0.30 |
| Johnson (1990) | Kirkton, Balquhidder | ~ 300 | 50-53 | 1983-86 | 2130 | 0.28 |
| Anderson & Pyatt (1986) | Kielder, NE England | 223 | 25-28 | 1977-80 | 1037 | 0.29 |
| Anderson & Pyatt (1986) | Kielder, NE England | 230 | 63-65 | 1979-81 | 997 | 0.50 |
| Gash *et al.* (1980) | Kielder, NE England | 220 | 27-28 | 1977-78 | 969 | 0.32 |
| Gash *et al.* (1980) | Hafren Forest, Plynlimon | 410 | 29-32 | 1975-78 | 1867 | 0.27 |
| Calder (1990) | Dolydd, Plynlimon | ~ 290 | 31-33 | 1981-83 | 2004 | 0.38[2] |
| Calder (1990) | Crinan, SW Scotland | ~ 50 | ~ 8-10 | 1978-80 | 2000 | 0.36[2] |

[1] Including cloudwater

[2] Net precipitation below canopy measured with plastic-sheet net-rainfall gauges

Table 7. Stem density of UK upland Sitka spruce plots in which interception studies have been conducted.

| *Reference* | *Location* | *Altitude (m a.s.l.)* | *Tree age (years)* | *Thinned* | *Stem density (ha$^{-1}$)* |
|---|---|---|---|---|---|
| *This study* | *Ballochbeatties, SW Scotland* | *350* | *37* | *No* | *4775* |
| Anderson & Pyatt (1986) | Kielder Forest, NE England | 223 | 25 | No | 3450 |
| Ford & Deans (1978) | Greskine Forest, SW Scotland | 355 | 14 | No | 3594 |
| Gash *et al.* (1980) | Kielder Forest, NE England | 220 | 27 | No | 3600 |
| Gash *et al.* (1980) | Hafren Forest, Powys | 410 | 29 | No | 4250 |
| Johnson (1990) | Kirkton, Balquhidder | ~300 | 50 | Yes | 2500 |

## FIGURE CAPTIONS

Figure 1. Location of Ballochbeatties catchment, catchment boundary and plan of catchment hydrological measurement network

Figure 2. Water depths measured in the Ballochbeatties catchment, 2001-2002: (a) rainfall, cloudwater, discharge, (b) mean throughfall of three collectors at each forest plot (± 1 SD at the Sitka north plot to illustrate variability between collectors), (c) mean stemflow for Sitka spruce and hybrid larch. The crosses in (b) indicate the five occasions on which the throughfall collectors overflowed and throughfall was estimated from the relationship between throughfall and rainfall on all other occasions.

Figure 3. Relationship between stemflow volume and $(DBH)^2$ for collectors in the Sitka spruce plots, Ballochbeatties catchment, for the period 7-20 January 2002

Figure 4. Relative stemflow and throughfall as a function of tree age in Sitka spruce stands in UK upland catchments (after Johnson, 1990). The unfilled points are the Sitka spruce stand in the Ballochbeatties catchment.

Figure 5. Annual fractional stand interception loss plotted against: (a) annual rainfall (excluding cloudwater), (b) annual precipitation (including estimated cloudwater contribution). (Data from Table 6 and Cape & Lightowlers (1988)). In (a) and (b) the Ballochbeatties value is expressed as the fraction of precipitation (including cloudwater).

Figure 1:

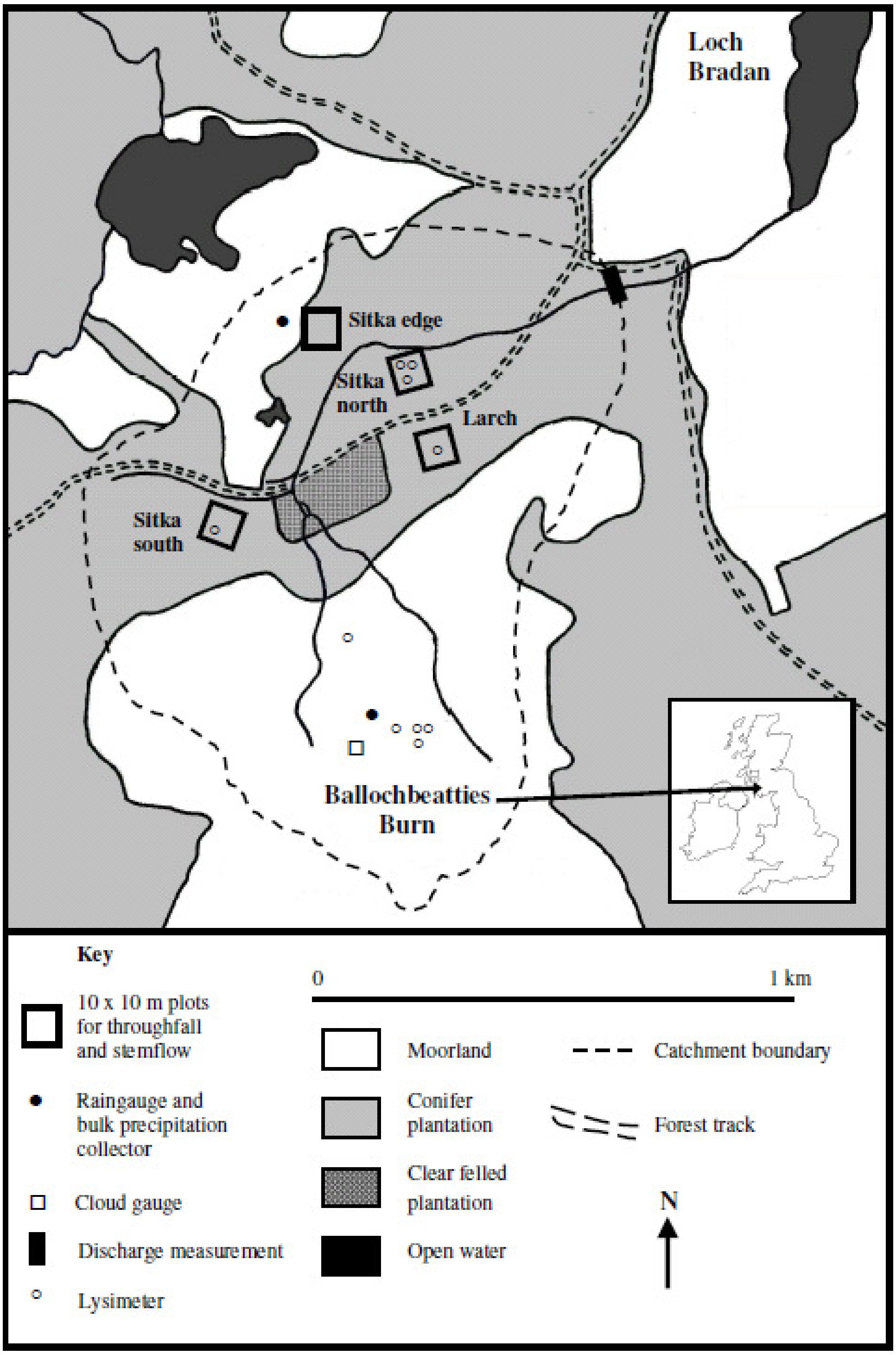

Loch
Bradan
Sitka edge
Sitka
north
Larch
Sitka
south
Ballochbeatties
Burn
Key
10 x 10 m plots
for throughfall
and stemflow
Raingauge and
bulk precipitation
collector
Cloud gauge
Discharge measurement
Lysimeter
0
1 km
Moorland
Conifer
plantation
Clear felled
plantation
Open water
Catchment boundary
Forest track
N

Figure 2

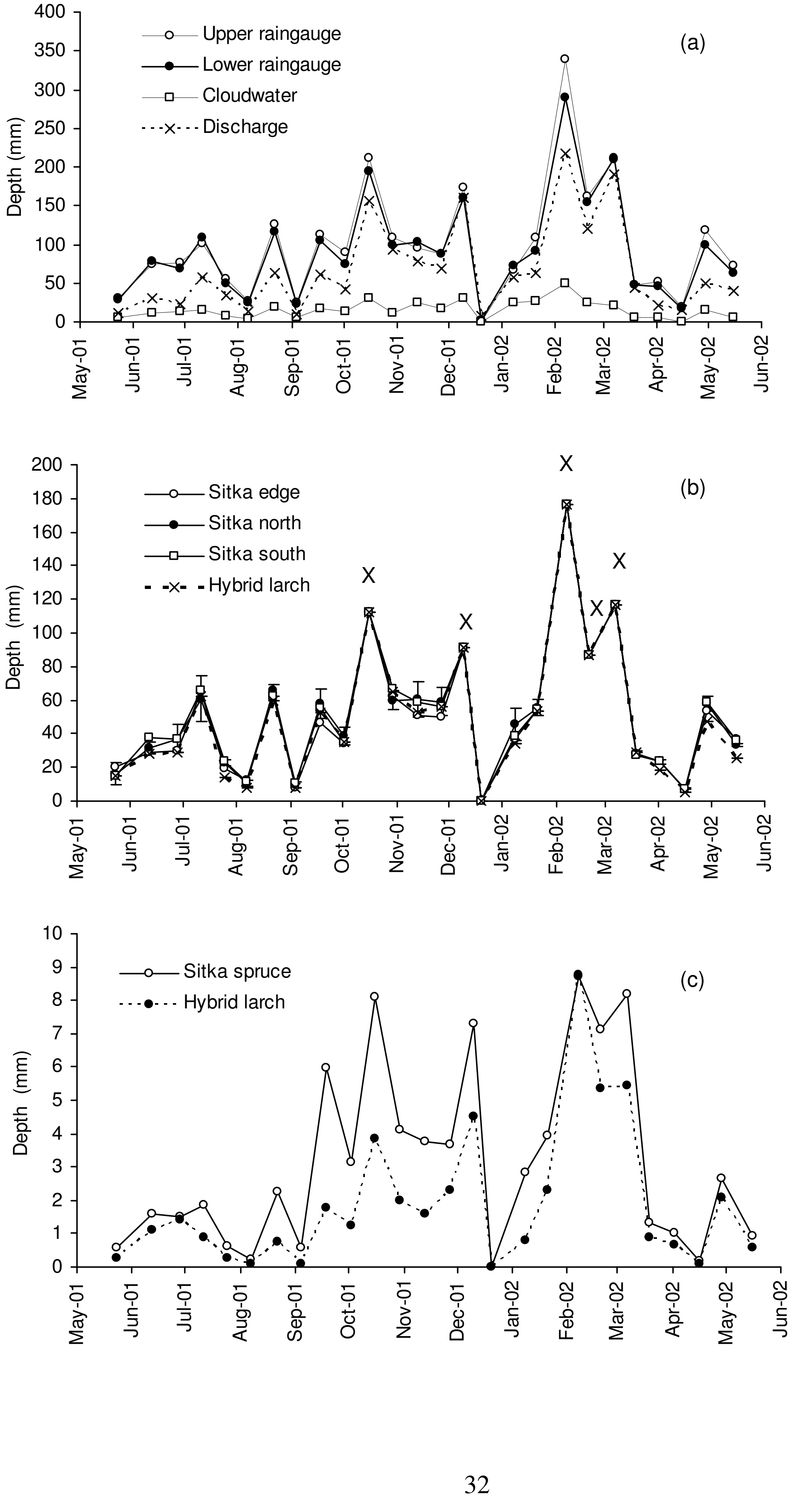

(a)
Upper raingauge
Lower raingauge
Cloudwater
Discharge
Depth (mm)
0
50
100
150
200
250
300
350
400
May-01
Jun-01
Jul-01
Aug-01
Sep-01
Oct-01
Nov-01
Dec-01
Jan-02
Feb-02
Mar-02
Apr-02
May-02
Jun-02
(b)
Sitka edge
Sitka north
Sitka south
Hybrid larch
X
X
X
X
X
Depth (mm)
0
20
40
60
80
100
120
140
160
180
200
May-01
Jun-01
Jul-01
Aug-01
Sep-01
Oct-01
Nov-01
Dec-01
Jan-02
Feb-02
Mar-02
Apr-02
May-02
Jun-02
(c)
Sitka spruce
Hybrid larch
Depth (mm)
0
1
2
3
4
5
6
7
8
9
10
May-01
Jun-01
Jul-01
Aug-01
Sep-01
Oct-01
Nov-01
Dec-01
Jan-02
Feb-02
Mar-02
Apr-02
May-02
Jun-02

Figure 3

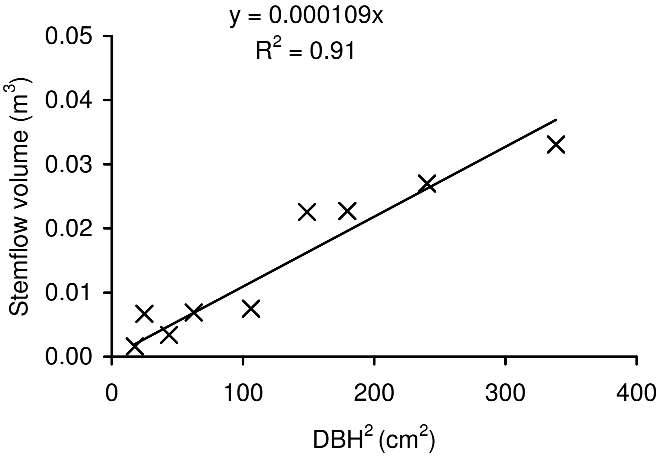


Figure 4

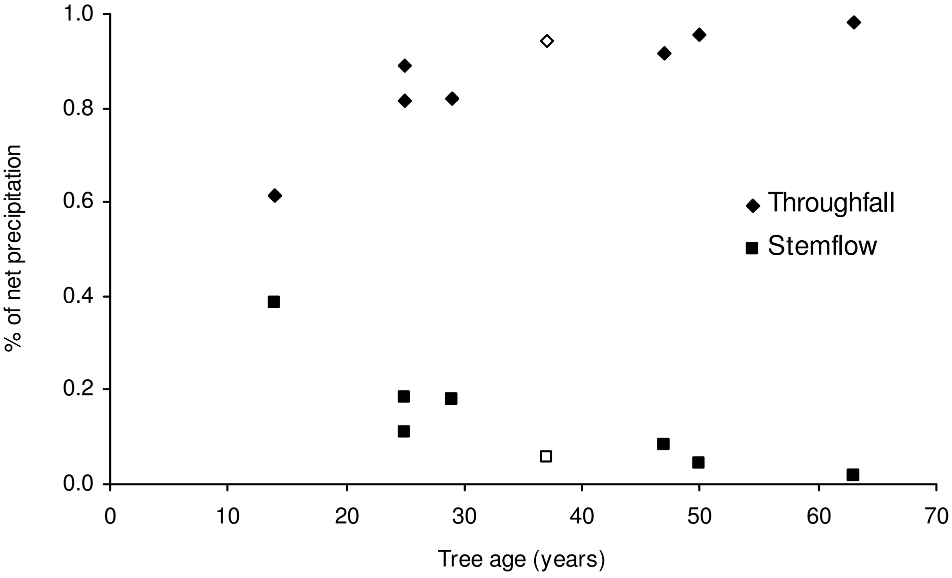
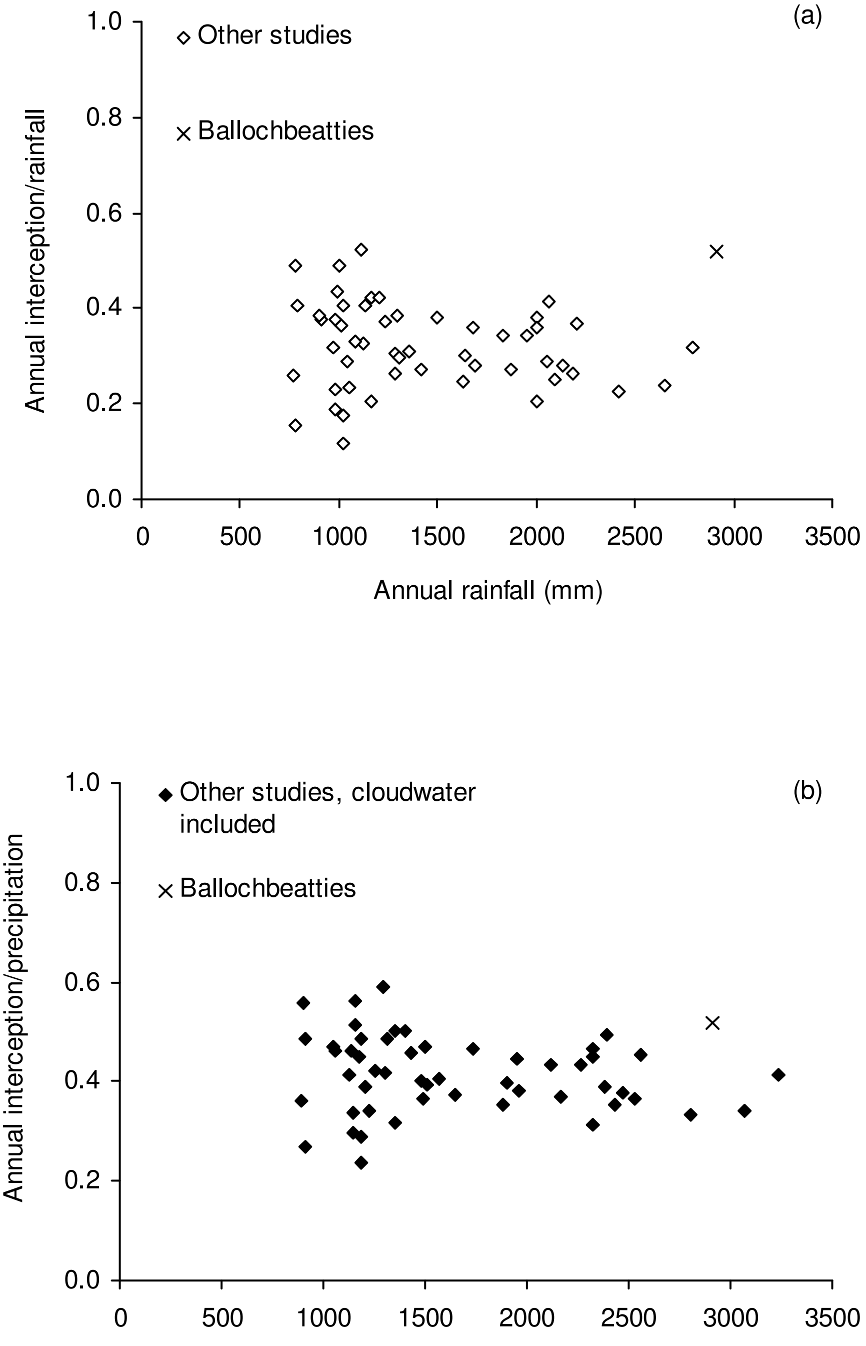


Figure 5


(a)
◇ Other studies
× Ballochbeatties
Annual interception/rainfall
1.0
0.8
0.6
0.4
0.2
0.0
0
500
1000
1500
2000
2500
3000
3500
Annual rainfall (mm)
(b)
◆ Other studies, cloudwater included
× Ballochbeatties
Annual interception/precipitation
1.0
0.8
0.6
0.4
0.2
0.0
0
500
1000
1500
2000
2500
3000
3500
Annual precipitation (mm)