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MODELLING THE EFFECT OF UPLAND AFFORESTATION ON WATER RESOURCES

(BALQUHIDDER)

Report to The Scottish Office Environment Department

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Institute of Hydrology
Unit 2
Innovation Park
Stirling
FK9 4NF
Scotland

Tel: 01786 447612
Fax: 01786 447614

Authors

D.J. Price
I.R. Calder
R.C. Johnson

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Abstract

The effect of upland afforestation on water resources has been studied at Balquhidder during the period 1981 to 1994. The two catchments studied are physically similar in all but one respect: the Kirkton catchment has mature plantation forest whilst the Monachyle catchment is open moorland. In the report the water balances for the catchments are presented. This includes the recent period during which approximately half of the Kirkton forest has been clearfelled.

An important objective of the work has been to develop an upland evaporation model that accounts for evaporative losses from coniferous plantation forest, heather, upland grass, brash and snow. The resulting daily evaporation model is presented in detail and the seasonality of the evaporative processes highlighted. The model is applied to the complete Balquhidder data set. The component losses associated with the different land uses are discussed and the predicted annual losses, synthesised from the component land uses, compared with the catchment water balance results. The model was also applied to seven Scottish upland catchments, selected to cover the likely range of climatic conditions experienced in the Scottish uplands, and the predictions compared with the measured water balances. The model's predictions are set within the context of application across Scotland.

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Executive Summary

The report summarises work by the Institute of Hydrology upon the monitoring and modelling of evaporative losses from the Balquhidder catchments, together with the application of the model to other upland catchments in Scotland. The project has been co-ordinated and funded by the Scottish Office Environment Department. Other funding members of the consortium have been: the Department of the Environment, the Natural Environment Research Council, the Forestry Commission, the North of Scotland HydroElectric Board and the Water Research Centre.

The main purpose of the report is not to re-issue the previously published results, but rather to present the recent developments and findings concerning the upland evaporation model, together with the latest catchment figures for water losses from the paired catchment study. Though the early modelling work has been described before, (Hall & Harding, 1993), there has, until now, been missing an up to date report upon the further development of the model and a detailed appraisal of the model's performance in comparison to the actual catchment results. It is the purpose of this report to address these topics and to place the model in the context of its application across the uplands of Scotland.

OBJECTIVES OF THE RESEARCH

The objectives of the research were:

1. To study the effects of upland afforestation upon catchment evaporative losses in Scotland where the indigenous vegetation, typically coarse grasses and heather, is aerodynamically rougher than that previously studied at the Plynlimon research catchments in Wales, and where the distribution and type of precipitation is also different.

2. To determine the relative magnitudes and seasonality of the various components of evaporation that relate to: the typical vegetation types, snow cover, transpiration and interception, and climatic factors.

3. To develop and improve the IH upland evaporation model, and to assess its performance as a water resources management tool upon representative catchments in Scotland.

BALQUHIDDER WATER BALANCE RESULTS

The catchment water balance studies have indicated that although the losses from the partially afforested Kirkton catchment have been consistently lower than those from the Monachyle (moorland) catchment, the annual P-Q values do suggest that a reduction in evaporation has occurred from the Kirkton since the inception of the clearfelling.

DEVELOPMENT OF THE EVAPORATION MODEL

1. The development of the upland evaporation model is presented. The following land uses are considered: coniferous plantation forest, heather, upland grass, brash (canopy debris left after clearfelling) and snow cover. The model runs on a time interval of one day and requires the following inputs: daily catchment precipitation, daily potential evaporation, vegetation coverage and, when applicable, daily snow coverage.

2. A soil moisture deficit term has been incorporated into the model. If a large enough deficit develops below a specific vegetation type the predicted transpiration rate will be reduced. This component of the model is most likely to be utilised when modelling drier regions, or years with a pronounced summer dry period.

3. The model shows that the seasonal pattern of the evaporation from forest to be largely influenced by the seasonality of the precipitation. Transpiration losses will always peak during the summer but losses attributable to interception, which dominate the overall total, will be determined by when the rain actually falls. It is predicted that daily winter evaporation rates can be as high as those during the summer.

4. The model also shows that the seasonal pattern of the evaporation from heather is also largely influenced by the seasonality of the precipitation. Transpiration losses will always peak during the summer but interception losses, which dominate the overall total, will be determined by when the rain falls. It is also predicted that non snow affected daily winter evaporation rates can be as high as those during the summer.

5. The water use for the upland grass is shown to be well estimated using the Penman potential evaporation (E_T) multiplied by a seasonally dependent function representing the change in the quantity of live foliage. The annual total is less than E_T, and exhibits a pronounced summer maximum.

APPLICATION OF THE MODEL TO BALQUHIDDER

1. The full available datasets (1983-1993) for the Kirkton and Monachyle, and for the Upper Monachyle (1987-1993) have been used to run the model. The resulting predictions and comparisons to catchment derived P-Q are presented and discussed in detail.

2. It is predicted that under the climatic conditions experienced at Balquhidder the evaporation from heather will, on average, be 1.5 times greater than that from upland grass, and the evaporation from forest will be 2.4 times larger than that from upland grass. Also the relative magnitudes of interception to transpiration losses for both forest and heather can significantly vary from year to year; reflecting annual variability in climate.

3. Snow is demonstrated to significantly reduce the annual evaporative losses at Balquhidder. If, for the 11 year period analyzed, the predicted influence of the snow were omitted it would lead to an average over estimation of evaporation of

approximately 10%. Large annual variation in the magnitude of this adjustment is likely, reflecting the changeable severity of the Scottish winters.

4. During the non snowy periods there is good agreement between the modelled and the P-Q values for both Monachyle catchments, (heather and upland grass). For periods including snow the catchment P-Q values are generally systematically higher than the model predictions.

5. For the Kirkton catchment the model predictions of annual evaporation are systematically higher than the P-Q values. Elimination of the snowy periods does not improve the correlation between the approaches, though the characteristics of the catchment make this analysis more difficult.

The effect of the clearfelling on the evaporative losses in the Kirkton has been masked by an upward trend in evaporation. This is a result of changes in the severity of the winters, and changes in the rainfall and potential evaporation patterns over the period of analysis.

APPLICATION OF MODEL TO OTHER SCOTTISH CATCHMENTS

1. Data from seven upland catchments, selected to investigate a range of afforestation and climatic conditions, were analyzed over the period 1987-1990. The catchments investigated together with the percentage of afforestation are: Ettrick (Borders), 25%; Tima (Borders), 90%; Dargal Lane (Loch Dee, Galloway), 0%; White Laggan (Loch Dee, Galloway), 18%; Green Burn (Loch Dee, Galloway), 67%; Kelty Water (Trossachs) 75%; and the Girnock (Grampians), 4%.

2. Significantly better correlation exists between the model's predictions and the catchment P-Q values, than exists between the Penman potential evaporation values and the P-Q values. The innate uncertainties of P-Q measurement means that no absolute water loss values exist to which the model can be unequivocally compared; the best approach would be to increase the sample size of the example catchments in order to reduce the random errors of measurement of P and Q.

3. Annual water losses from homogenous covers of vegetation are calculated over the rainfall range 800-4000mm. Predicted forest losses range from 700mm to over 1200mm and are always significantly higher than the moorland losses: heather 550-800mm, upland grass 400-450mm. In the low rainfall areas (<1000mm) it is predicted that a 100% coverage of mature forest will result in over three-quarters of the rainfall being evaporated. The relationship between the evaporative losses and precipitation for both heather and forest is predicted to be non linear.

4. The modelling results suggest that climatic variability between locations in Scotland prevent the production of simple rules quantitatively describing upland evaporative losses. Of most importance is the variability in snow cover, precipitation (number of rain days and amount) and Penman potential evaporation.

5. Preliminary comparisons of the model's predictions to the crude rule that a 10 % increase in mature forest cover results in a 1.5 to 2 % reduction of the original non-afforested catchment yield suggest that this crude rule may be too cautious in its estimate of the impact of afforestation. Secondly the inability of the crude model to distinguish between the pre-afforestation land uses (heather and upland grass) can result in large discrepancies in the crude model's estimates of evaporative losses from mature forest.

ADVANTAGES OF THE MODELLING APPROACH

1.The semi-empirical methodology followed in the report allows the findings of the most sophisticated and rigorous approaches, which have general applicability, to be incorporated into a simpler model.

2. The strictly empirical approach of quantifying the evaporative losses via catchment water balance studies provides little understanding of either the actual processes involved, or of the effects of different site factors; and consequently can only be considered a really valid approach for the catchment in which the estimates are derived. Conversely, since the modelling approach is based upon an understanding of the processes, and the climatic conditions that control them, its predictions will be more widely applicable than the catchment water balance results.

3. The semi-empirical model, as described in this report, requires less detailed meteorological data than highly sophisticated models whose complex data requirements usually restricts their use to only research applications. The general paucity of meteorological data in the Scottish uplands precludes the use of the more sophisticated modelling approaches and can also hinder the direct application of the simpler semi-empirical model. But since the semi-empirical model requires simpler input data it is possible to synthesis any missing datasets; enabling useful comparisons of predicted water losses to be made for different landuse scenarios at any particular upland location in Scotland.

4. The daily time step of the evaporation model permits the investigation of the seasonal consequences of altering the landuse.

POSSIBLE REFINEMENTS TO THE MODEL

1. Further understanding of the following issues may enhance the performance of the model: forest edge effects, cloud deposition, evaporative losses from young trees and losses associated with snow.

2. The environmental conditions in the drier eastern uplands of Scotland are slightly different to those in the west. There are differences in climatic variables, forest species composition and likely soil moisture status. It is not known if the impact of these will significantly alter, if at all, the model or the modelling results as presented in this report. Validation of the model and further modelling studies would much enhance the confident application of the model in such areas.

MODEL'S USE IN PRACTICE

The model is designed specifically to predict the evaporative losses from Scottish upland areas where the land cover is comprised of hill grass, open moorland or mature plantation coniferous forest. In practice it will principly be used to assess the impact that varying degrees of afforestation will have upon the evaporative losses of a catchment, and hence the impact of plantation forestry upon the average catchment yield. The paucity of meteorological data in the uplands is not seen as a problem. Synthetic data can be produced, to a suitable degree of accuracy, to enable valid assessment of the relative magnitudes of the evaporative losses associated with differing land use scenarios, at any upland location.

1 Introduction

The Balquhidder paired catchment study has for 14 years investigated the impact of afforestation upon upland water resources. The programme of research over this period has been formulated to meet the requirements of the following consortium objectives:

1. To replicate and extend the Plynlimon study in mid-Wales, on the effects of upland afforestation on water resources, into upland Scotland where the indigenous vegetation, typically coarse grasses and heather, is aerodynamically rougher than the short cropped grass found in Wales and where the distribution and type of precipitation is also different.

2. To develop and improve applied evaporation models for upland areas.

3. To determine the seasonal differences in evaporation rates, including snow conditions, between forest, heather and grass and also the spatial variability of upland meteorological parameters which control evaporation rates.

4. To determine, in typical Scottish upland conditions of climate, topography and soils, the integrated effects of two different forms of land use: coniferous plantation forest and grazed open moorland, on streamflow and the sediment and nutrient loadings.

Many of the findings in respect to these objectives have already been published either in scientific journals or as reports to the funding consortium. Three publications are of particular importance:

> i) **IH Report 116: Effects of upland afforestation on water resources** (Johnson, 1991). This report summarised the work carried out by the Institute of Hydrology in the two Balquhidder catchments between 1981 and 1991. This report mainly addressed the water use issues by presenting the paired catchment results and introducing the development work of the evaporative model together with the results of the fluvial sediment studies.
>
> ii) **The effects of forestry practices on water quality and biota in the Balquhidder catchments 1983-1993** (Harriman & Miller, 1994). This report provided an integrated assessment of the effects of forestry practices on water quality and biota in both the Kirkton and Monachyle catchments.
>
> iii) **Journal of Hydrology Special Issue: The Balquhidder catchment and process studies** (Whitehead & Calder, 1993). In this special publication the key findings from the Balquhidder experiment were drawn together in the form of individual scientific papers. Papers included are relevant to all four objectives listed above.

The main purpose of this report is not to repeat the previously published results, but rather to present the recent developments and findings concerning the upland evaporation model, together with the latest catchment figures for water losses from the paired catchment study. Though the early work upon the model and the process studies has been described before, (Calder, 1990), (Hall & Harding, 1993), there has been no observation of recent developments of the model nor a detailed appraisal of the model's performance in comparison to actual catchment results. It is the purpose of this report to address these topics and to place the model in the context of its application across the uplands of Scotland.

2. Catchment Water Balance

2.1 INTRODUCTION

To calculate the water use of a catchment the runoff is subtracted from the precipitation according to:

$$E = P - Q - \Delta S$$

where, over a given time period, E is the catchment evaporation, P the catchment rainfall, Q the runoff and ΔS the increase in catchment storage. At Balquhidder the ΔS term is mainly influenced by snow storage and sub-surface stores. To reduce the magnitude of the storage term the results are presented using the hydrological year time period (1^{st} October to 30^{th} September).

To monitor the precipitation inputs a dense network of over 30 raingauges were installed across the catchments, (Johnson *et al*, 1990). Precipitation figures from 1981 to 1993 are presented, table 1. To place these in the context of a longer local data set the Loch Venachar (Met. Office, 1930-92) annual values are illustrated in figure 1. Loch Venachar is located 15 km to the south of Balquhidder.

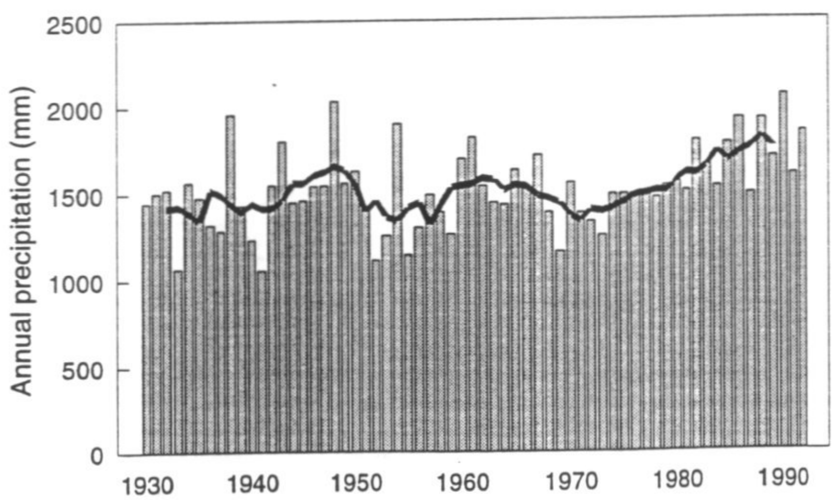


Figure 1 *Loch Venachar 1930 to 1992 precipitation time series. 5 year running mean plotted to highlight trends.*

To measure the runoff crump weirs were installed at the outlets of the main two catchments, and a flat "V" weir at the Upper Monachyle site, (Johnson and Hudson, 1987).

2.2 BALQUHIDDER P-Q

The values of precipitation, runoff , P-Q and (P-Q)/P for each of the three Balquhidder catchments are presented in table 1. The precipitation figures for the Monachyle catchment are displayed in figure 2; and the water loss values are shown in figures 3 and 4. Clearfelling commenced in Kirkton during 1986 when 34.5% of the catchment had canopy cover. By 1993 this coverage had been reduced to 13.4%. During 1988 14% of the Monachyle catchment was planted with young trees, (canopy closure is expected after 12 to 15 years). No land use change has occurred in the Upper Monachyle.

A full discussion of these results is made in chapter 4 in comparison to the model's predictions.

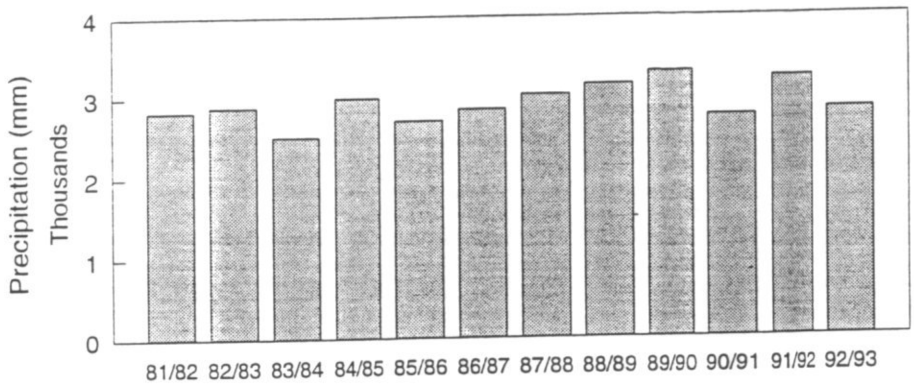


Figure 2 Balquhidder precipitation, plotted in hydrological years.

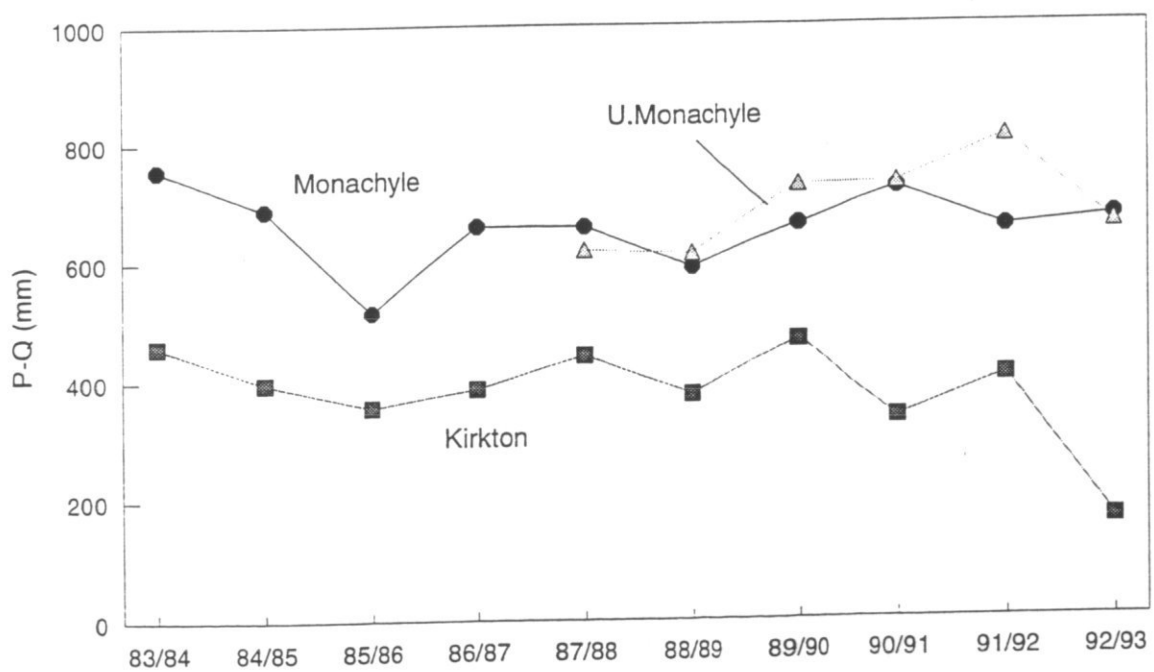


Figure 3 P-Q for the Balquhidder catchments. Plotted in hydrological years.

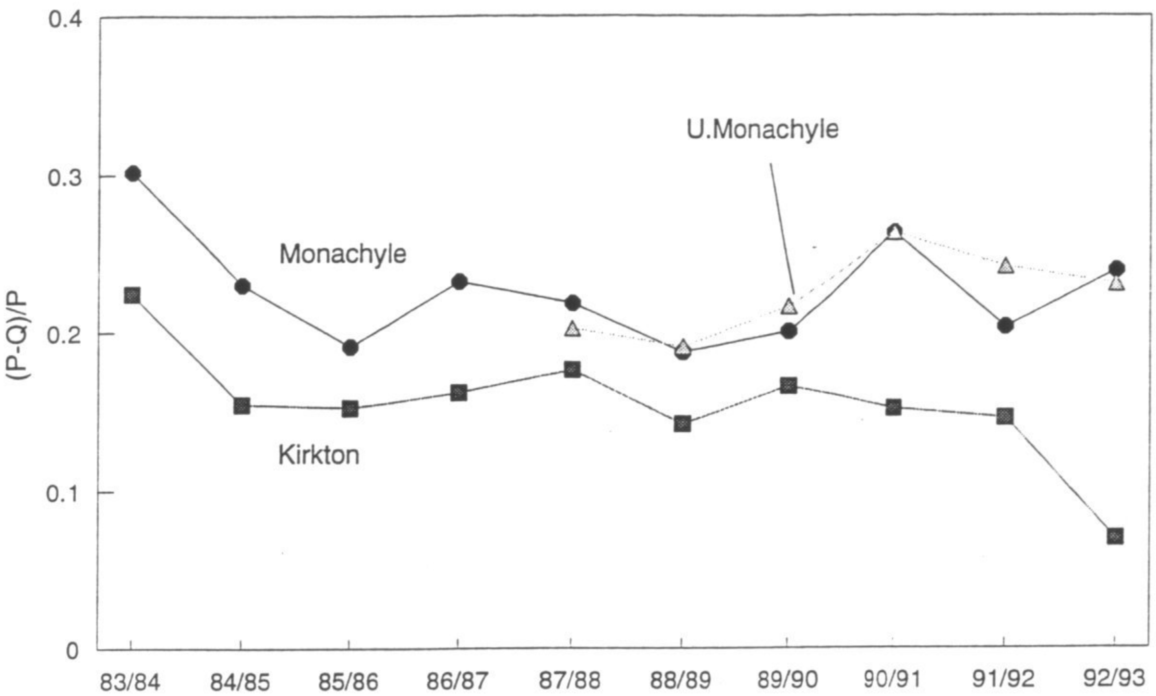


Figure 4 *(P-Q)/P for the Balquhidder catchments. Plotted in hydrological years.*

	KIRKTON				MONACHYLE				U.MONACHYLE			
YEAR	P	Q	P-Q	(P-Q)/P	P	Q	P-Q	(P-Q)/P	P	Q	P-Q	(P-Q)/P
81/82	2457				2822				2924			
82/83	2541				2881				2913			
83/84	2045	1586	459	0.224	2508	1752	757	0.302	2544			
84/85	2568	2171	397	0.155	2994	2305	690	0.230	3021			
85/86	2349	1991	358	0.153	2702	2185	517	0.191	2725			
86/87	2392	2004	388	0.162	2845	2184	661	0.232	2901			
87/88	2513	2070	443	0.176	3024	2364	660	0.218	3057	2438	620	0.203
88/89	2657	2279	377	0.142	3151	2559	591	0.188	3222	2607	615	0.191
89/90	2827	2359	469	0.166	3304	2641	663	0.201	3366	2637	729	0.217
90/91	2235	1896	339	0.152	2753	2030	723	0.263	2786	2055	732	0.263
91/92	2795	2387	408	0.146	3228	2572	656	0.203	3346	2538	808	0.241
92/93	2367	2202	165	0.070	2826	2151	675	0.239	2876	2212	663	0.231
Means												
83/93	2475	2095	380	0.154	2933	2274	659	0.227				
87/93	2566	2199	367	0.142	3048	2386	661	0.219	3109	2414	694	0.224

Table 1 Yearly values of precipitation, runoff, P-Q and (P-Q)/P for the Balquhidder catchments.

3 Evaporation model: Description

3.1 INTRODUCTION

The production of a suitable evaporation model for the uplands of Scotland has been a major objective of the research programme at Balquhidder. Over the last 14 years much effort has been expended in its development to enable the project's findings to be transportable to other upland regions within Scotland, and the rest of the UK.

The key issues that the model is able to address are principally those of land use change, and, to a lesser extent, the effects of climatic change. For example, the conversion of moorland to coniferous plantation forest, and vice versa, has long been recognised as being of hydrological importance and, as a consequence, brings the requirement for operational hydrological models that can assess the impact of the change upon catchment water yields. Such tools have clear benefits for water resource and environmental managers alike.

Ideally the model should be simple; partly for easy application but more importantly because of the general paucity of environment data for the upland regions, which effectively constrains the model's possible complexity. Yet with this in mind the model's accuracy should not be compromised and careful selection of model complexity is necessary such that the limited input data can be effectively accommodated. The model is required to account for evaporation from the major upland vegetation classes of upland grass, heather and coniferous forest. Snow also constitutes an evaporation surface and, in the terms of the UK, is of particular significance in the Scottish uplands and therefore also needs to be incorporated. As does brash, which after the clearfelling of forest also represents a significant land cover for some time.

3.2 MODELLING APPROACH

The approach adopted to develop and construct the physically realistic model was as follows. Detailed process studies were conducted to investigate the evaporative losses from each of the key vegetation types. These small scale studies were located at environmentally representative sites within the catchments, and were run over a time scale of no less than a year to ensure proper accounting of seasonality. From these plot studies the dominant processes governing the rates of evaporation were identified and related to the climatic variables that control potential evaporation. The evaporation loss, with respect to transpiration and interception from each of the vegetation types, are then brought together to construct the final model, which can be applied over much larger scales, ie a whole catchment.

The model is run in a lumped deterministic form; though, if advances are made in spatial and temporal distributed modelling it will be eminently suitable for incorporation into a fully distributed format.

Implicit within an evaporation model is the requirement of a variable that describes the climatic potential for evaporation. This variable can then be used within the structure of the model as an index to which rates from different surfaces can be compared. Several approaches and formulae exist to do this but the one that has tended to gain the greatest recognition, and has hence been incorporated into this model, is the Penman potential (E_T) equation (Penman, 1948), and (Appendix 1). Importantly for Scotland, and particularly for the upland regions, there is complete data coverage for this variable via the figures presented in the MAFF Technical Bulletin No. 16 (MAFF, 1967) and in a comparable form from the MORECS (Thompson *et al.*, 1981) datasets, 1961 to present. The availability of these data prevents the necessity of local weather station data for all but the most detailed studies when applying the model.

3.3 MODEL DESCRIPTION

Evaporation from a vegetated surface can be split into two general processes: transpiration and interception. Transpiration refers to the water that is released from the plant's stomata as a result of photosynthesis. Physical controls such as sunlight, evaporation potential and soil moisture status influence the water loss as well as physiological controls such as stomatal control, rooting characteristics and root water potential. Since photosynthesis is fundamental to the process it is obvious that a high degree of seasonality will be observed for all plants.

Interception is the evaporation of precipitated water from a plant's surface. The plant's ability to intercept rainfall (or snowfall) will to a large extent determine the evaporative losses. This will depend upon the density and size of the canopy, its physical structure and the ability of water to wet the vegetation's surfaces. There is also an obvious dependence upon the frequency of wetting, hence the rainfall and snow characteristics of the region are a key component of any model and will, to a great extent, determine the seasonality of the interception losses.

The aerodynamic roughness presented by the vegetation is also important to both processes. Aerodynamically rougher surfaces ensure greater turbulence and a higher degree of vertical mixing within the air column which is fundamental to evaporation processes. Rough canopies such as those of trees are therefore more likely to be able to maintain higher rates of evaporation than smoother surfaces such as grass or snow.

The model, where possible, addresses the transpiration and interception separately for each landuse type. In the case of the upland grass this is not possible and the preferred approach is to combine the processes in to one expression. Snow and brash surfaces only effectively have an interception term. The model therefore has the following forms:

$$E_D = f_g E_g + f_h E_h + f_f E_f + f_b E_b + f_s E_s$$

or

$$E_D = f_g E_g + f_h (T_h + I_h) + f_f (T_f + I_f) + f_b E_b + f_s E_s$$

Where E_D is the total daily actual evaporation (mm); $f_\#$ the fraction of region covered; g, h, f, b and s represent upland grass, heather, conifer plantation forest, brash and snow respectively; $E_\#$ is the daily evaporation (mm); $T_\#$ the daily transpiration component (mm) and $I_\#$ the interception component (mm). Each of the major component parts has been investigated via detailed process studies as outlined below. For a full mathematical description of the model refer to appendix 2 and 3.

3.3.1 Upland grass process study

Interception studies upon grass are impractable, therefore the water uses due to interception and transpiration were investigated together. To accomplish this two weighing lysimeters were operated during 1988 and 1989 at Balquhidder. The site was judged to be representative of the local upland grass, and was at an altitude of 595 metres, (Wright & Harding, 1993). The results showed an evaporation rate significantly below that of Penman potential (E_T). This was particularly evident during the spring and early part of the year when the grass was described as being more dormant. This water use was well estimated using E_T multiplied by either a temperature dependent function or a seasonally dependent function representing the change in the quantity of live foliage. The latter function, which also incorporates a simple interception function, was used in the main model:

$$E_g = \{(1 - 0.5A) + 0.5A \sin[2\pi(d - 141)/365]\}E_T \quad \text{if } P < E_g$$

$$E_g = E_T \quad \text{if } P > E_T$$

$$\text{otherwise } E_g = P$$

where A is the amplitude of the seasonal function, d is the day number and P the daily rainfall. See Appendix 3 for details of constants.

3.3.2 Heather and forest process studies

It is convenient to discuss both these vegetation types together since the mathematical expresssions for their evaporation are similar but with differing parameter values. The expression is of the form:

$$E = \Gamma(1-\omega) + I$$

where ω is the fraction of the day that the vegetation's canopy is wet, Γ is the daily potential transpiration rate and I is the daily interception loss. For heather $\omega = 0.068P$, or $\omega = 1$ for $P \geq 14$mm, a relationship derived, together with the interception parameters, from modelling studies of interception loss from heather using a wet-surface weighing lysimeter (Hall, 1985; Hall, 1987). For the forest $\omega = 0.045P$, or $\omega = 1$ for $P \geq 22$mm, (Calder, 1986).

Soil moisture observations from Balquhidder and Crinan Canal reservoirs, (west coast of Scotland), over a 3 year period, (Calder, 1986), were used, together with information from heather lysimeter work in the North Yorkshire Moors, (Wallace *et al., 1982),* to determine the transpiration rate (Γ_h) as $0.5E_T$. Similarly for forest the transpiration rate, $\Gamma_f = 0.9E_T$, (Calder, 1977).

Daily interception losses are modelled using an exponential model, (Calder, 1990).

$$I = \gamma(1 - e^{-\delta P})$$

where γ (mm) is a parameter that describes the maximun predicted loss in 1 day and δ (mm^{-1}) is an empirical interception parameter. For heather the values used for these parameters were taken from Hall (1987). The interception parameters for forest were obtained from the net rainfall measurements of Johnson (1990) that were taken over a three year period (1983-1986) within the Kirkton forest. For a full list of the parameter values used in the model refer to Appendix 3.

3.3.3 Evaporation from snow and brash

When snow covers short vegetation the resulting surface becomes aerodynamically very much smoother, hence inhibiting the turbulent transfer of heat and water vapour and hence the evaporation rate. Snow also reflects considerably more of the incident short wave radiation. Fresh snow has an albedo value of about 0.95, (Oke, 1987), which helps to suppress the net radiation term to nearly zero. The snow also provides a surface suitable for condensation. These effects collectively reduce the evaporation from snow covered short vegetation to almost zero, as demonstrated experimentally by Harding (1986) from regions with similar climates to Scotland.

From conifer stands the situation is more complicated due to the canopy's surface roughness, the canopy's differing ability to intercept different forms of snow and the processes that redistibute the canopy held snow to the ground. To investigate this in Scotland, where the frequent occurrance of thaw events makes normal interception studies difficult to interpret, a γ-ray attenuation system was installed in the Queens Forest near Aviemore in 1983. This was subsequently operated during the winters of 1983/84 and 1984/85, (Calder, 1990). From both these observations and subsequent modelling the interception losses for snow were identified as being of the same order of magnitude as that for rain. Intercepted snow losses from the forest is therefore treated in the same way as rainfall losses though transpiration losses are reduced to zero.

Brash, the branches and tree tops that are left on site after felling, constitute a distinct land cover class, albeit a transitory one. For the purposes of the model the brash's residence time is taken to be two years after which the land is classed as short or medium height vegetation depending upon the characteristics of the new growth. Due to the variability of the brash characteristics (due to differing harvesting techniques) it is difficult to assign an accurate interception term. The interception term therefore adopted is that for heather (medium height vegetation) due to their similar physical dimensions. No transpiration term is applicable.

3.4 SOIL MOISTURE DEFICITS

During dry periods utilization of water by plants results in the formation of a soil moisture deficit (SMD). The longer this occurs the more moisture depleted the rooting zone becomes, and, unless rainfall replenishes this deficit, it can adversely effect the metabolism of the plant and reduce transpiration. A rooting constant (RC) is commonly used to specify the maximum deficit that the plant can withstand before transpiration is inhibited. The root constant is considered to be a function of both plant and soil characteristics. High interception rates will also influence soil moisture deficits by reducing the net rainfall to the ground; replenishment after a dry period will then occur later.

Many soil moisture deficit models, covering a large range of complexity, have been devised using the concept of rooting constants, (Calder *et al.*, 1983). Within this upland evaporation model a relatively simple form is incorporated since the lack of soil moisture datasets typical of both upland vegetation and soil precludes detailed description on a nationwide basis. Also, higher degrees of complexity applied to detailed plot studies seem only to provide limited improvements, (Calder *et al.*, 1983), and these are probably of limited value when applied on the catchment scale.

The SMD model operates on a daily timescale. Transpiration is assumed to occur at the normal uninhibited rate until a threshold RC is reached. Transpiration rate is thereafter reduced to 1/12th until the SMD is replenished to above the RC threshold and the normal transpiration rate is assumed to return. A similar regulating function was proposed by Penamn (1949) which gained common acceptance for operational SMD forecasting in the lowlands. Within the model it is assumed that: i/ there is no drainage from the soil once the soil moisture field capacity is reached; ii/ that the moisture content of the soil will, if it exceeds the field capacity, return to field capacity after one day; and iii/ that the change in moisture content of the soil is equal to the precipitation minus the interception and transpiration, (as regulated by the above function). i.e.

$$\Delta SM_{h,f} = P - I_{h,f} - T_{h,f} \quad \text{or} \quad \Delta SM_g = P - E_g \quad \text{for grass,}$$

$$SMD_{i+1} = SMD_i + \Delta SM_{i+1} \quad \text{for } SMD_i \leq 0$$

$$SMD_{i+1} = \Delta SM_{i+1} \quad \text{for } SMD_i > 0$$

where: $\Delta SM_{\#}$ is daily change of soil water content; P daily rainfall; $I_{\#}$ daily interception loss; and $T_{\#}$ daily transpiration loss where $T_{\#} = T_{\#}$ when $SMD_{\#} > RC_{\#}$, and $T_{\#} = T_{\#}/12$ when $SMD_{\#} \leq RC_{\#}$, (where E_g is equivalent to T_g). Note that a soil moisure deficit is given a negative value, as is the rooting constant. This description of SMD is used to regulate transpiration losses during dry periods in the main evaporation model.

Taking single, absolute values of RC for the different vegetation types is perhaps inappropriate due to the RC's dependence upon soil type. Within this report a range of RC values for each vegetation type is therefore the favoured approach, table 2, (Shaw, 1991), (Ward & Robinson, 1990), (Thompson *et al.*, 1981).

Table 2 Upland rooting constants.

Vegetation	Rooting constants (mm)		
	Min.	Max.	Avg.
Upland grass	-50	-150	-100
Heather	-100	-200	-150
Coniferous trees	-150	-250	-200

3.5 EXAMPLE MODEL PREDICTIONS FOR DIFFERENT LAND COVERS.

In order to illustrate the relative magnitudes and seasonality of the inter and intra-species components of the model the 1992 Kirkton rainfall and Penman potential evaporation datasets (Figure 5) are used upon example 100% land cover classes .

Figure 5 illustrates a potential evaporation series typical of the climate of the Scottish uplands. The low winter daily rate, of just above zero, contrasts strongly with the mid year maximum of just over 3mm/day. This strong seasonal pattern will be mirrored in how the model describes the transpiration terms for the respective vegetation types.

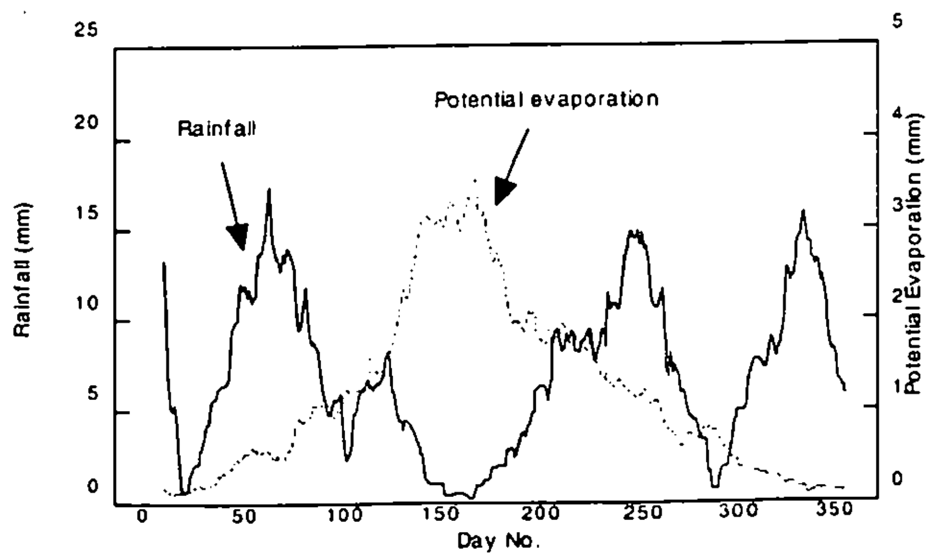


Figure 5 1992 Kirkton catchment precipitation and potential evaporation daily data, smoothed using a 20 day running mean.

The precipitation pattern depicted is more complex and can only be used as an example year as opposed to a typical distribution since there is considerable year to year variation. The figure clearly shows several wetter periods during the course of the year. This time series plays an important role in controlling the interception losses estimated by the model.

Though some of the winter precipitation did fall as snow it is all treated as rainfall to enable full seasonal examination of the different vegetation types under non snowy conditions. The water use of each vegetation is calculated on a daily basis and is illustrated in two ways: i) daily water use, ii) accummulative time series. To reduce noise in the data and emphasize the seasonal trends a 20 day running mean is deployed through the daily time series.

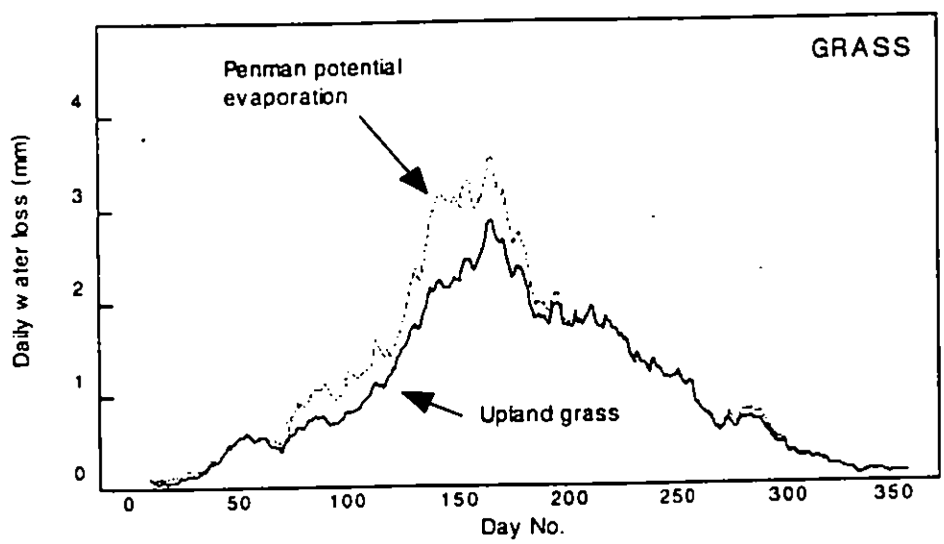


Figure 6 Daily evaporation rates for upland grass as predicted by the model.

Figure 6 shows the model's prediction of daily evaporation from upland grass. Its seasonal trend closely follows that of the Penman estimate for lowland short grass but deviates significantly during the spring and early summer. This reflects the relatively dormant state of upland grass after the winter period, (Wright & Harding, 1993). During this example year the soil moisture deficit modelled below the grass was not sufficient to affect the transpiration rate. If the grass were covered by snow the evaporative rate would be assigned a value of zero. It is evident that this would only have a relatively small impact upon the total annual evaporation since losses from grass are relatively low during the winter.

Figures 7 and 8 illustrate the seasonal water use of heather. Figure 7 shows that there is not a pronounced summer maximum in total evaporation. For this example year the the total rate remains relatively constant throughout the year. Transpiration appears to be the dominant process for only a relatively short period during the summer, and at this time the losses from heather are only about two-thirds of those of the upland grass. For this example year the soil moisture deficit modelled beneath the heather was also not sufficient to affect the transpiration rate.

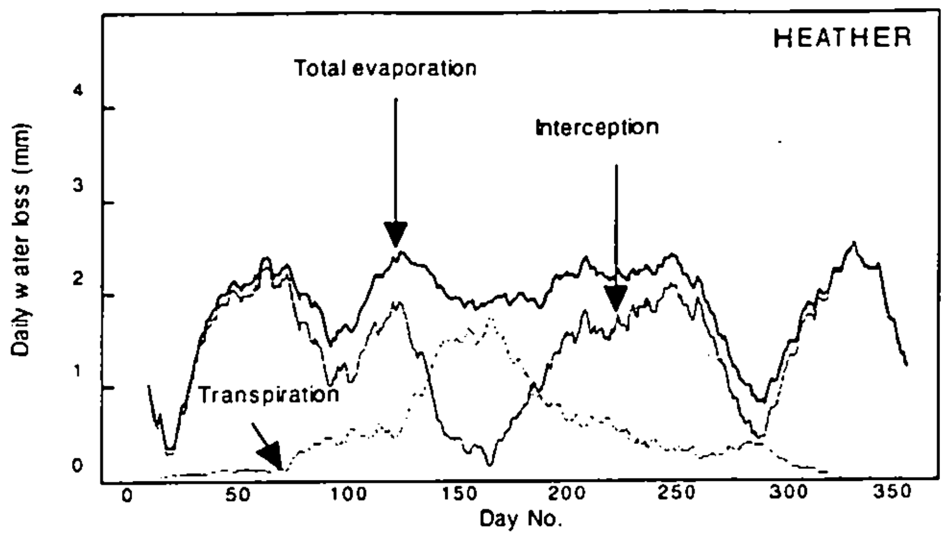


Figure 7 Daily evaporation rates for heather illustrating the seasonal distribution of transpiration and interception, as predicted by the model.

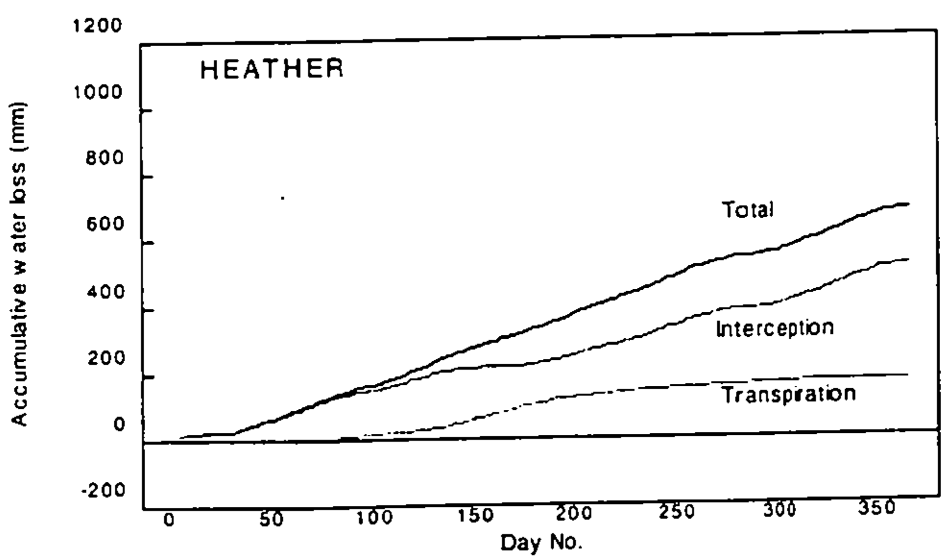


Figure 8 Accummulative totals for heather, as predicted by the model.

During the rest of the year the interception term clearly dominates with the variability closely reflecting the rainfall's own variability. The annual dominance of the interception term is illustrated in figure 8 where its accummulated magnitude is almost three times that of the transpiration term.

Figures 9 and 10 illustrate the seasonal water use of coniferous trees. As for the heather there is not a pronounced seasonal maximum. The transpiration process is dominant only for a relatively short period during the summer. The rest of the year the interception term is dominant, and again reflects the rainfall pattern.

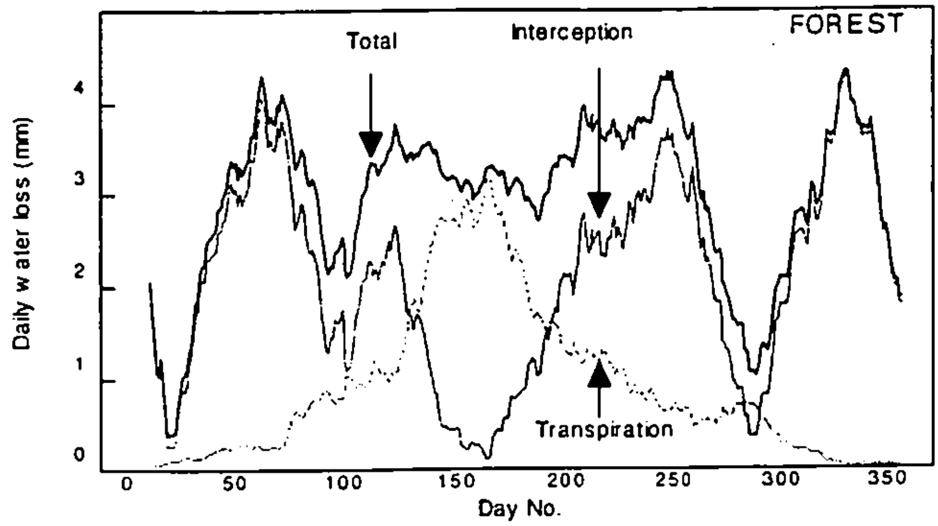


Figure 9 Daily evaporation rates for coniferous forest illustrating the transpiration and interception components, as predicted by the model.

Again, as for both grass and heather the soil moisture deficit was not sufficient to affect the transpiration rate in this example year.

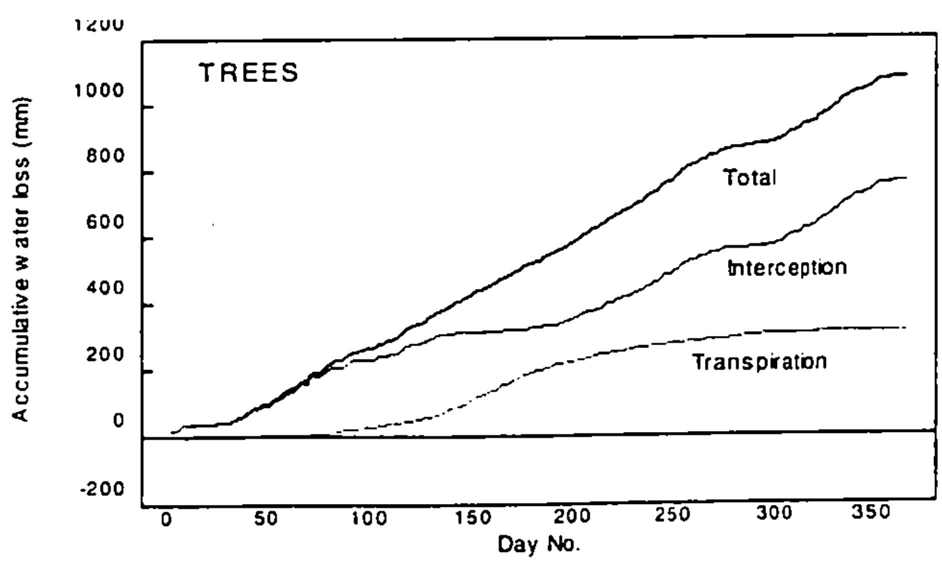


Figure 10 Accummulative totals for coniferous forest, as predicted by the model.

Figure 10 suggests that the interception process causes significantly more water loss from forest than transpiration. The interception term is roughly two and a half times that of the transpiration for these datasets.

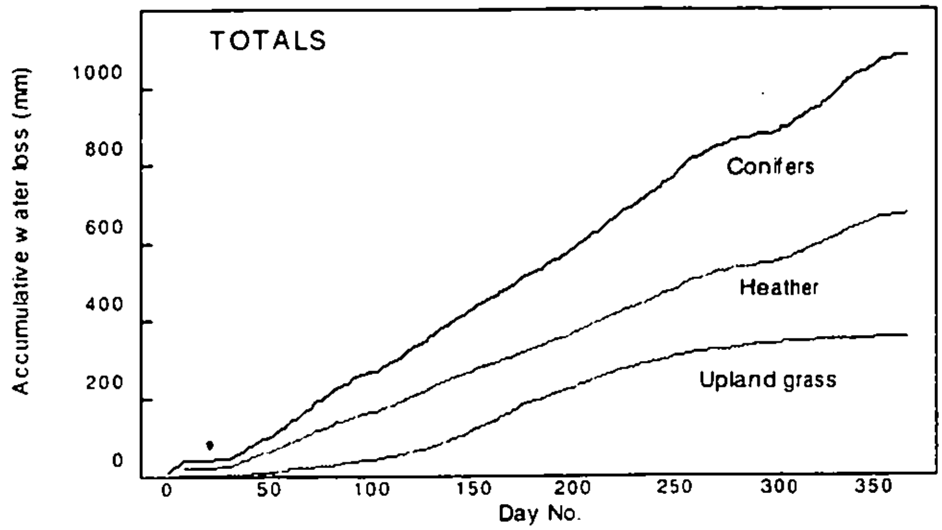


Figure 11 Total cumulative water use for upland grass, heather and coniferous forest.

Figure 11 shows the total water uses of the three types of vegetation. For the Kirkton weather data set used here the model predicts that the forest will use about 3 times as much water as the upland grass and that heather will use nearly twice as much as the grass. Also the heather and conifers will exhibit a similar seasonal water use, whereas the upland grass will, due to its dormant winter state, follow a different pattern that has a summer maximum.

4 Evaporation model applied to Balquhidder

4.1 INTRODUCTION

The Balquhidder hydrometric monitoring offers the opportunity to apply the model to continuous datasets from three different upland catchments: the Kirkton, Monachyle and U.Monachyle sub-catchment. The catchments have been operated for sufficient duration to encompass much of the natural climatic variation typical of the Scottish uplands. This is of importance since variations in such factors as snow coverage or precipitation may have important implications for catchment evaporation rates. Complete daily input data for the model exists from 1983 to 1993 for both the Kirkton and Monachyle catchments, and for the U.Monachyle from 1987 to 1993.

To minimize the seasonal storage term, ΔS, in the water balance, the model has been applied to hydrological years (1st October-30th September) as opposed to calender years. This has the considerable advantage of reducing annual snow storage errors to zero.

It is also important at Balquhidder to include the altitudinal variation in the model's input parameters. Snow line, and hence snow coverage, have an obvious altitude dependence that is related to temperature. Rainfall and E_T are also, to some degree, a function of altitude. Since these parameters govern the respective rates of evaporation from the vegetation types it is clear that altitudinal distribution of vegetation could also have a significant effect upon overall water losses. Forestry is a good example of altitude dependent vegetation: tree lines rarely exceed 500 metres above sea-level. To accommodate this altitudinal variation and to investigate its likely importance, the model has been run in two ways in the following sections. Firstly whole catchment averages of the model inputs have been used, this assumes that the inputs and land covers are evenly distributed throughout the catchment; and secondly the catchments are split into areas above and below 500 metres and treated separately. This roughly divides the catchments into two similar sized parts, (Kirkton area: 60% > 500m, 40% < 500m; Monachyle area: 45% > 500m, 55% < 500m).

4.2 BALQUHIDDER INPUT DATA

4.2.1 Precipitation

Figure 12 shows the precipitation inputs for the three catchments plotted by hydrological year. These values are calculated from measurements made from a dense network of rain gauges (Johnson *et al.*, 1990) and are daily distributed for input into the model. Precipitation above and below 500 metres was calculated from the comparison of the zonal raingauge sub-network totals to those of the whole catchment network, table 3.

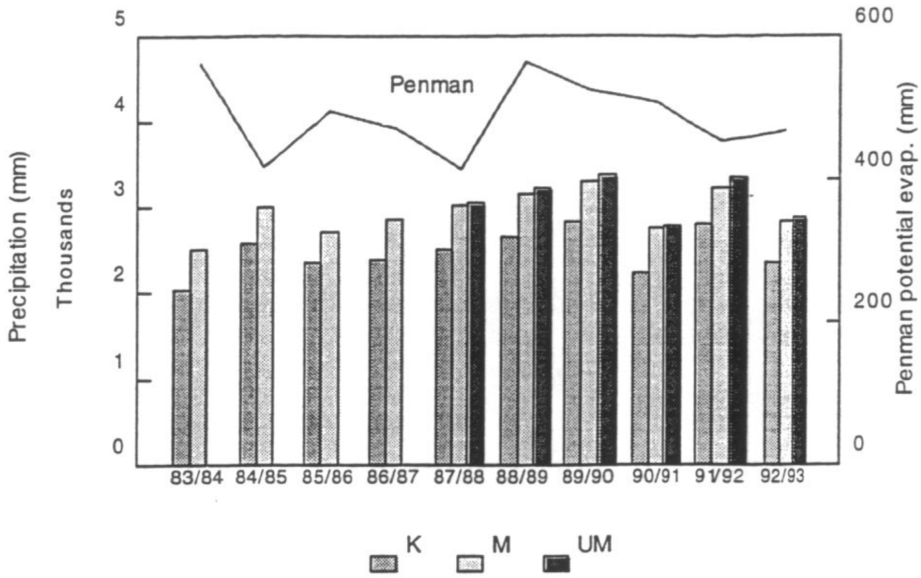


Figure 12 *Hydrological year annual values for whole catchment precipitation and Penman potential evaporation.*

Table 3 *Altitude zone precipitation ratios compared to whole catchment figures.*

Catchment	< 500 metres	> 500 metres	Whole catchment
Kirkton	0.954	1.031	1
Monachyle	0.949	1.063	1
U.Monachyle	-	-	1

In both the main catchments the input above 500 metres is roughly 10% larger , compared to that below. The U.Monachyle catchment was not split since it only has a small altitude range that is centred around 500 metres.

4.2.2 Penman potential evaporation (E_T)

Figure 12 also shows the yearly variation of E_T at Balquhidder. The values are derived from the four automatic weather stations located within the experimental catchments. These stations were carefully sited to: i) sample different altitudes; and ii) to be located in positions representative of their altitude. Hence the input into the whole catchment model is a daily average of all four sites. Work by Blackie and Simpson

(1993) suggests that within the Balquhidder study area the magnitude of E_T increases with altitude. To incorporate this into the data the average E_T value, described above, was multiplied by a factor of 1.05 for the zone above 500 metres, and by 0.95 for that below.

4.2.3 Vegetation coverage

Two independent classifications of the same satellite imagery (Roberts *et al.*,1993), (Cummins, 1994) were used to determine the vegetation within the catchments. Each method was given the same weighting and average values of the two techniques taken. Forest felling was monitored in the field on a monthly basis. Brash was classed as such for two years, thereafter it was proportionally split between the emergent vegetation types. The growth of young coniferous trees was related to mature trees via a linear function that gave trees mature canopy status after 15 years.

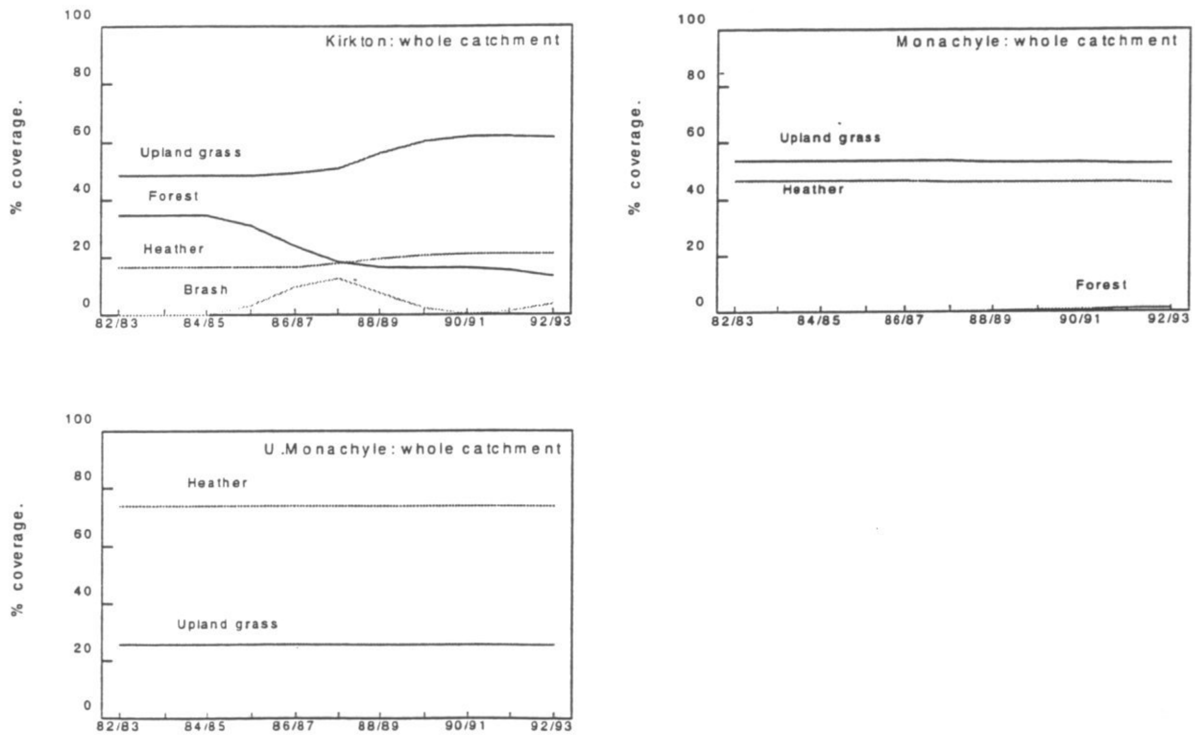


Figure 13 *Time trends in vegetation coverage for Kirkton, Monachyle and the Upper Monachyle.*

Figure 13 shows the chronological progression of the coverage of the various vegetation classes in the 3 whole catchments. Important, in particular to the Kirkton catchment, is the altitudinal distribution of the vegetation. Figure 14 shows the vegetation coverage as a percentage of the altitudinal zone. In the Monachyle the altitudinal variation between the heather and the upland grass is not obvious, but in the Kirkton there is marked vegetation distribution according to altitude. This suggests that the whole catchment estimates of evaporation may vary with those of the zonal model since the different vegetation types are likely to be subject to different climatic conditions.

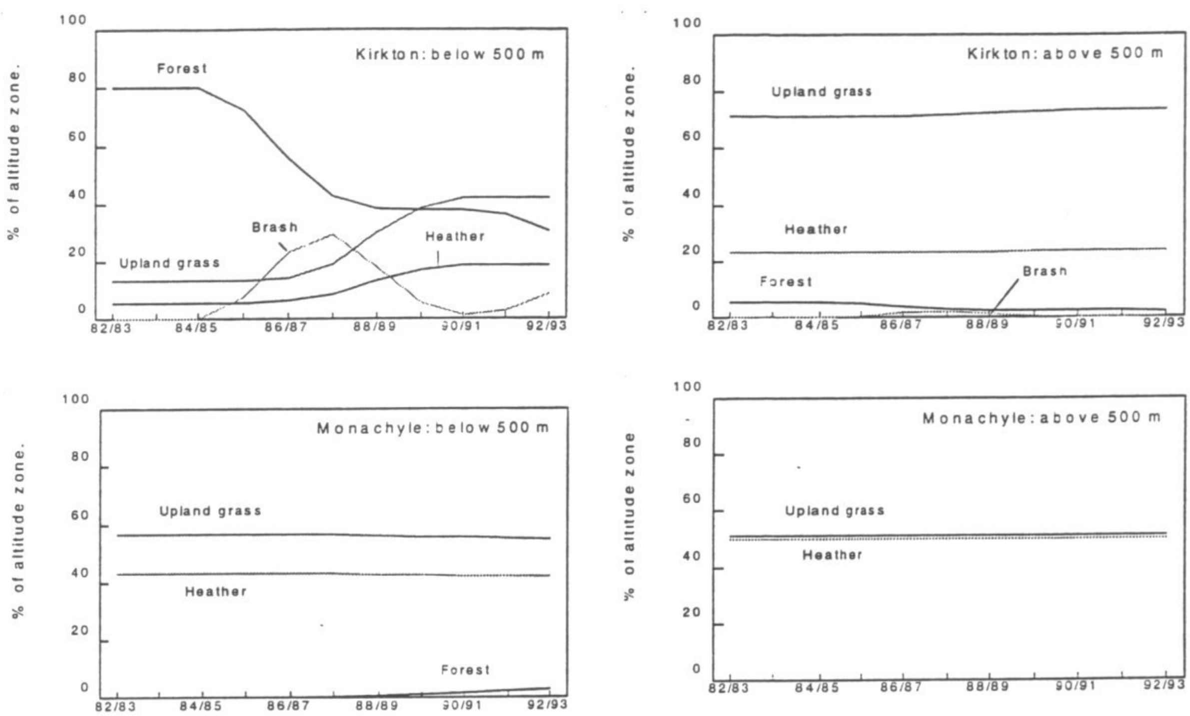


Figure 14 Catchment vegetation coverage split between two altitudinal zones above and below 500 metres for Kirkton and Monachyle.

4.2.4 Snow coverage

Snow in the uplands of the UK is often transitory, and only rarely are there winters in which a permanent snow pack forms that can be considered to be a stable seasonal land cover. Daily percentages of snow cover for each of the catchments are determined from daily snowline observations. These values were then used to calculate the catchment specific average snow cover for each winter, (figure 15). Winter in this instance is classed as the period when there is significant snow lying in the catchments. On average for the Balquhidder area this is from mid November to mid April.

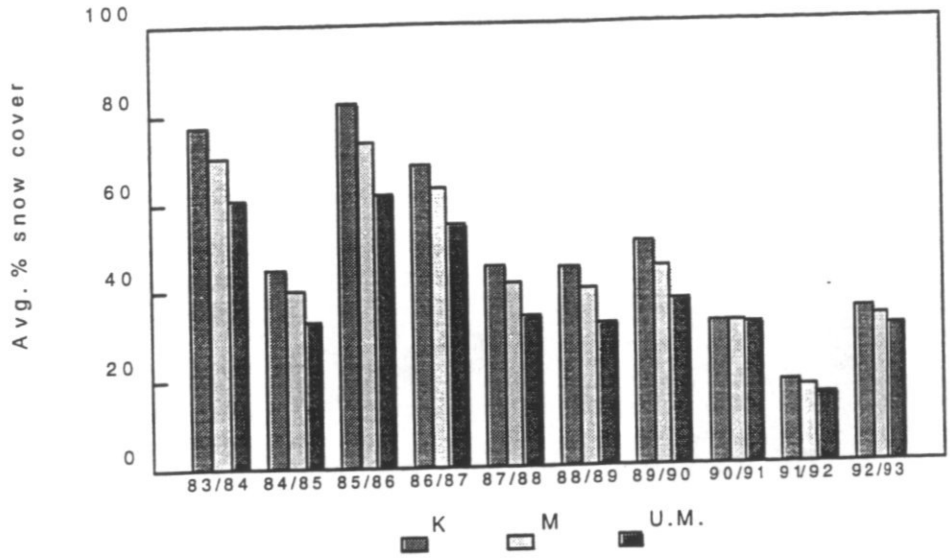


Figure 15 *Average annual snow cover for each catchment at Balquhidder.*

From the figure it is interesting to note that the average values for the catchments differ. This reflects the percentage of land at higher altitudes for each catchment. For example about 60% of the Kirkton is above 500 metres whilst for the Monachyle it is only 45%, hence the Kirkton will tend to have a larger percentage snow cover.

To incorporate these figures into the model the average snowlines for the catchments are used to re-calculate the vegetation distributions for each winter.

4.3 BALQUHIDDER MODEL RESULTS

4.3.1 Relative effects of vegetation and snow

Figures 17 a) and b) show the estimated contributions from the different vegetation types, with and without the assumed affects of the snow, for both the Kirkton and Monachyle Glens. The Kirkton graphs show that the forest's contribution in the early eighties constituted nearly half of the overall losses, even though the forest covered was only a third of the catchment. The model also predicts that the relative forest contributions reduce as the clearfelling proceeds from 1986 onwards, (refer to figure 13). The losses associated with the brash during and just after the most active felling period (1986-88) are significant. When the brash was most extensive, covering nearly 12% of the whole catchment, the losses from it accounted for 11.7 % of the yearly total. An interesting feature demonstrated by these graphs is the relative ratios of interception to transpiration, I/T, for forest and the heather. For 1992 (section 3.3.5) the I/T ratios for forest and heather were 2.5 and 3.0 respectively. Figure 17 shows that this relationship is not fixed. The variability of I/T with time is illustrated in figure 16.

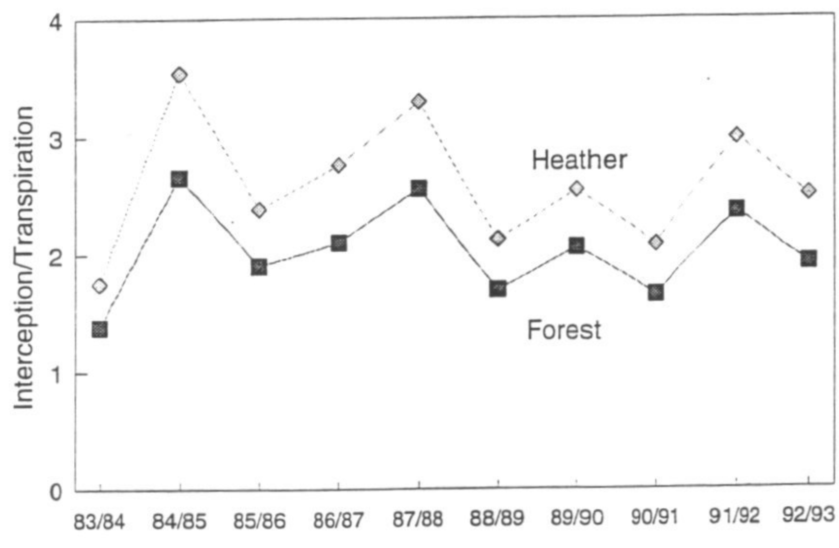


***Figure 16** Ratio of interception to transpiration for both coniferous forest and heather. (Interception divided by transpiration) Derived from annual totals taken from the Kirkton catchment.*

The variation is controlled by the magnitude and characteristics of the rainfall pattern together with the rates of potential evaporation experienced during the year. For example if more rain fell, or it were more evenly distributed throughout the days of the year, the model will predict an increase in the magnitude of the interception loss. More rain also reduces the time available for the vegetation to transpire. (Regression analysis of the I/T forest ratio against the annual rainfall gives $R^2 = 0.33$). The yearly variation in E_T also strongly influences the ratio. (Regression of the I/T forest ratio against annual E_T gives $R^2 = 0.8$). The mean ratios of interception to transpiration from

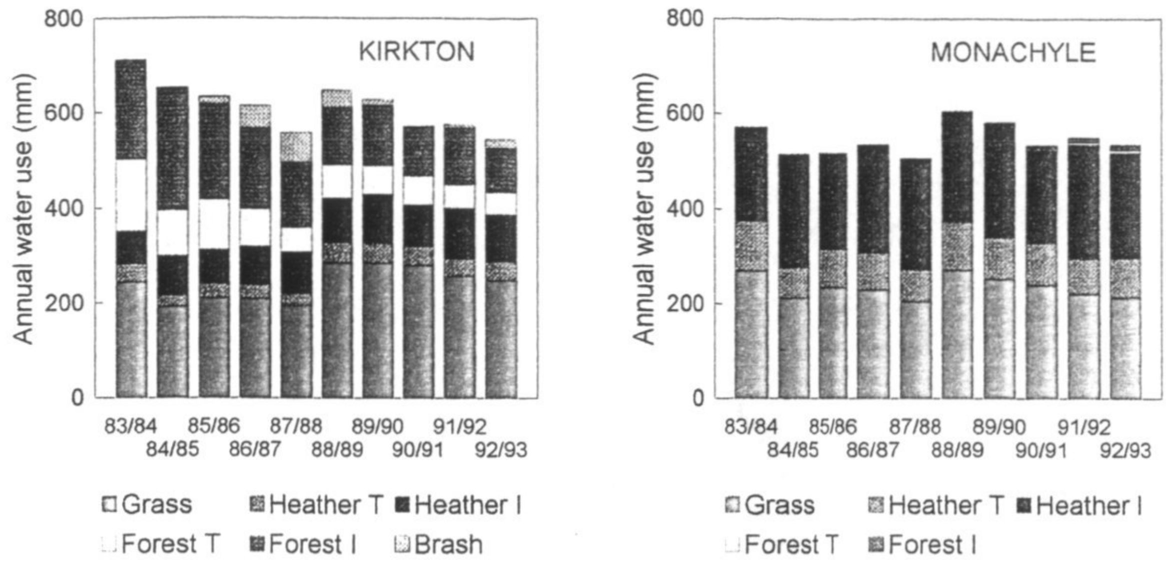


Figure 17a) *Model predictions of annual evaporation, without the inclusion of assumptions about snow evaporation rates.*

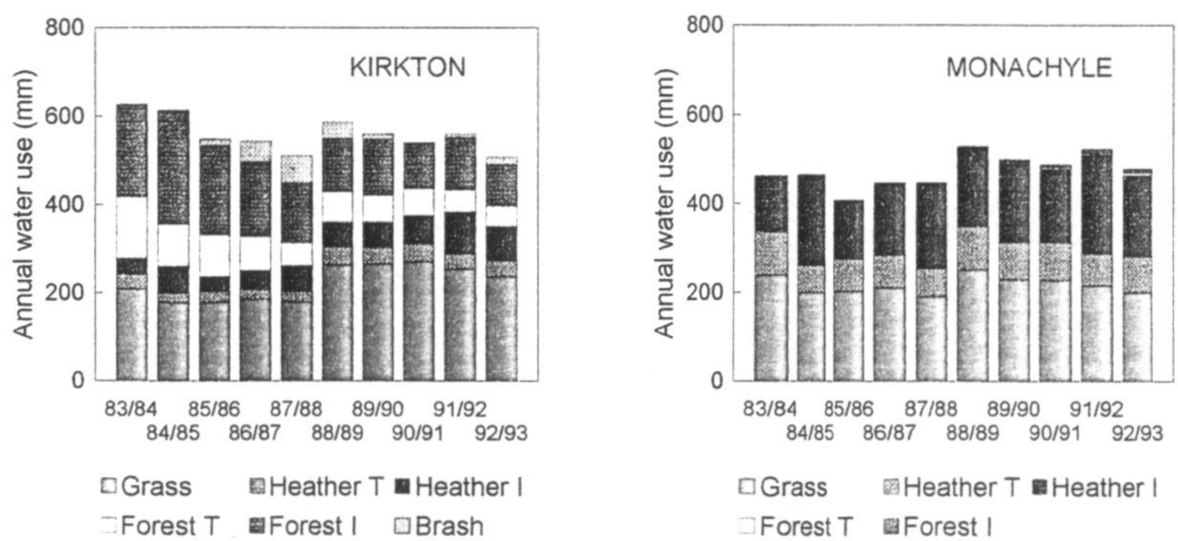


Figure 17b) *Model predictions of annual evaporation, with the inclusion of assumptions about snow evaporation rates.*

the ten years are: for the forest 2.02 (standard deviation 0.41), and for the heather 2.59 (standard deviation 0.56). The model predictions indicate that no simple, fixed ratio relates the magnitude of interception to transpiration for either the forest or the heather, and that the relationship is controlled by the prevailing climatic conditions.

Figure 17b) shows the lower catchment evaporation which is predicted when the effects of the snow lying on the vegetation are taken into account. Figure 18 more clearly indicates this. Good correlation between the magnitude of the decrease in evaporation and the "snowiness" of the year exists, (refer to figure 15). The 3 particularly snowy winters of 83/84, 85/86 and 86/87 cause smaller reduction for the Kirkton than for the Monachyle. This is because in these years the average snow level lowered to beneath the tree line. Since interception losses in the forest are assumed to continue unabated during the snowy periods this effectively lessens the influence of the snow in the Kirkton on evaporation as compared to the Monachyle where the evaporation is assumed zero where snow occurs.

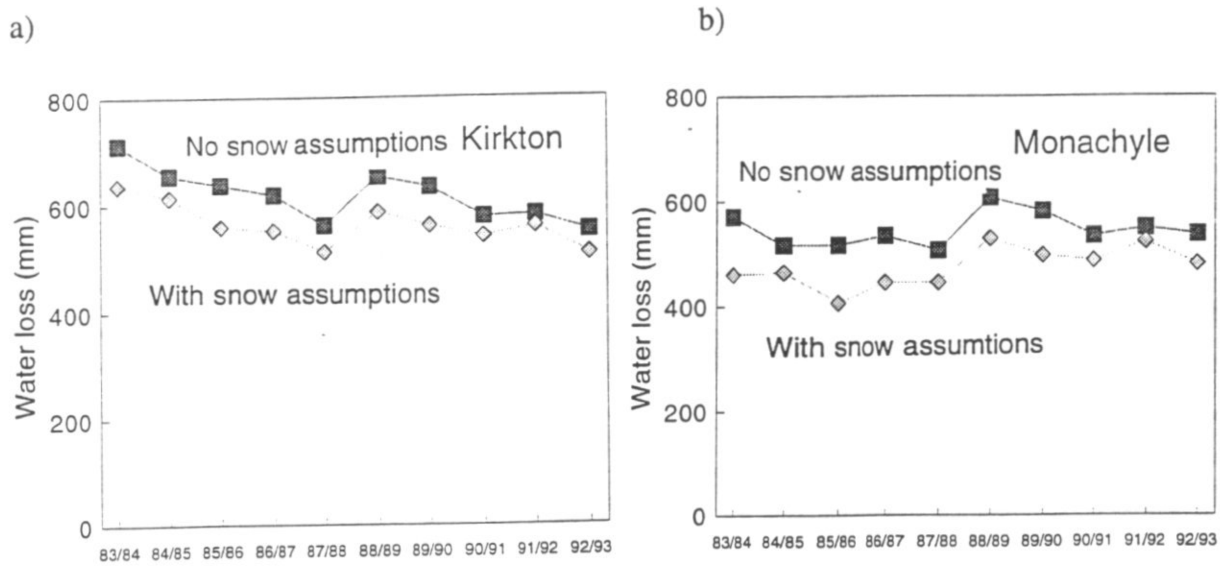


Figure 18 *a) Kirkton model estimates with and without the snow cover incorporated into the model. b) Monachyle model estimates with and without the snow cover incorporated into the model.*

The magnitude of the decrease, when snow is taken into account, is significant. The average yearly decrease for the Monachyle is 71mm which is equivalent on average, over the eleven years, to a reduction in the evaporation estimate of 13%. The maximum decrease in the Monachyle of 110mm occurs for both 83/84 and 85/86, which constitutes 19% and 21% respectively of the values when lying snow is not taken into account. In the Kirkton the average yearly decrease is 51mm, equivalent to 8% reduction in losses. A maximum reduction of 75mm occurs for both 83/84 and 85/86, which constitutes 10.5% and 11.8% respectively of the values when lying snow is not taken into account. These values indicate the sensitivity of model predictions of evaporation to the occurrence of lying snow. This also raises the question whether the assumptions that the evaporation from snow covered grass and heather is zero is valid and whether further process studies are required to investigate this component of the water balance.

Winter conditions have varied over the duration of the Balquhidder project, and, as a result, have introduced a complicating factor to the interpretation of the water use results. The predicted effect of snow is to suppress the catchment losses to a greater degree in the snowy years of the early 1980s. If nothing else had changed this would imply a slight increase of water use for the less snowy years of the late 1980s.

However there is evidence that the climatic conditions have varied during the course of the experiment. Not only have the severity of the winters changed but so has the potential evaporation and the rainfall. The potential evaporation showed a marked increase over the years 1988 -1991 compared to the period 1984 - 1988 suggesting increased losses. The precipitation totals have increased, and due to the reduction of the snowiness of the winters, more has fallen as rain. These changes suggest increased losses, as indicated (Figure 17b)) in the modelled estimates for the Monachyle catchment (which closely represents a control catchment). Conversely the partial clearance of the Kirkton forest suggests, that for this catchment, the potential catchment evaporation has been reduced. Thus the observed reduction of the catchments water use due to the removal of forest will be offset by the climatic factors. This indeed is suggested in figure 17b) where the relative importance of the forest has diminished from being responsible for just over half of the water losses to that of only about a quarter, yet the overall losses have reduced little.

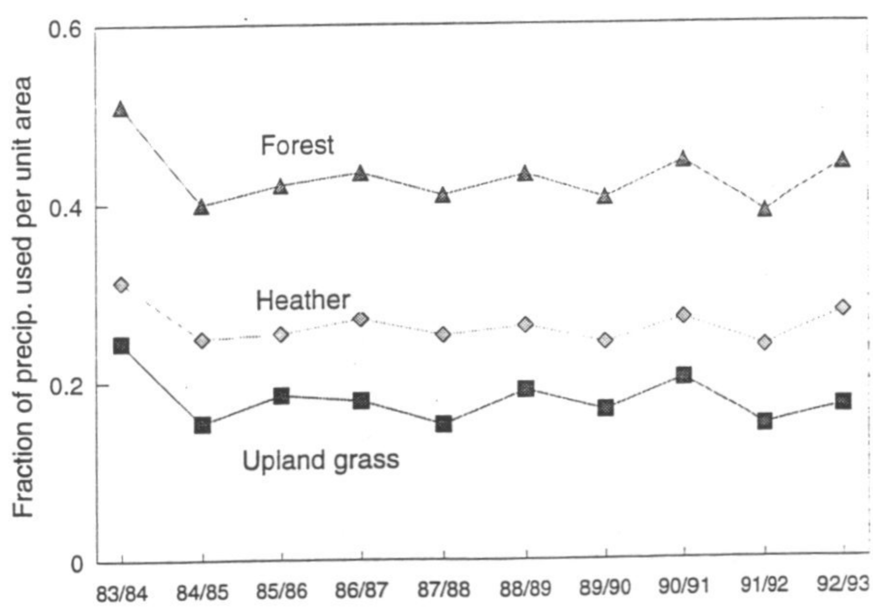


***Figure 19** Ratio of evaporative losses per unit area of homogeneous vegetation to the input precipitation.*

Figure 19 shows the predicted evaporative losses from unit areas of homogeneous vegetation cover plotted as a proportion of the input precipitation for the full

Balquhidder time series (no snow adjustment). The average values are: upland grass 0.18 ± 0.03; heather 0.26 ± 0.02 and forest 0.43 ± 0.03. The losses associated with the heather are 1.46 ± 0.04 times larger than that for the grass. The losses associated with the forest are 2.39 ± 0.04 times larger than those for the grass. The uncertainty of these values reflect the variability experienced in the climatic factors that control the evaporative processes. Consequently care should be taken with the application of these ratios to areas with differing climates outside of Balquhidder.

4.3.2 Whole catchment and altitudinal split models

Figure 20 illustrates the effect of running the model upon the whole catchment or in two altitude zones (above and below 500 meters). When applied to the Monachyle the

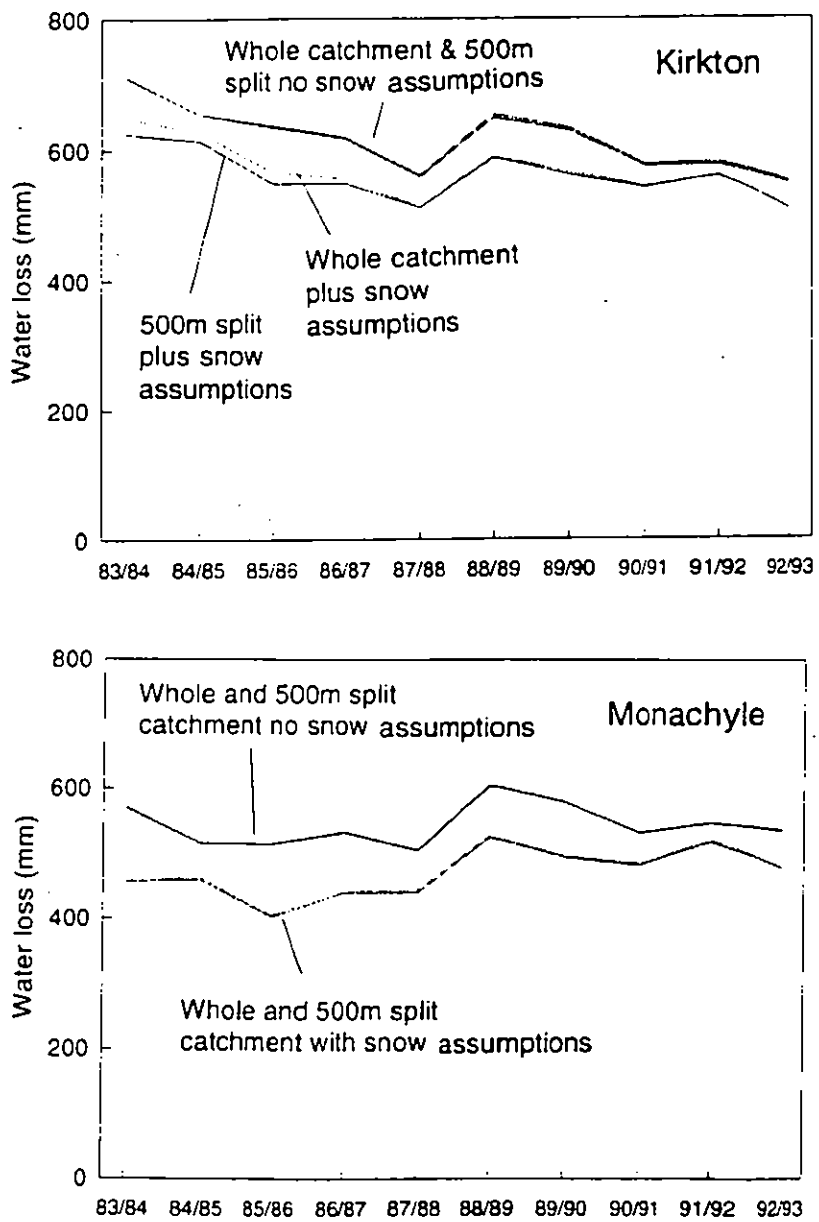


Figure 20 Comparison between whole catchment and altitudinally split modelling approaches, with and without the assumptions about snow included.

two approaches predict almost identical losses, which is to be expected since the two zones are similar in size and vegetation content.

The Kirkton catchment shows little difference between the two approaches when no snow is assumed. This is surprising since there is an altitudinal distribution of the vegetation types. The high loss forest is mostly located below 500 metres and as a consequence receives less rain and has a lower potential evaporation, implying a significant drop in calculated total losses. In the higher altitude moorland grass zone of low loss shorter vegetation the converse is true. The areal extent of the higher zone is nearly one and a half times that of the lower zone. Therefore although the increases in water use per unit area are small higher up, there is a sufficiently large area of it to balance out the reduction lower down in the forest. This is rather fortuitous and will not necessarily happen in all afforested catchments.

There is a small but significant difference between the two approaches when snow is incorporated into the model for the Kirkton. This results from the amount of forest in the catchment and the way in which the snow is divided between the various vegetation types. The differences manifest themselves most strongly when the lower zone is mostly filled with trees and when the snowline coincides with the treeline.

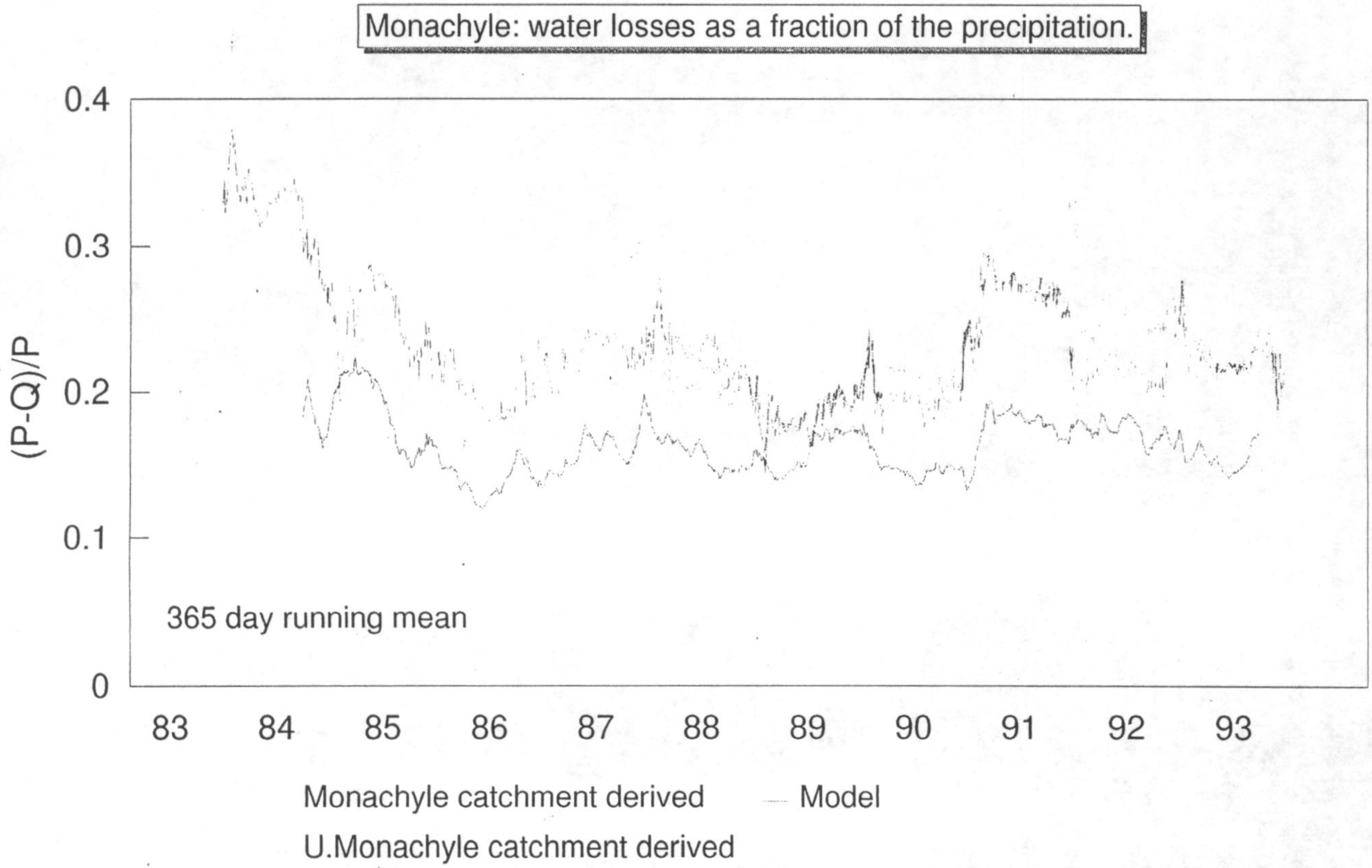
4.3.3. Model results compared to catchment results

In figures 21 and 22 the proportion of the precipitation lost in both the major catchments is illustrated for both the modelled and catchment derived results using a 365 day running mean.

Presenting the results in this format is preferable to the presentation of solely the annual values since it enables continuous comparative analysis of trends and features within the 11 year time series. Each calculation within the running mean is equivalent to a "snapshot" calculation of an annual (P-Q)/P. It is evident from the amount of variability in the traces that one-off annual water use calculations will be dependent upon the chosen start date. It can also be seen from the figures that although similar long term trends are reflected in both traces the short term patterns of variation can be quite different. This may reflect the finite times required for precipitation to work its way out of the catchment as discharge. Conversely no lag times are associated with the modelling approach. Therefore single "snapshot" calculations between the two methodologies for comparative analysis can be misleading. The period of 365 days was selected to minimise seasonal variation in catchment storages.

***Figure 21** Modelled and catchment derived estimates of evaporation in the Monachyle catchment. Presented as fraction of precipitation evaporated, and displayed using a 365 day running mean.*

***Figure 22** Modelled and catchment derived estimates of evaporation in the Kirkton catchment. Presented as fraction of precipitation evaporated, and displayed using a 365 day running mean.*


Monachyle: water losses as a fraction of the precipitation.
(P-Q)/P
0.4
0.3
0.2
0.1
0
365 day running mean
83
84
85
86
87
88
89
90
91
92
93
Monachyle catchment derived
Model
U.Monachyle catchment derived

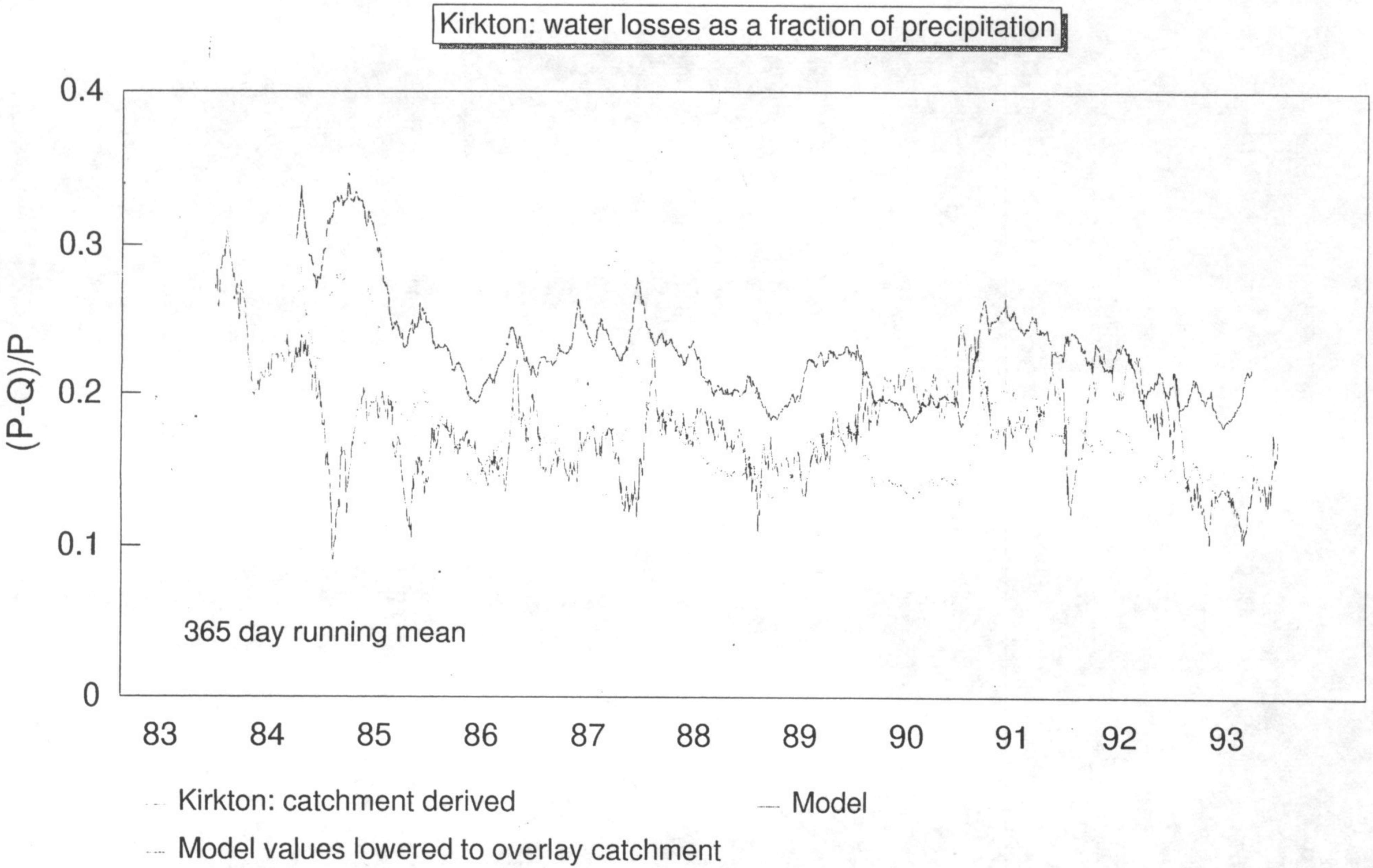

Kirkton: water losses as a fraction of precipitation
(P-Q)/P
0.4
0.3
0.2
0.1
0
365 day running mean
83
84
85
86
87
88
89
90
91
92
93
Kirkton: catchment derived
Model
Model values lowered to overlay catchment

Figure 21 shows that the model predictions and observations differ by a relatively constant amount throughout the period of investigation in the Monachyle. The average percentage of precipitation evaporated as calculated from the catchment study is 22.5%, compared with 16.1% for the model. But the traces correlate well, not only for the whole Monachyle catchment but also for the similar U.Monachyle catchment. Distinctive features are mirrored in the approaches, even down to relatively short time scales of approximately a month. This good short term correlation may in part be due to the rapid runoff response of the Monachyle catchments causing only short lag times in the P-Q approach. It is encouraging that the traces display similar trends and patterns.

For the Kirkton catchment (figure 22) the model predicts higher losses than the catchment derived values. The average percentage of precipitation evaporated as calculated from the catchment study is 15.4% and for the model 22.6%. The catchment derived trace varies to a greater extent than the similar one for the Monachyle. This is probably due to the less flashy nature of the Kirkton; implying greater sub surface storage capacity which will have a pronounced effect upon short term P-Q values. Consequently the features are less distinct than those for the Monachyle. and, are less easy to match up to features in the model's trace. This may go some way to explaining the short term disparity of the traces from 1990 onwards. To help compare traces the modelled curve has been lowered in the figure by the average difference between the two. From this it can be seen that the overall trend in the later years is generally the same though there does appear to be a difference centred around 1990.

The differences between the estimates of the two approaches can, in theory, arise for several reasons. Calder, (1993) considered these possibilities: (1) the process model is incorrect, or the process measurements on which the model is based have large errors, or there are hydrological fluxes or processes present that have not been taken into account within the model. (2) There are other sources of catchment inputs and outputs that have not been measured in the catchments. (3) the differences are within the measurement errors of the catchment P and Q.

With respect to (1), the model being incorrect, the model parameters have been determined and verified by comparison with a number of independent measurement methods. Agreement between parameters between sites and between workers using different measurement methods is generally at the 10-15% level, (Calder, 1990). Uncertainties in the model's predictions are therefore assumed to be of this order. All the key processes have been incorporated into the model, with the exception of direct cloud deposition, which Calder, 1993, identified as a process requiring further investigation. Cloud deposition is known to be maximised, (Fowler *et al.*, 1989), (Rusinov, 1994), when dense cloud is carried quickly over an aerodynamically rough surface for sufficiently long durations for the deposition to collect and fall as drops to the ground. Such climatic conditions are likely to occur in the Scottish uplands at the higher altitudes during the frequent westerly depression episodes. High level forestry is therefore likely to exhibit the most pronounced rates. Inclusion into the model may help to reconcile the difference between prediction and observed for the Kirkton Glen, but it would be surprising if it were to fully account for the difference since the areal extent of the high altitude forest is relatively small. This effect will be more significant to catchments containing larger coverages of cloud prone forest.

With respect to explanation (2), unmeasured fluxes in the catchments, groundwater flows from outside the catchment boundary have been recognised as a possible cause for concern. Geological investigations, (Robins & Mendum, 1987), suggest that this is unlikely and that such considerations could only produce catchment boundary uncertainties of 1 or 2%.

In respect to (3), the uncertainty in P-Q, the errors associated with the calculation of yearly precipitation are put at between 3 to 8 %, with rainfall only errors about 2% and snow errors between 20 and 50%, (Johnson, 1991). The rainfall network has not altered throughout the project, therefore, the errors associated with truely representative sampling will be systematic. A small quantity of random uncertainty will also exist. The measurement of snow is recognised as a formidable task due to: varying physical characteristics of flakes, dependence upon prevailing wind conditions and its varying ability to be redistributed after settling. Therefore the sizeable errors associated with snow may have a larger degree of randomness than the rainfall, though a high degree of systematic uncertainty is inevitable since snow corrections have always been accomplished using the same methodology. Discharge errors are given by Johnson as 2-4%, and again, to a large degree, are systematic. Since the methodology of the monitoring has been consistent throughout the project it is likely that the unavoidable systematic errors will have been perpetuated resulting in the estimates of P-Q deviating from the absolute values by a constant amount but, at the same time, still allowing trends to be reasonably described.

Figure 23 shows the cumulative estimates of water use for the Kirkton and Monachyle together with the range of uncertainty (one standard deviation) for both methods of estimation. The results for both catchments do not differ statistically.

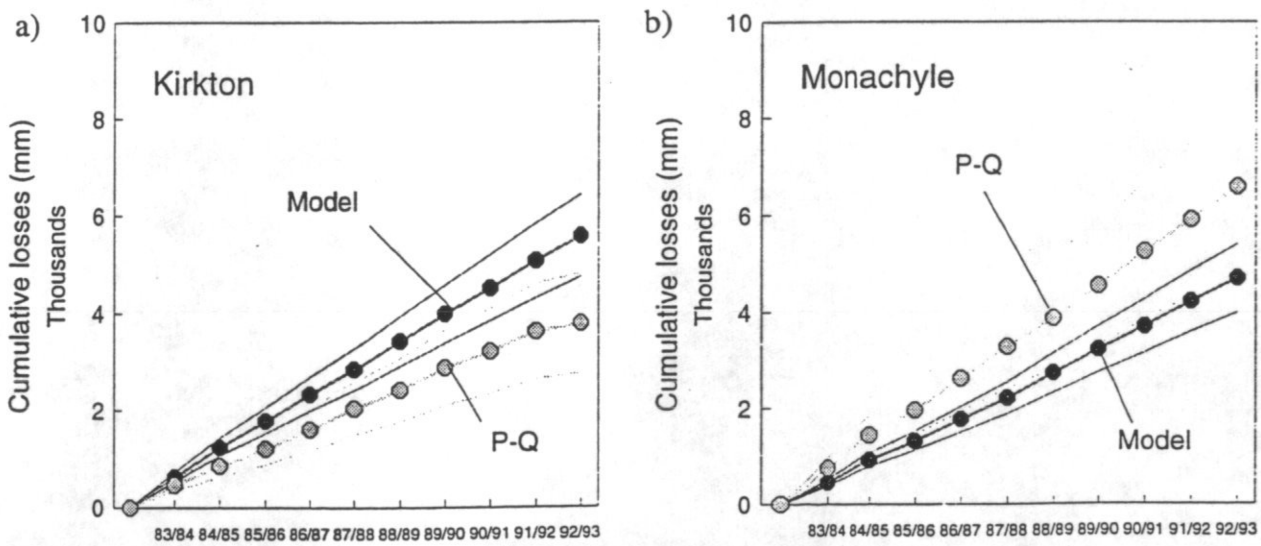


Figure 23 a) Kirkton modelled and catchment derived cumulative losses, b) Monachyle modelled and catchment derived cumulative losses. Ranges of uncertainty plotted in the same shade as bare lines.

Figure 23 also illustrates the trends in the data. Both sets do show trends though they are only slight. For the Monachyle the slope of the graph for the last 4 years is slightly greater than that for the previous years. In the Kirkton this is not seen. In this respect the model and the catchment values agree, though it should be noted that these changes are only witnessed over a relatively short period and longer datasets would be more conclusive.

As described above the largest errors in the calculation of the catchment water balances occur during the snowy periods. It is therefore useful to compare the non winter model estimates to those of the non winter water balances. Difficulties arise, however, in determining the ΔS term for periods of less than a year. Assessment of catchment stores is necessary from interpretation of hydrographs to enable accurate estimates of Q. The problem is less for the flashy Monachyle catchments where the stores are relatively small compared to those in the Kirkton. Selection was made by identifying similar periods of low flow at the start and the end of the water balance

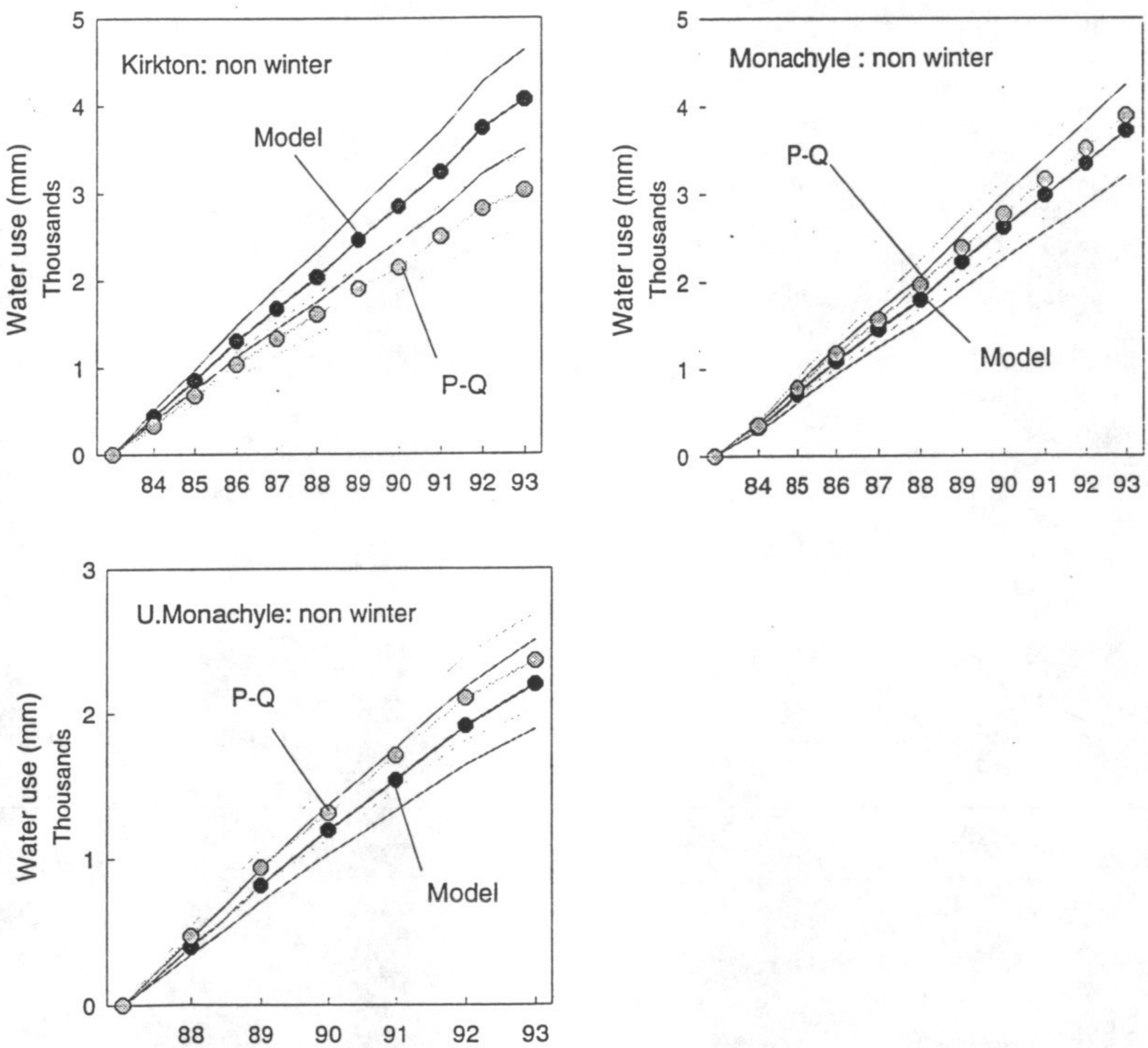


Figure 24 Model and catchment cumulative losses from non winter periods for all three catchments. Ranges of uncertainty are plotted as bare lines.

period. It is assumed that similar base flows reflect similar storage status. Direct comparison of totals is therefore of little use, since the periods of analysis differ between catchments, but comparison between the P-Q figures and the modelled predictions specific to each catchment are valid. Figure 24 shows the cumulative results together with the associated range of uncertainty (one standard deviation). The model predictions and catchment observations for the Kirkton are still just within the experimental uncertainties though the P-Q values remain systematically lower (25% difference).

For the Monachyle there is closer agreement between catchment observations and model predictions. For the whole Monachyle results differ by only 4% and for the Upper Monachyle difference is 6.5%.

4.4 SUMMARY

• The model predicts that in the climatic conditions experienced at Balquhidder that evaporation from heather will be an average of 1.46 times greater than that from upland grass; and evaporation from coniferous forest will be an average of 2.39 times greater than that from upland grass.

• The annual ratio of interception to transpiration for a particular vegetation cover is not constant. This reflects the variation in climatic conditions that control the two processes. The model suggests that, for the period analyzed at Balquhidder, the average I/T for heather to be 2.6 ± 0.6 and for the forest to be 2.0 ± 0.4.

• The model can be used to indicate the sensitivity of catchment evaporation to lying snow. Without the presence of lying snow being incorporated in the model the catchment evaporation would be over estimated by about 10%. The sensitivity of the model predictions to the presence of lying snow raises the question of whether the assumption of zero evaporation from snow covered heather or grass is adequate. This may indicate the need for further process studies or model development on the topic. No process studies have been carried out to investigate snow interception from heather.

• Splitting the model into altitudinal bands to accommodate altitudinal variations in rainfall and potential evaporation has little effect upon the model's predictions at Balquhidder.

• An upward trend in evaporation over time, due to changes in the severity of the winters and changes in the rainfall and potential evaporation patterns over the period of analysis, has masked the effect of the clearfelling in the Kirkton catchment.

• Comparison between annual catchment P-Q and modelled predictions for both the Monachyle and the Upper Monachyle show that the P-Q values are systematically higher than the modelled values. Elimination of the snowy periods, where precipitation errors are largest, results in good agreement between the two approaches.

• Comparison between annual catchment P-Q and modelled predictions for the Kirkton shows that the modelled values are systematically higher than the P-Q. Elimination of the snowy periods does not improve the correlation between the approaches, though the characteristics of the catchment make this analysis more difficult to execute successfully.

• The evaporative losses predicted by the model and from catchment observations do not statistically differ. The uncertainties associated with the catchment derived P-Q are intrinsically large.

• There is good agreement between the trends predicted by the model and those seen in the catchment P-Q.

• The magnitude of cloud water deposition is not known and merits further investigation. This effectively reduces interception losses, and is most likely to be experienced in high altitude forest.

5 Model application outside of Balquhidder

5.1 INTRODUCTION

To investigate the performance of the model over a wide range of geographical conditions the model has been applied to eight catchments, selected to cover much of the climatic range experienced within the Scottish uplands. Other selection criteria for these example catchments include the necessity to be located in regions with plantation forestry; and that the catchments should be well monitored and be subject to no unmonitored abstractions. The problems of accuracy, as outlined in the previous chapter, will again be present, and in those catchments without intensive hydrometric networks the errors are likely to be even greater, and all comparisons should be made with this in mind.

5.2 CLIMATIC VARIATION OF INPUT DATA

5.2.1 Precipitation

Distinct annual precipitation gradients occur across Scotland, mainly determined by the prevailing moist, westerly air flow and the distribution of the upland areas. Generally the eastern ranges are drier: areas in the north eastern Grampians and the more easterly hills in the Borders can receive 1000mm or less a year. Whilst annual values of over 3000mm are common in the Western Highlands. The hills in Galloway also receive high inputs of up to 2500mm.

Seasonality, intensity and duration characteristics of the precipitation will also inevitably differ to some extent across the country and will consequently have some effect upon the evaporative losses.

Snow cover is more likely to have a significant impact upon catchment water losses in the higher hills of the Highlands and Grampians. Clearly its impact upon the lower hills will be less.

Annual precipitation for the catchments are taken from the Hydrometric Register and Statistics, (IH & BGS,1993). In the derivation of these precipitation figures no correction factor is made to accommodate the likely under catch of the raingauges that stand at the standard height of 12 inches above the ground, compared to more realistic ground level gauges. To account for this the precipitation is increased by a factor 1.066, (Rodda, 1967), this is consistent with the relationship between both types of gauges at the low level sites in the Balquhidder catchments. (Johnson, per. comm.).

Snow coverage is derived from daily snowline observations from the nearest monitored hill, (Met. Office, 1988,89,90). Average catchment coverage is derived by converting the snowline observations to areal coverage, and an average value for the snowy period of each year is calculated from this.

5.2.2 Potential evaporation

The variation in the Penman potential evaporation estimate is more conservative than that for the precipitation. MORECS data suggests that the average (1961-93) annual potential evaporation rate calculated from the 40 by 40 km grid squares that cover the whole of Scotland is 483 ± 31.5mm (one standard deviation). The highest potential rates are suggested to be located along the coastal margins and the lowest inland in the upland areas.

Comparison between the measured potential evaporation, during the period 1987 to 1990, at Balquhidder and that suggested by MORECS gives a difference of only 2%, which is within the errors of estimate. The MORECS values are therefore directly used as an index from which to operate the model. Daily values are determined by evenly dividing the monthly totals between the number of days in the month.

5.3 CATCHMENTS EXAMINED

Seven catchments were selected, (figure 25):

a) Ettrick

Location: Tweedsmuir Hills, 15 km NE of Moffat.
Gauging Station: Ettrick Water at Brockhoperig (O.S. NT 234132)
Size: 37.5 km^2
Maximum altitude: 692 m Minimum altitude: 259 m
Vegetation: 52% upland grass, 27% heather, 21% plantation forest[1].
Mean annual rainfall: 1891 mm (1965-1990)
Location of nearest snow observations: 45 km, ESE, observed hill - Carter Bar.
Period of analysis: 87/88, 88/89 and 89/90.

b) Tima

Location: Tweedsmuir Hills, adjacent to the Ettrick catchment, 18 km ENE of Moffat.
Gauging Station: Tima Water at Deehope (O.S. NT 278 138)
Size: 31.0 km^2
Maximum altitude: 545 m Minimum altitude: 232 m
Vegetation: 17 % upland grass, 8 % heather, 75 % plantation forest[1].
Mean annual rainfall: 1747 mm (1973-1990)
Location of nearest snow observations: 43 km, ESE, observed hill - Carter Bar.
Period of analysis: 87/88, 88/89 and 89/90.

[1] The extent of the mapped forest area is multiplied by a correction factor of 0.84 to account for clearings, wind throw and forest roads. Factor derived from forestry in the Balquhidder area.

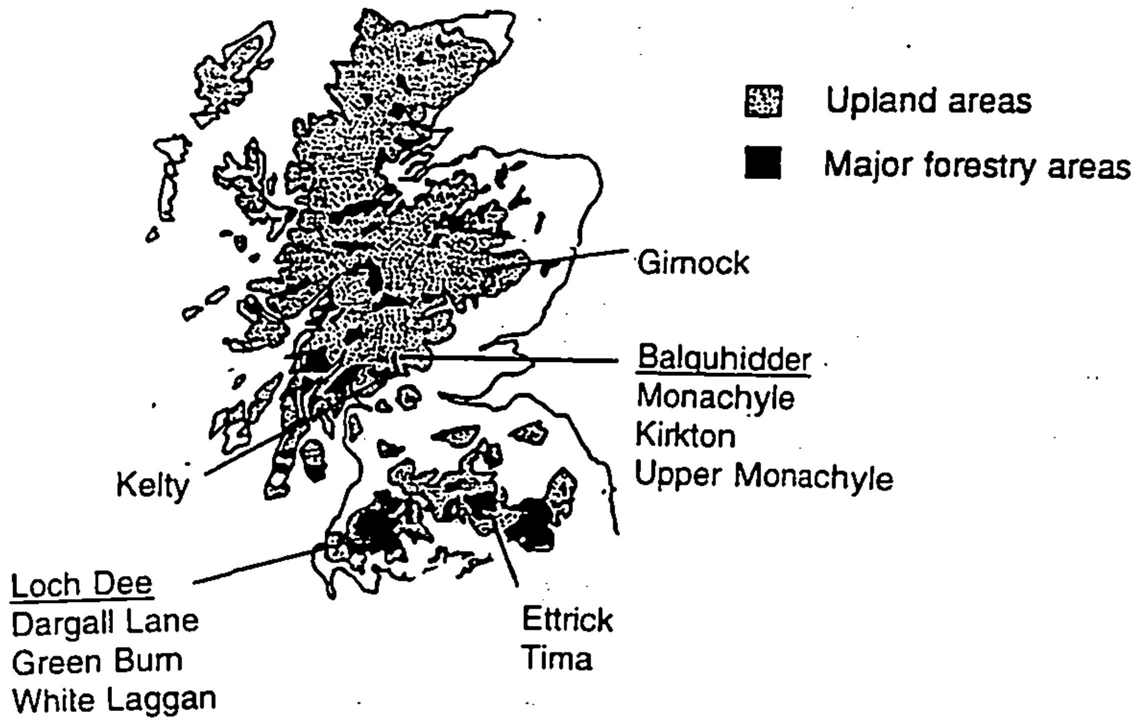


Figure 25 Location of example catchments together with the distribution of forestry and upland areas above 300m.

c) Girnock Burn

Location: 7 km west of Ballater .
Gauging Station: Girnock Burn at Littlemill (O.S. NO 324 956)
Size: 30.3 km^2
Maximum altitude: 862 m Minimum altitude: 245 m
Vegetation: 5 % upland grass, 91% heather, 4% plantation forest.
Mean annual rainfall: 1146 mm (1969-88)
Location of nearest snow observations: 30 km, west, observed hill - Ben Macdui.
Period of analysis: 87/88 and 88/89.

d) Dargall Lane

Location: Loch Dee, Galloway.
Gauging Station: Dargall Lane at Loch Dee (O.S. NX 451 787).
Size: 2.1 km^2
Maximum altitude: 716 m Minimum altitude: 226 m
Vegetation: 50 % upland grass, 50 % heather, 0 % plantation forest.
Mean annual rainfall: 2703 mm, (1983-90)
Location of nearest snow observations: 7 km, NW, observed hill - Merrick.
Period of analysis: 87/88, 88/89 and 89/90.

e) Green Burn

Location: Loch Dee, Galloway.
Gauging Station: Green Burn at Loch Dee (O.S. NX 481 791).
Size: 2.6 km^2
Maximum altitude: 557 m Minimum altitude: 220 m
Vegetation: 22.5 % upland grass, 22.5 % heather, 55 % plantation forest[2].
Mean annual rainfall: 2754 mm, (1988-90)
Location of nearest snow observations: 7 km, NW, observed hill - Merrick.
Period of analysis: 87/88, 88/89 and 89/90.

f) White Laggan

Location: Loch Dee, Galloway.
Gauging Station: White Laggan Burn at Loch Dee (O.S. NX 468 781).
Size: 5.7 km^2
Maximum altitude: 656 m Minimum altitude: 226 m
Vegetation: 42.5 % upland grass, 42.5 % heather, 15 % plantation forest.
Mean annual rainfall: 2642 mm, (1980-90).
Location of nearest snow observations: 7 km, NW, observed hill - Merrick.
Period of analysis: 87/88, 88/89 and 89/90.

g) Kelty Water

Location: Loch Ard Forest, 7km SW of Aberfoyle.
Gauging Station: Kelty Water at Clashmore.
Size: 2.7 km^2
Maximum altitude: 550 m Minimum altitude: 200 m
Vegetation: 0 % upland grass, 25 % heather, 75 % plantation forest.
Mean annual rainfall: 2249mm, (1986-90).
Location of nearest snow observations: 25 km, N, observed hill - Balquhidder.
Period of analysis: 87/88, 88/89.

All periods of analysis was made over hydrological years.

The predictions of the model and the catchment derived P-Q for the Scottish catchments are shown in figures 26 and 27.

[2]The figure of 67% afforestation (Johnson *et al*, 1994) is reduced to 55% to account for the widening of tributary corridors and the incomplete nature of the young canopy (accounted for by using a linear correction factor that assumes a mature canopy develops after 15 years).

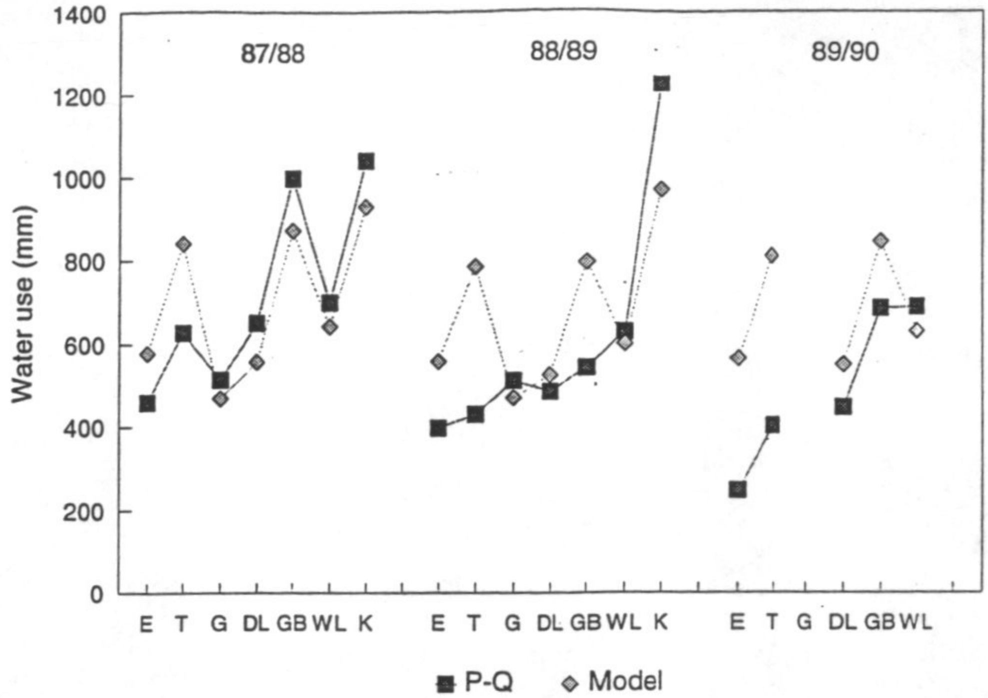


Figure 26 Modelled and measured water use in the selected Scottish catchments between 1987-90. E - Ettrick, T - Tima, G - Girnock, DL - Dargall Lane, GB - Green Burn, WL - White Laggan, K - Kelty. (Analysis in hydrological years)

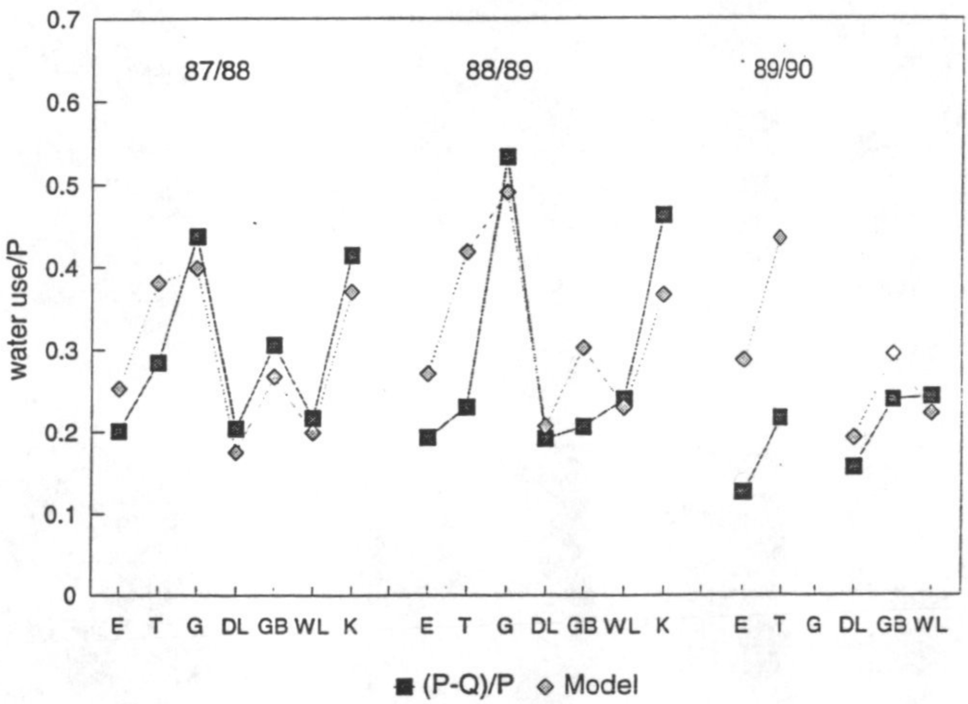


Figure 27 Modelled and measured water use shown as a percentage of the precipitation in the selected Scottish catchments between 1987-90. E - Ettrick, T - Tima, G - Girnock, DL - Dargall Lane, GB - Green Burn, WL - White Laggan, K - Kelty. (Analysis in hydrological years).

Correlation between the two approaches for the Loch Dee catchments, the Kelty and the much drier Girnock catchment are good; and within the uncertainties of the approaches with perhaps the exception of the Green Burn in 88/89. Higher losses are predicted and measured for those catchments with larger amounts of afforestation, again with the exception of the Green Burn 88/89.

Since the consistent pattern obtained from the model for the Loch Dee catchments is mirrored in the 87/88 and, to a slightly lesser extent, in the 89/90 measured P-Q results, and that the pattern is consistent with our current understanding of evaporative losses, it is difficult to justify the 88/89 Green Burn measured P-Q. It may reflect the possible large uncertainties associated with this catchment approach.

The results for the relatively snowy Girnock catchment suggests that the model copes well with the predominantly heather catchment. It illustrates and confirms the high percentage usage of the precipitation in the drier regions.

The Kelty demonstrates the high evaporative losses possible from forestry. 75% of the catchment was afforested leading to average yearly predicted losses of 951mm (avg. P-Q 1133mm). If the forest were replaced by open moorland (75% heather, 25% grassland), and the same climatic data sets used, the predicted losses would be only 569mm. This suggests that the forestry in the catchment increases the annual water losses by 382mm, (for the years investigated). This total loss is equivalent to 167% of the original moorland value.

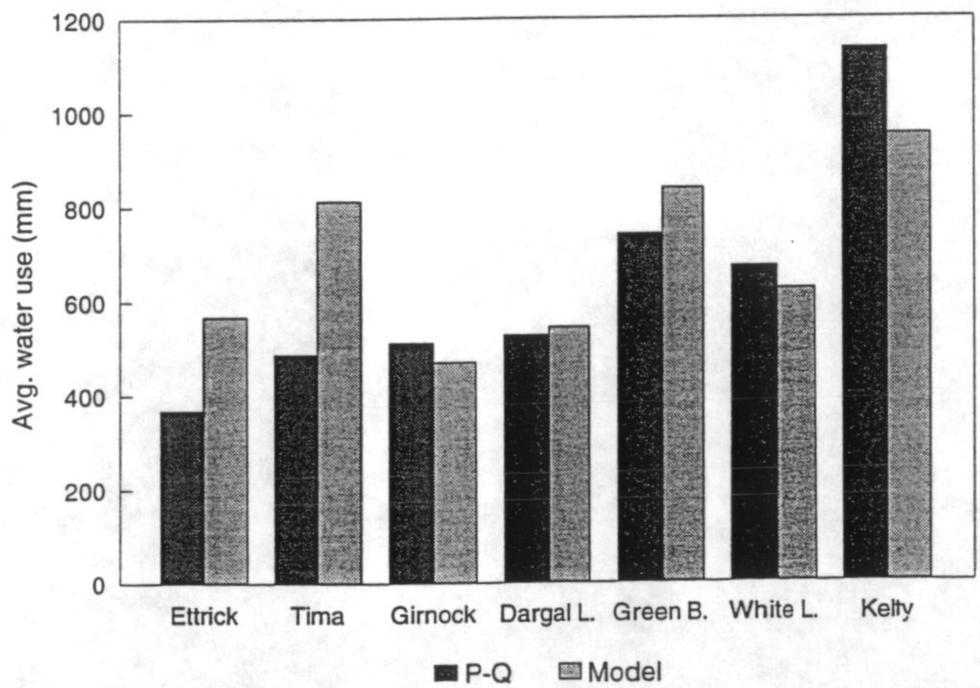


Figure 28 Average yearly estimates of water use for the full period of analysis.

The values for the adjacent catchments of the Ettrick and Tima suggest that the field measured losses are significantly less than that for the model, but that the difference between the catchments is similar to the difference predicted by the model. Such low P-Q losses are unlikely; for example the measured losses during 89/90 in the Ettrick were 247mm and in the Tima 404mm (catchments with 21% and 75% forestry respectively), yet the Penman potential which is accepted as a reasonable estimate for grass is 460mm. The low values suggest a systematic error in the derivation of the catchment rainfalls of the area; their accuracy is deteremined by the ability to interpolate rainfall surfaces from a low density rain gauge network outside of the catchments.

Figures 28 and 29 show the average yearly losses for the whole period of analysis. Good agreement is observed between the Loch Dee and Girnock catchments.

For the varying input data sets the model consistently predicts that the catchments with the greater forest coverage will be subject to higher total evaporative losses compared to the open moorland catchments. Though the percentage of precipitation lost ([P-Q]/P) will also reflect the catchments total rainfall.

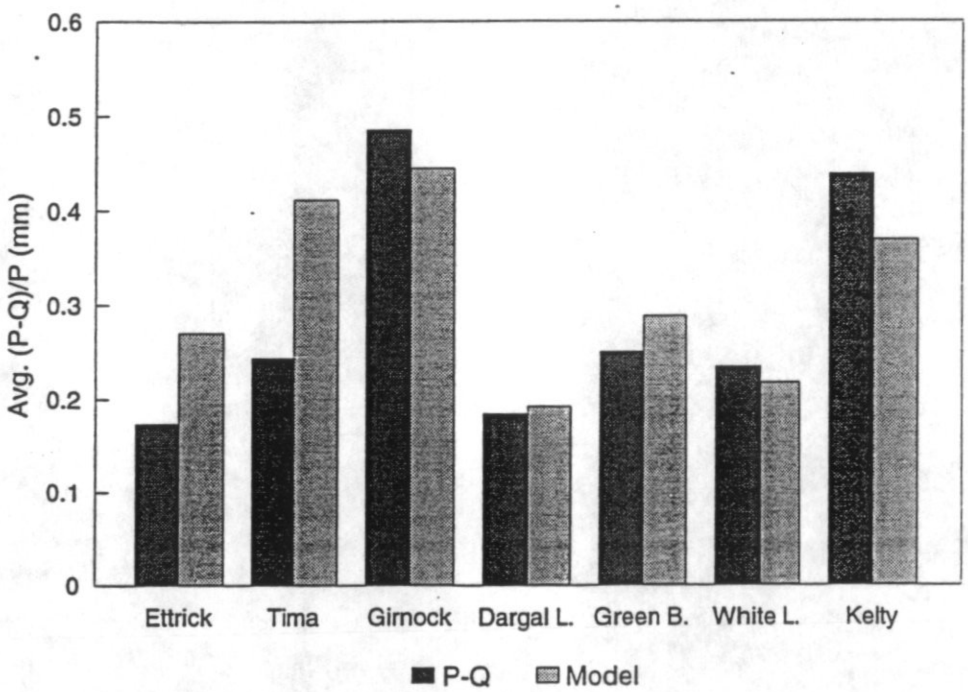


***Figure 29** Average estimate of fractional use of precipitation for the full period of analysis.*

Figure 30 plots the average model predictions against the P-Q values. The one to one line is included to indicate complete agreement between the two approaches. The average Penman potential (E_T) specific to each catchment is also plotted against the P-Q for comparison, and is notable for its lack of variability between sites. The graph clearly indicates that a linear one to one relationship between P-Q and E_T does not exist, suggesting E_T is a poor estimate of evaporative losses from highly afforested catchments. The relationship between the P-Q values and the model's predictions are better. Both the Kelty (75% forest canopy coverage) and the Green Burn (55% forest canopy coverage) exhibit reasonable agreement with the one to one line. The third catchment with a high percentage of afforestation, the Tima (75% forest canopy coverage), is less close; though its plotted relationship to the Ettrick would be consistent to the one to one line if, as postulated above, there is a systematic error in the catchment rainfall calculations.

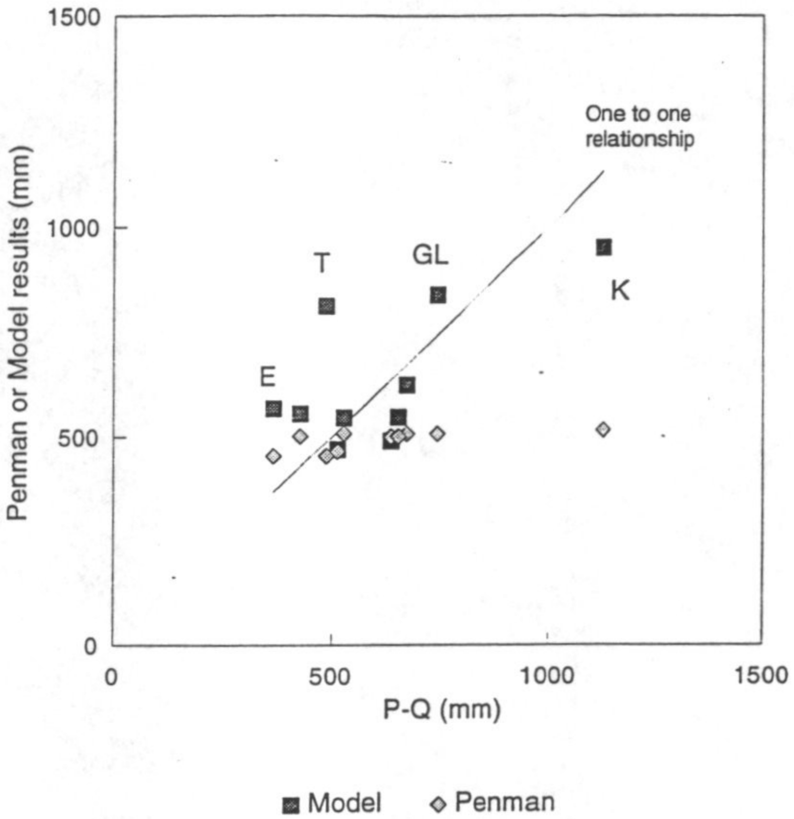


Figure 30 Average annual model predictions and Penman potential values plotted against average P-Q for all seven catchments plus the Balquhidder catchments. (K-Kelty, GB-Green Burn, T-Tima and E-Ettrick).

5.4 SYNTHETIC RAINFALL SERIES

To investigate the model's dependence upon rainfall the 1992 Kirkton precipitation data set was incrementally scaled to cover a rainfall range of 800 to 4000 mm and used as input data for the model. This range corresponds to that experienced in the Scottish uplands. The 1992 potential evaporation values are input with no correction relating to the changes in the rainfall. Due to this, small errors may result when trying to translate the model's predictions to specific locations in Scotland, but the generally conservative nature of the Penman potential evaporation across the country and the lack of an evident relationship with the east west rainfall gradient suggest that the errors will be reasonably small.

Figure 31 shows the predicted annual quantity of water used per unit area by each vegetation type. The relationship between evaporative losses and rainfall is not linear; the gradient of the curves reduce at higher rainfalls. At the drier end of the scale it is predicted that soil moisture deficits may start to influence the evaporative loses. Two example rooting constants (RC) are plotted in the figure. For grass an RC of 100mm is the average value quoted in table 2. The average RC values of 200mm given in table 2 for the forest results in little change from the curve with no rooting constant applied, though the most severe RC of 150mm does. None of the rooting constants suggested for the heather effected the prediction for these data sets.

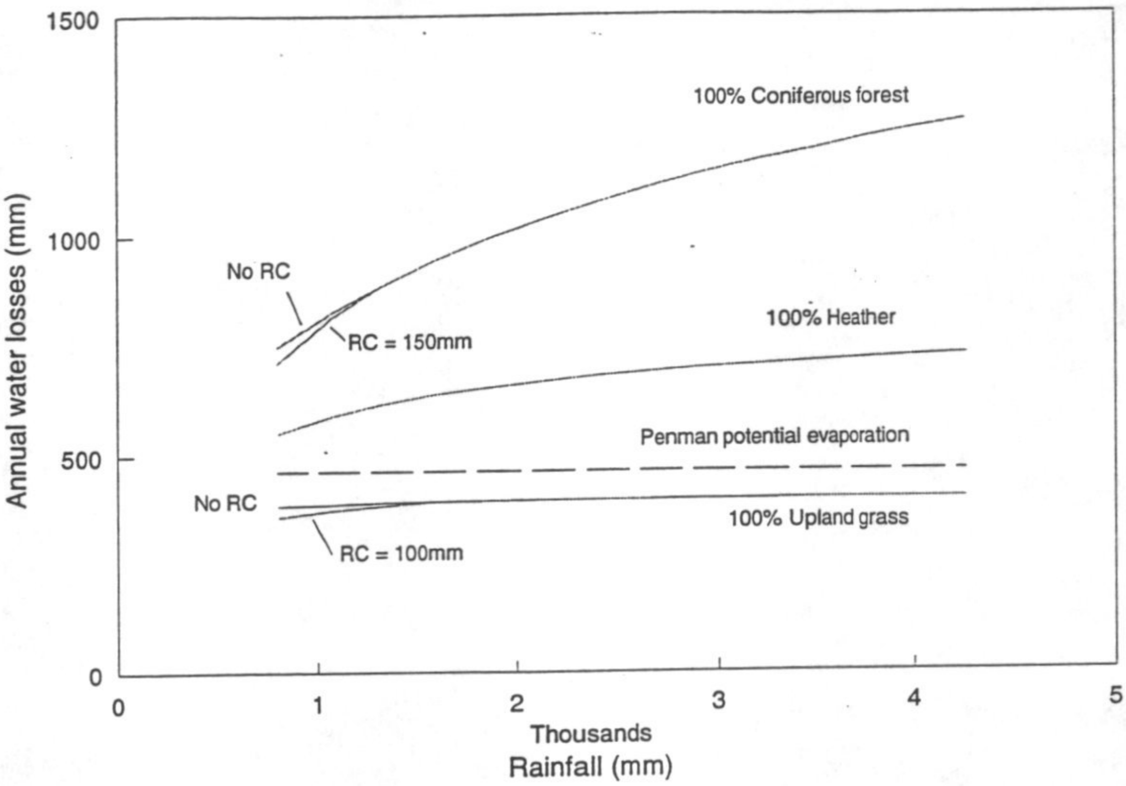


***Figure 31** Water use per unit area of vegetation, predicted over a range of synthetic annual rainfalls derived from the Kirkton 1992 data set. RC - rooting constant.*

Figure 32 shows the predicted water use per unit area of vegetation plotted as a function of the annual rainfall. This also clearly indicates that the evaporative losses are not linearly related to the total rainfall. Forest losses of greater than 80% of the rainfall inputs are predicted below 1000mm annual rainfall, even when the most severe rooting constant is applied. It is interesting to note that the model for the coniferous trees has been developed predominantly from the study of sitka spruce. This species of tree tends not to be planted in these drier areas.

Since the occurrence of snow varies across Scotland and its influence changes from year to year the model is run without any assumptions regarding the effects of snow. This may affect the transportability of the results to actual sites within Scotland. In the snowier regions a further snow adjustment may be advisable. This will always reduce the total evaporation and will depend upon the areal extent of the snow experienced, as described in section 4.3.1. Differences in rainfall pattern, either between site or from year to year, will also cause slight differences between that predicted with the Kirkton 1992 data and other locations in other years in Scotland. Despite these caveats the analysis may be of value for indicating the general trend in evaporative losses across the Scottish uplands.

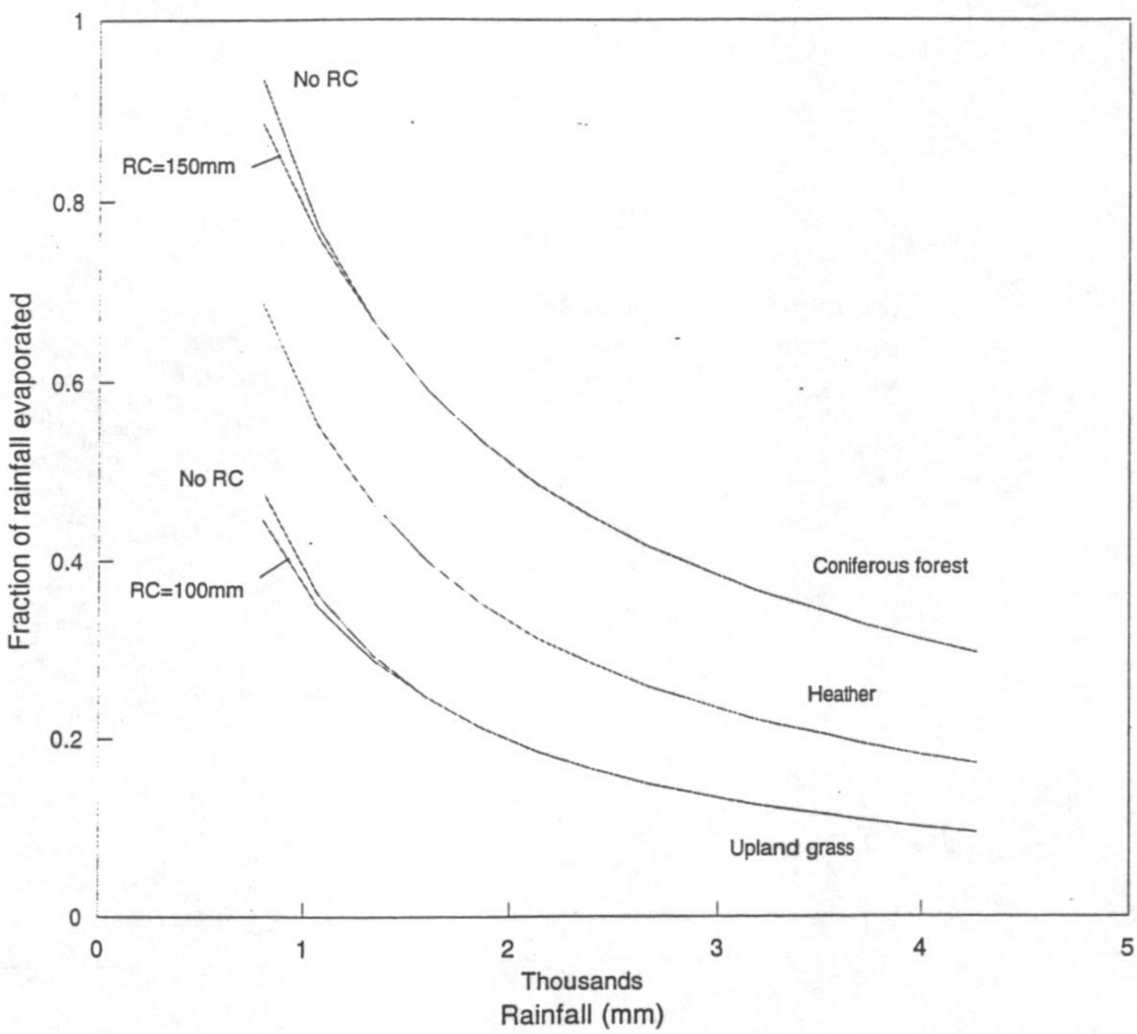


Figure 32 Water use, as a fraction of the rainfall, per unit area of vegetation, predicted over a range of synthetic annual rainfalls derived from the Kirkton 1992 data set. RC - rooting constant.

Figure 33 shows preliminary comparisons between the model's predictions and the crude rule quoted in the "Forest and Water Guidelines" (Forestry Commission, 1993) which suggests that in the uplands every 10% of a catchment area covered by mature forest will result in a 1.5 to 2.0 % loss of the original (non afforested) water yield. This is equivalent to a 15 to 20 % loss if the whole catchment is converted to mature forest. For clarity only the predicted forest losses, via the daily model, and the Penman potential curves are transferred from figure 31.

The distinction between the magnitude of the losses associated with upland grass and heather immediately makes application of the crude rule more complicated. Therefore the pre-afforested catchment is taken to be represented by:

i/ 100% heather catchment (H),
ii/ 100% upland grass catchment (U.G.),
iii/ A catchment that has a mixture of grass and heather that gives a pre-afforestation water loss equal to Et.(Et).

In the following analysis it is assumed that the estimates of water loss determined by the daily model for the moorland vegetations are exactly accurate. It therefore follows that if the predicted losses for each of these three catchments are deducted from the precipitation inputs the pre-afforestation yields of the respective catchments can be derived. These yields are taken as the starting values to which the crude rule is applied. The rule is applied at both the 15 and 20 % level, as if the whole catchment had be converted to mature forest.

Figure 33 shows the predicted water loss curves derived from the 15 and 20 % reduction in yield levels for the catchment that had a pre-afforestation loss equal to Et. Also shown are minimum and maximum curves selected from the predictions related to the other two catchment types. These form an upper and lower envelope of estimated forest losses.

The results illustrate the crude nature of the prescribed rule, emphasising the error of assuming that the evaporative losses from heather and upland grass are similar and can hence be treated in the same way by the rule. Losses from heather are much larger than those from upland grass, the resulting prediction, via the crude rule, for forest losses are therefore quite different.

The curves associated with the catchment originally with losses equivalent to Et, ie conceptually a mixture of heather and grass, may reflect a more realistic catchment. Both the 15 and the 20% curve lie below the curve derived by the more sophisticated daily model. This may indicate that the crude rule is only approximately correct for catchments with relatively high coverages of heather (medium height vegetation), or that the proposed percentage corrections are too low. It is interesting to note that during 1992 (the year used to crudely synthesis the rainfall sets) Balquhidder received a little under 3000mm of precipitation. The two modelling methodologies of estimating the forest losses at Balquhidder are approximately in agreement, but only if it is assumed for the crude rule that the original catchment were 100% heather and that the correction to yield was 2% for every 10% forest. This may suggest that the crude rule is a little cautious in its predictions of the impact of mature forest.

The largest discrepancies are found at the lower rainfalls. Since the dataset used has the rainfall characteristics of Balquhidder it is harder to interpret the discrepancy at the lower end of the range where in reality the rainfall characteristics may be different.

Further work targetted at the lower rainfall end would significantly enhance the quality of figures 31,32 and 33.

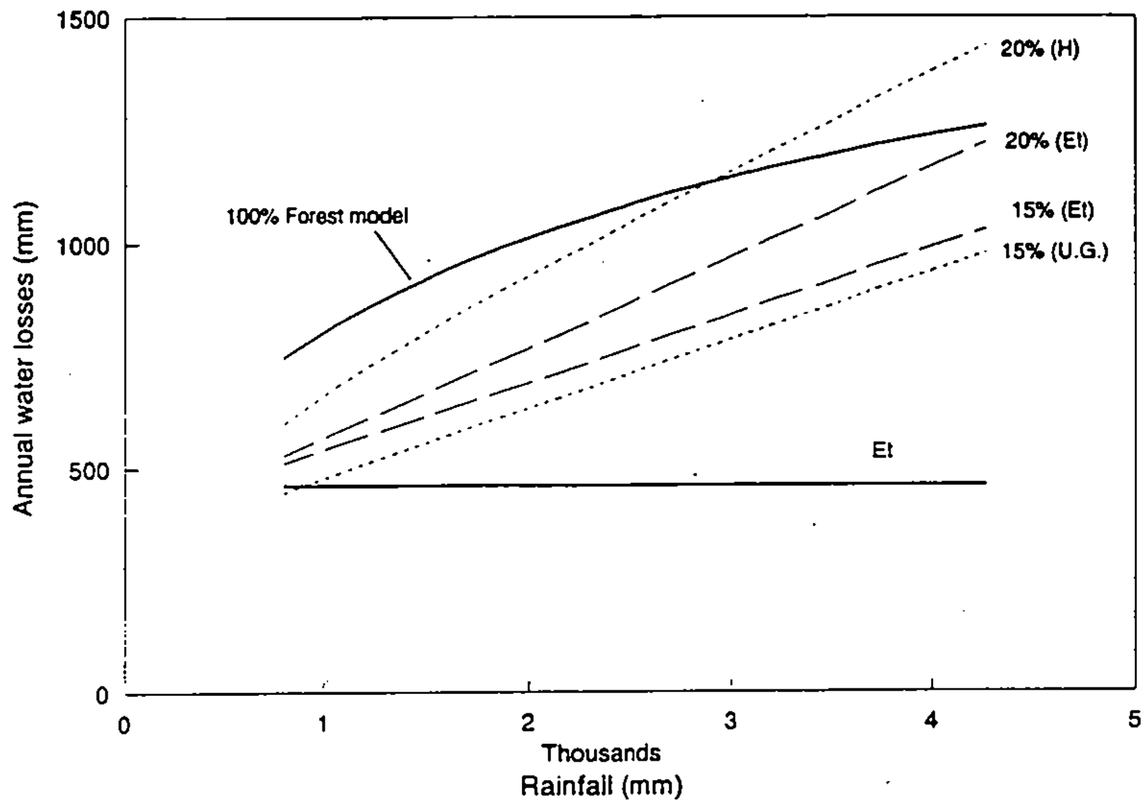


Figure 33 Water use per unit area of forest as predicted over a range of synthetic annual rainfalls derived from the Kirkton 1992 data set. The 100% forest model curve represents the losses as predicted by the more sophisticated daily model. The dotted lines represent the predictions derived from the crude rule: a 10 % increase in mature forest reduces the original non-afforested catchment yield by 1.5 to 2%. 20% (H) - the higher reduction applied to what was originally a heather catchment, 15% (U.G.) - the lower reduction applied to what was originally an upland grass catchment, 15 or 20% (Et) - the reductions applied to a catchment that originally had non-afforested losses equal to the Penman potential value.

6 Future possible refinements to the model

The results presented in this report are the culmination of 14 years work at the Balquhidder research sites. The derivation of the model has also drawn upon other similar studies carried out by the Institute of Hydrology at other sites both within the uplands of Scotland and the rest of the UK over the last 25 years. As such the model represents the Institute's best available tool for predicting the evaporative losses associated with mature plantation forestry in the uplands of Scotland, given the scarcity of meteorological data. All the major factors identified at the inception of the project have been investigated and the findings, when significant, incorporated into the model. During the course of the work many questions were raised concerning the significance of issues not initially identified for research. Where possible experiments have been conducted to examine the magnitude of these effects, though several issues still remain unresolved. The main ones are listed briefly below.

a) Forest edge effects - The edges of forests are recognised as features where high canopy/atmosphere exchange rates are possible. Historically process studies have been sited away from the edges in order to sample a homogeneous canopy cover away from the complicating edge effects. As a result the magnitude and extent of the edge effects have not been quantified and their significance is yet to be established. This issue is likely to become more prominent in the future as canopy structures are altered to accommodate environmental corridors and the possible adoption by the forestry industry of staggered planting patterns.

b) Cloud deposition - A process whereby airborne water droplets are scavenged from the atmosphere by the forest canopy, form drops which subsequently fall to ground. This process effectively helps to mitigate the high loss rates associated with canopy interception. Dense cloud and high wind maximize the effect, therefore suggesting the effect will be most prominent in high altitude forest and may also depend upon geographic location. Evidence from studies around the world suggest that this process can be highly significant.

c) Evaporative losses from young trees - Mature canopies have usually been investigated due to the assumption that a mature canopy causes the maximum effect. Little work has been conducted to investigate when the evaporative characteristics of young trees become significant. This is currently an important issue, as much of the Scottish timber is reaching the harvesting age and the area under going replanting is increasing. Also if staggered planting prevails the impact of afforestation upon water resources may be alleviated. Quantification of losses from different ages class would improve the applicability of the model.

d) Evaporation from snow - In the report only assumptions regarding the rates of evaporation from snow covered vegetation are incorporated within the model. The assumptions are based upon experimental work, but the variable nature of snow together with only a limited amount of data available precluded the derivation of general relationships. The use of the assumptions have highlighted evaporative processes from snow as being significant. The model would benefit from a fuller understanding of the processes involved.

e) Model performance in the relatively dry eastern uplands - The majority of the experimental sites used to formulate the model were located in uplands that can be considered to be relatively wet. The drier eastern uplands in Scotland are subject to a slightly different climate and importantly the preferred plantation tree species is more likely to be a pine than a spruce. The effect of these differences to the performance of the model is unknown.

The model's predictions over the annual rainfall range in Scotland (section 5.4) uses rainfall data synthesised from Balquhidder. The rainfall characteristics in the drier areas will be different. The significance of these differences upon the output of the model has not yet been investigated and is advised.

The model would also benefit from further comparison to a larger sample of suitably accurate upland catchment water balances. As noted in the previous sections water balance estimates of evaporative losses are very sensitive to monitoring errors. To validate the model using this approach therefore necessitates a large number of catchments. A better coverage of the afforested areas within Scotland would also be beneficial.

It is hoped that the current lumped deterministic model can be modified to run within a GIS. This will more easily allow the convolution of the rainfall, evaporation and snow patterns with the actual pattern of the land use which should lead to both an easier framework for operating the model and more realistic predictions of the impacts of land use change.

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Appendix 1: Penman equation

The Penman equation implicity includes aerodynamic and surface resistances for short vegetation, and as such is a special case of the physically based Penman-Monteith equation (Monteith, 1975). The Penman equation estimates the evaporative flux from short, homogeneous, non moisture stressed vegetation and is given by:

$$\lambda E_T = \frac{\Delta R_n + \rho C_p E_a}{\Delta + C_p/\lambda}$$

Where:

E_T	Penman evaporative rate (kg m^{-2} s^{-1})
λ	latent heat of evaporation of water (J Kg^{-1})
Δ	slope of the saturated specific humidity vs. temperature for water at air temperature (Kg Kg^{-1} K^{-1})
R_n	net radiation flux (W m^{-2})
ρ	density of moist air (Kg m^{-3})
C_p	specific heat of air at constant pressure (J Kg^{-1} K^{-1})
E_a	a ventilation term given by

$$E_a = 0.004D(1 + 0.54u)$$

u	wind speed 2 metres vertically above the ground (m s^{-1})
D	specific humidity deficit (Kg Kg^{-1})

Appendix 2: Full mathematical description of the upland evaporation model.

The daily evaporation E_D (in terms of millimetres depth over the whole of the region considered) for a region with the following land covers: mature coniferous forest, brash, heather, upland grass and snow is given by:

$$E_D = f_g E_g + f_h E_h + f_f E_f + f_b E_b + \sum_{(i=f,h,g,b)}(f_{s,i} E_{s,i})$$

also written as:

$$E_D = f_g E_g + f_h(T_h + I_h) + f_f\,(T_f + I_f) + f_b E_b + \sum_{(i=f,h,g,b)}(f_{s,i} E_{s,i})$$

Where E_D is the total daily evaporation (mm); f_* the fraction of region covered; g, h, f, b and s represent upland grass, heather, conifer plantation forest, brash and snow respectively; E_* is the daily evaporation (mm); T_* the daily transpiration component (mm) and I_* the interception component (mm) of E_*.

The following variables are used in the model:

E_T	Daily Penman potential evaporation for short no stressed vegetation.
P	Daily precipitation.
d	Julian day number.

The parameter values below are described and given for each relevant vegetation and land cover type in Appendix 3.

• Daily grass evaporation:

$$E_g = \{(1- 0.5A) + 0.5A \sin[2\Pi(d - 141)/365]\}E_T \quad \text{if } P < E_g$$

$$E_g = E_T \quad \text{if } P > E_T$$

otherwise $E_g = P$

• Daily heather and forest transpiration and interception:

$T_{h,f} = \beta_{h,f} E_T(1-\omega_{h,f})$ where $\omega_{h,f}$ is a function of P and is described in appendix 3.

$$I_{h,f} = \gamma_{h,f}\,(1 - e^{-\delta(h,f)P})$$

• Daily brash interception:

$$I_b = \gamma_b \,(1 - e^{-\delta(b)P}) \quad \text{where } \gamma_b = \gamma_h \text{, and } \delta_b = \delta_h.$$

• Daily snow evaporative losses:

$$E_{sf} = \gamma_f \,(1 - e^{-\delta(f)P})$$

$$E_{sh} = 0 \text{ ,and , } E_{sg} = 0$$

• Daily change in soil moisture. Used in the sub-programme to regulate transpiration if a soil moisture deficit develops that is sufficient to limit root access to moisture.

$$\Delta SM_{h,f} = P - I_{h,f} - T_{h,f} \quad \text{for heather and forest.}$$

$$\Delta SM_g = P - E_g \quad \text{for upland grass.}$$

where ΔSM is the daily change in soil moisture. The soil moisture deficit (SMD) on day i+1 is given by:

$$SMD_{i+1} = SMD_i + \Delta SM_{i+1} \quad \text{for } SMD_i \leq 0$$

$$SMD_{i+1} = \Delta SM_{i+1} \quad \text{for } SMD_i > 0$$

Note: SMD is given a positive sign when the water content is above that of field capacity. Therefore soil with a soil moisture deficit is given a negative value.

The transpiration rate of the vegetation is modified according to:

$$T_{h,f} = T_{h,f} \quad \text{when } SMD_{h,f} > RC_{h,f}$$

$$T_{h,f} = T_{h,f}/12 \quad \text{when } SMD_{h,f} \leq RC_{h,f}$$

$$E_g = E_g \quad \text{when } SMD_{h,f} > RC_g$$

$$E_g = E_g/12 \quad \text{when } SMD_{h,f} \leq RC_g$$

where RC_g is the rooting constant as given in Appendix 3.

Appendix 3: Daily model parameter values.

Parameter	Value	Description	Origin
A	0.68	Amplitude of seasonal grass evaporation equation.	Wright & Harding (1993)
β_f	0.9	Daily transpiration factor for coniferous forest.	Calder (1986)
β_h	0.5	Daily transpiration factor for heather.	Calder (1986, 1990)
γ_f	6.432 (mm)	Coniferous forest interception parameter, equivalent to maximum predicted daily interception loss.	Hall & Harding (1993)
γ_h	2.65 (mm)	Heather interception parameter, equivalent to maximum predicted daily interception loss.	Calder (1986), Hall (1987)
δ_f	0.092 (mm^{-1})	Coniferous forest interception parameter.	Hall & Harding (1993)
δ_h	0.36 (mm^{-1})	Heather interception parameter.	Calder (1986), Hall (1987)
ω_f	0.045P or 1 if P $\geq$ 22mm	Fraction of day that the coniferous forest canopy is wet. (P is the daily rainfall).	Calder (1986)
ω_h	0.068P or 1 if P $\geq$ 15mm	Fraction of day that the heather canopy is wet. (P is the daily rainfall).	Hall (1987)
RC_g	50 - 150 (mm)	Rooting constant for upland grass.	Thompson *et al.* (1981), Ward & Robinson (1990), Shaw (1991)
RC_h	100 - 200 (mm)	Rooting constant for heather.	
RC_f	150 - 250 (mm)	Rooting constant for coniferous forest.	