Forests and Water Resources: Problems of Prediction on a Regional Scale [and Discussion]

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Forests and water resources: problems of prediction on a regional scale

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Forests have profound effects on water resources and it is essential that water resources be jointly considered with forests wherever in the world these assets are valuable for national development or for environmental balance. However, despite a strong and often urgent need for prediction in forest hydrology, universality of scientific guidance is seldom possible across climatic boundaries, between soil types, between land management practices and, occasionally, between species of tree. This paper reviews the current state of predictability of water use by forests, of hydrological extremes and of water quality factors, all of which affect the utilization of water resources. Contrasts between climatic zones are stressed in relation to evaporation processes. In reviewing hydrological extremes and water quality, the influence of local soil- and land management is drawn out. There seems some justification for a continuation of lengthy and expensive hydrological experimentation, despite the urgency of the need for guidance in land use and land management. It is essential, however, to make maximum use of new spatial techniques that aid extrapolation from the detail provided by studies of process.

1. Introduction: identification of scientific and water management problems

It is clear from studies done in many parts of the world that forests have very profound effects on water resources. Although these effects, which include alteration of the quantity, quality and temperature of runoff and alteration of rates of erosion, have been identified it is not generally possible to quantify them in all environments because the magnitude and scales of all the interacting processes are not yet sufficiently well understood.

The controls on the water use of forests are principally determined by climate, soil water availability, physiological and aerodynamic controls and the extent to which the actual evaporation modifies the mesoscale climate. Of these, perhaps the best understood are the aerodynamic controls. Forests have tall, aerodynamically rough surfaces and the aerodynamic transport processes for vapour, heat and momentum are more efficient than those over shorter vegetation. In wet conditions, when surface (physiological) controls are removed, very enhanced rates of evaporation of intercepted water are to be expected from forests compared with shorter vegetation, in all climatic zones. The least well-understood of these controls is the interaction between forest evaporation and mesoscale climate (see Morton 1984; Calder 1986*b*; Morton 1985; Calder 1987).

The results from evaporation studies done in three broadly different climatic zones (the uplands of the U.K., west Java and southern India) are illustrative of the very large variation in the importance of the different controls between zones. The uplands of the U.K. are characterized by a wet, maritime, temperate climate where synoptic-scale advection of energy is possible through the rapid movement of frontal systems. The availability of soil water is not usually a limiting factor. Because forests are generally small in size (less than 10 km scale), and synoptic-scale air circulation is rapid, feedback effects of evaporation on the mesoclimate are likely to be small. Evaporation from forests is dominated by interception and the energy requirement for evaporation, because it can be supplemented by advection can exceed, even on a long-term basis (Calder 1982) the available net radiation.

The west Java site in the humid tropics experiences a climate dominated by two monsoons, which supply rainfall throughout the year; consequently, soil water is rarely a limiting factor. The generally slow movement of synoptic-scale air circulation patterns in the tropics provides less opportunity for large-scale advection and the combination of slow air circulation and the presence of large forests (greater than 10 km scale) increases the likelihood of forest evaporation strongly affecting the mesoscale climate. In these circumstances it is likely that evaporation from forests will be quite closely constrained by the availability of net radiation.

In contrast, the southern Indian site experiences a seasonally dry tropical climate. Two monsoons occur between July and December but the rest of the year is generally without rainfall. The principal controls on forest evaporation at this site are the availability of soil water and the physiological controls. Mesoscale climate is likely to be influenced by evaporation and an important question, which has not yet been answered, is whether large scale afforestation in this area would alter the mesoscale climate to the extent that desertification would be reduced.

It is only in the U.K. uplands where, because of the dominance of interception and the ease by which it can be estimated by semi-empirical methods, we are in a position to predict with some confidence the increased water use of forest compared with other vegetation types (Calder & Newson 1979; Calder 1988).

In many situations the assessment of the effects of forests on water quantity, quality, temperature and erosion are confused because it is often the management practices involved in afforestation or deforestation that are responsible for the reported deleterious effects rather than the presence of the forests themselves.

The situation in Britain illustrates the complex nature of the demands on forest hydrology. In Britain the hydrological interest in forests has been concentrated for 30 years on the plantation cropping of conifers in the uplands. Plantations were introduced in the 1920s in an attempt to compensate for a heavy dependence on imported softwood, the result of centuries of unplanned extraction of natural timber. Afforestation is one of a small group of potential land uses in the British uplands; the lack of clear land allocation policies in the U.K. has frustrated direct application of the hydrological results obtained to date (Newson 1988).

It was the protagonist of these studies (Law 1956, 1957) who first revealed to the British water industry that its liquid assets were, he claimed, likely to be reduced significantly by upland afforestation via the process of interception of precipitation. However, even the water industry's interest in forest hydrology has shifted emphasis, principally from quantity to quality, during the past decade. This has meant a movement of research interest to support a change of official emphasis from land use to land management. Essentially, a commercial coniferous forest canopy in the British uplands cannot be managed (species differences in interception rate are small) but forestry establishment and harvesting practices can be managed for the requirements of the water industry. Other national interests, for example nature conservation, have now joined the water industry in expressing concern over the effects of both forest land use and land management on the broader aqueous environment (Nature Conservancy Council 1986).

Because of the rate at which the world's tropical forests are being removed, the possible impact of tropical deforestation on water resources, climate and ecology is a source of major concern (Myers 1985). Generally, it is supposed that removal leads to an increase in floods and soil erosion, and to a reduction in evaporation and the recycling of precipitation, all of which contribute to degradation of the environment and may contribute to desertification. It is surprisingly difficult to extrapolate in forest hydrology from one climatic zone to another; even within Britain results derived from the uplands are not applicable to the lowlands (Gash & Stewart 1977) and it has taken the establishment of at least 36 research projects on 29 sites (Roberts 1983) to develop an inchoate national picture. Deforestation is not the only concern in the tropics: hydrological effects are also likely, following large-scale afforestation with fast-growing, often exotic, species.

2. Forest evaporation in upland Britain: predictable processes?

Following the lead set by Law, the Institute of Hydrology, Wallingford, U.K., has made several investigations involving both catchment studies and process studies to quantify further the effects. Law's observations on the reduction in runoff following afforestation of upland grassland were confirmed (Calder *et al.* 1982*b*).

A practical method, involving a minimal requirement of data, for calculating the effects on annual evaporation, E_a, of afforesting upland grassland catchments was proposed by Calder & Newson (1979, 1980). It was assumed that evaporation losses from grassland and transpiration losses from forests could be approximated by the annual (Penman) potential transpiration estimate (E_{Ta}), and the annual interception loss from the forest could be obtained from a simple function involving annual rainfall (P_a):

$$E_a = E_{Ta} + f(P_a \alpha - w_a E_{Ta}), \tag{1}$$

where α is the annual interception fraction (35–40% for areas of the U.K. where annual rainfall exceeds 1000 mm), w_a is the fraction of the year when the canopy is wet ($\approx 0.000122\, P_a$), and f is the fraction of the catchment area under canopy coverage.

This model indicated that in the wet, upland regions of the U.K. annual evaporation rates from forested catchments (with 75% of their area afforested, equivalent to 50% canopy coverage) may be double those from grassland with the result that streamflow will be reduced, typically by about 20%. More recent research on evaporation from heather moorland has established that transpiration losses are smaller but that interception losses are larger than from grassland. These observations suggest (Calder 1985, 1986*a*) (Table 1) that the annual interception losses from heather moorland can be estimated with an equation of the form:

$$E_a = \beta E_{Ta}(1 - w_a + \alpha P_a), \tag{2}$$

where the transpiration fraction, $\beta = 0.5$ and $\alpha = 0.2$.

This equation indicates that similar increases in evaporation and reductions in streamflow are to be expected when forests replace heather moorland that experiences an annual rainfall of about 1250 mm. In regions with annual rainfall totals greater than this, the increased interception losses from heather moorland (compared with rough pasture) outweigh the reduced transpiration so that the total annual evaporation from heather is greater than that from rough pasture; the converse is true in regions with smaller annual precipitation totals.

Therefore the effects on streamflow of afforesting heather moorland will be less than the effects resulting from afforesting grassland when annual rainfall exceeds 1250 mm.

The approach adopted for the annual model has been developed and extended through the use of a daily interception model to produce a method for estimating evaporation from the major upland vegetation types on a seasonal basis. It was proposed (Calder 1986*a*, 1988) that seasonal estimates of evaporation from forest, heather moorland and rough pasture can be obtained by integrating daily evaporation estimates, E_d. These daily values are calculated from the sum of transpiration and interception losses. Transpiration is obtained as the product of the parameter, a climatologically derived, daily Penman E_T estimate and a term $(1-w)$ that represents the fraction of the day that the canopy is dry. Interception loss is derived from an exponential relation involving daily precipitation, P. Thus

$$E_d = \beta E_T(1-w) + \gamma(1-\exp(-\delta P)), \tag{3}$$

where w is the fraction of the day that the canopy is wet ($= 0.045P$, for $P < 22$ mm; $= 1$ for $P \geqslant 22$ mm (after Calder & Newson 1970)) and the parameters γ and δ define the interception relation.

Estimates of the parameters α, β, γ and δ for the different vegetation types and the sources from which they were derived are shown in table 1.

TABLE 1. INTERCEPTION AND TRANSPIRATION OBSERVATIONS SUMMARIZED IN TERMS OF THE AVERAGE ANNUAL INTERCEPTION FRACTION (TO ANNUAL RAINFALL), α, THE DAILY INTERCEPTION MODEL PARAMETERS, γ, δ, AND THE FRACTION OF ANNUAL PENMAN $E_T{}^{c}$ ACCOUNTED FOR BY ACTUAL EVAPORATION

		interception parameters			transpiration
		α	γ (mm)	δ (mm^{-1})	fraction β
source	period	(annual)	(daily)		(annual)
FOREST					
all sites interception:					
Plynlimon, Dolydd, Crinan and Aviemore	—	0.35	6.9	0.099	
Plynlimon Forest, Lysimeter	1974–76	0.30	6.1	0.099	0.9
Dolydd	1981–83	0.39	7.6	0.099	—
Crinan	1978–80	0.36	6.6	0.099	—
Aviemore	1982–84[a]	0.45	7.1	0.099	—
HEATHER					
Model estimate derived using automatic weather station data and measured interception parameters. (Calder *et al.* 1986*c*)	1981	—	2.65	0.36	—
Crinan, neutron probe (Calder *et al.* 1982, 1984)	1981–83	—	—	—	0.58–0.67
Law's heather lysimeters (Calder *et al.* 1983)	1964–68	0.16	—	—	0.47
Sneaton moor lysimeter (Wallace *et al.* 1982)	1980	0.19	—	—	0.25–0.5
GRASS[b]					
Wye catchment, Plynlimon indicates total annual evaporation consistent with β					1.0

[a] Not including snow periods.

[b] Wye catchment Plynlimon indicates total annual evaporation consistent with transpiration fraction β (annual) 1.0.

[c] Estimated potential total evaporation and transpiration.

Although predictions of total annual evaporation have been vindicated by field evidence it is clear from the Institute of Hydrology's catchment experiment at Balquhidder in the Scottish Highlands that difficulties remain. Blackie (1987) reported initial conclusions that, 'water use by the partly forested catchment is lower than that by the control and also lower than Penman ET'. It seems likely that the Balquhidder results may be explained by early problems of instrumental calibration or, if real, either by a poorly ventilated forest canopy (if it is in a deep sheltered glen) or by a marked winter–spring restriction on transpiration by grass as a result of the harsh climate.

3. WATER USE IN TROPICAL FORESTS, HUMID AND DRY

Although many studies of rainfall interception and water use of tropical rainforest have been done (Coster 1937; Dabral & Rao 1968; Odum 1970; Low & Goh 1972; Jackson 1975; Edwards & Blackie 1981; Shuttleworth *et al.* 1984; Calder *et al.* 1986*a*) the results have sometimes been contradictory. To what extent the contradicitions reflect real site differences, rather than deficiencies in technique, is not known.

However, in the absence of other methods for estimating water use of rainforests it is suggested (de Bruin 1983; Calder *et al.* 1986*a*) that for humid tropical rainforests, which are not subject to long periods of water stress, it may be possible to estimate annual evaporation by assuming that the energy equivalent of the annual evaporation is equal to the annual net radiation. At the experimental site in west Java where transpiration and interception measurements were done (Calder *et al.* 1986*a*) the equivalence was exact within experimental error. This site rarely experiences soil moisture deficits, the maximum daily temperature is always within ±1 °C of the 'partition' temperature of 32 °C. There is some theoretical justification (Priestley 1966; Priestley & Taylor 1972; de Bruin 1983) for expecting that when this temperature is reached, and soil moisture is non-limiting, virtually all net radiation will be converted to latent rather than sensible heat. The measured transpiration and interception losses over one year were 886 mm and 595 mm, respectively.

In the seasonally dry tropical regions of the world forest evaporation is regulated principally by soil water availability and physiological controls. In these regions water resources are often scarce and any alteration to the environment that affects them is clearly a cause for concern. Of particular interest are the effects of afforestation with fast-growing, often exotic, tree species. This concern has been most fiercely directed towards *Eucalyptus* plantations (Vandana Shiva *et al.* 1982; Vandana Shiva & Bandyopadhyay 1983, 1985). Although there are claims that *Eucalyptus* plantations lead to erosion damage, have poisonous effects on other plant species and are not desirable for social forestry plantations, the central concern is that they use more water than other tree species or agricultural crops and lead to a lowering of groundwater levels. This last concern is easily understood as certain species have been used to reclaim swamps in different parts of the world and are currently being used in Australia, the home of most *Eucalyptus* species, as 'waterpumps' to deliberately lower water tables in regions that are experiencing salinity problems. The Australian studies of water use by *Eucalyptus* species (see Carbon *et al.* 1981, 1982; Colquhoun *et al.* 1984; Greenwood & Beresford 1979; Greenwood *et al.* 1982, 1985) are among the most detailed and comprehensive process studies of water use on any tree species. They indicate that *Eucalyptus* species tend to have a very effective stomatal response mechanism to soil moisture deficits that enables them to survive droughts, but that certain *Eucalyptus* species may not have a well-developed stomatal response to atmospheric humidity deficits. This response to atmospheric humidity, which is common in plant and tree species, tends to limit water use in times of high atmospheric demand. Colquhoun *et al.* (1984)

found wide differences in this response between different *Eucalyptus* species growing in Western Australia: *Eucalyptus marginata* Donn ex Sm. and *E. calophylla* R. Br. ex Lindl. showed no evidence of a stomatal response to water vapour saturation deficits although *E. maculata* Hook., *E. resinifera* Sm., *E. saligna* Sm. and *E. wandoo* Blakely all tended to show increased stomatal resistance with increasing water vapour saturation deficit (although no causal relation was established). From measurements of stomatal resistance on *E. grandis* W. Hill. ex Maiden in South Africa, Dye (1987) found that the response varied seasonally and that at high atmospheric water vapour saturation deficits (not less than 1 kPa) the response lessened. Körner (1985) and Körner & Cochrane (1985) report from their own studies, and by reviewing other work, that although *E. pauciflora* Sieb. ex Spreng, *E. globulus* Lobill and *E. leucophloia* Migum show the response, the threshold at which it occurs (about 1.2 kPa) is higher than that of any of the other seven non-*Eucalyptus* species reported. Körner (1985) also makes the point that 'species of high vigour of growth and with short lived assimilation organs are less sensitive (to atmospheric saturation deficit) than slow growing evergreen species'.

The net result is that when atmospheric demand is high, and certain species of *Eucalyptus* have access to groundwater reservoirs, remarkably high transpiration rates may prevail. Greenwood *et al.* (1985) report annual transpiration rates of 2700 mm from *Eucalyptus globulus* and *Eucalyptus cladocalyx* F. Muell. at a site in the Hotham Valley in Western Australia. These rates exceed the annual rainfall, of 680 mm, by about a factor of four.

However, it is by no means clear to what extent these, mostly Australian, observations of the behaviour of certain species in a particular environment can be related to *Eucalyptus* plantations elsewhere in the world (Calder 1986*b*). In many situations the 'alarmist' observations of high water use may be quite inapplicable. The Institute of Hydrology is currently doing studies in Karnataka State, Southern India, a region where extensive *Eucalyptus* plantations now exist. Results so far obtained from a site near Shimoga indicate an entirely different view. In this area the land under afforestation was formerly degraded forest that was exploited only for firewood and rough grazing. The annual average rainfall is about 1100 mm. The soils are fairly shallow, 2–3 m, and overlie granitic bedrock. The groundwater levels are usually at about 20 m. Initially, studies using deuterium as a tracer (Calder *et al.* 1986*b*) to measure flow through individual trees indicated flow rates, expressed as ground area depth, of about 1 mm per day in the dry season compared with the Penman potential value of 5–7 mm per day. These low rates in the dry season have since been confirmed by neutron probe measurements. Although there are insufficient data available to calculate values for the annual transpiration it seems unlikely that in this area, where root systems do not appear to penetrate beneath a depth of 2–3 m and presumably do not have access to groundwater reserves, the water use will be found 'excessive'; it is probably little different from the scrub vegetation it replaces.

It is also possible to speculate that in certain areas *Eucalyptus* plantations may be a positive benefit to the environment. In the drier northern parts of Karnataka, where the mean annual rainfall is 400–600 mm, the degraded forests, through continued cutting and grazing, are fast approaching desert conditions. Preliminary trials on *Eucalyptus* species have shown that they are as able as indigenous species to survive drought in these areas but their long-term potential for survival is better because they are unattractive to grazing animals. The extent to which *Eucalyptus* afforestation of these areas may reduce or reverse desertification through reducing soil erosion and by altering the mesoscale climate is not known, but results from studies directed at answering these questions are urgently awaited.

4. Forests and extreme flows: problems of management and scale

It is essential to preface this section with a reminder of the differences in spatial scale between British upland forests and their tropical counterparts. This contrast must be taken into account when interpreting any field data; the comparison of regional results becomes particularly difficult in assessing the effects of a forest cover, or its loss, on extreme flows. Furthermore, there are complications introduced by management issues, particularly in Britain where drainage of soils is a prerequisite of much upland afforestation.

In the tropics, as yet, the evidence for the effects of large-scale forest removal on river floods is unclear. Gentry & Parody (1980) reported an increase in the height of the flood crest for the Amazon at Iquitos for the period 1970–78. They argued that as there was no significant change in rainfall the cause was the deforestation of the upper reaches of the Amazon basin. Nordin & Meade (1982) contested this conclusion. They found that for the Rio Negro at Manaus the flood stages oscillated from highs during the period 1942–56, to lows during 1957–69, and to highs again between 1970–79. Clearly the earlier period of highs cannot be associated with large-scale deforestation.

Although evaporation from rainforest is likely to be high compared with that from other vegetation types, and deforestation is likely to result in increased runoff in the long term, there is no reason to suppose that increased evaporation during the storm periods responsible for floods will have other than a marginal effect on flood runoff. Any effects on flood runoff are more likely to arise from alterations in the maximum infiltration rates of soils. Lal (1981, 1987) and Salati *et al.* (1983) report that after forest removal infiltration rates are decreased. However, as the effect of deforestation on infiltration rates is likely to be dependent on the particular soil type and on management practices it is likely to be very site specific; it is therefore very difficult to draw any conclusions concerning the effects of tropical forest removal on either floods or soil erosion in the absence of local information on soil properties and climatic factors.

In the British uplands proven changes in flood régime are associated almost entirely with ground preparation that involves cultivation and drainage of poorly drained soils. Field studies of the effects of ground preparation on stream response have come mainly from three British sites: Coalburn in Northumberland (Robinson 1986), the Ettrick in the Southern Uplands (Acreman 1985), and Llanbrynmair in Wales (Leeks & Roberts 1986). However, other studies are also relevant, e.g. those relating to moor 'gripping' (the open drainage carried out by farmers (Stewart & Lance 1983; Robinson 1985)) and to the flow of drainage networks beneath mature forests (Robinson & Newson 1986).

All of these studies reveal a shorter time interval between rainfall and flood peaks after ground preparation than before, and because volumes are undiminished, peaks of runoff are therefore higher. The results obtained by Robinson show that the time-to-peak flow decreased appreciably after drainage (2.1–1.6 h according to Robinson (1986); also peak flows increased by 40% but both effects had diminished slightly 10 years later). Leeks & Roberts (1986) recorded a 20% increase in hydrograph peak flows and a reduction of time-to-peak from 2.7 to 1.8 h after ground preparation at Llanbrynmair.

However well proven the relation within small experimental areas (the Coalburn catchment is 1.5 km^2), care must be exercised in extrapolating downstream. Beyond the forest margin, the natural smoothing effect of distance from the source reduces the flood peak. As Acreman

(1985) found on the Ettrick catchment (37.5 km^2), although a 30% increase in unit hydrograph peaks was caused by ground preparation for afforestation of the upper catchment, somewhat reduced flooding resulted from forest cultivation and drainage schemes lower down. Before this investigation, Howe *et al.* (1967) had claimed that post-war increases in flood peaks in the larger rivers of Wales were linked to extensive afforestation in catchment headwaters.

Ground preparation for upland forestry in Britain is also thought to affect low flows. Field evidence here is scarce and inconsistent in its conclusions. At Coalburn, the evidence points to 'dewatering' of peat providing an increase in low flow drainage following cultivation and drainage (Robinson 1986); at Moor House the moor gripping scheme did not conclusively alter low flows, but Robinson (1985) suggests that heather burning reduced low flows. Green (1970) reported increased annual runoff after ground preparation in the Brenig catchment. It should be noted that these studies refer to peats only.

Effects of drainage vary between peat and mineral soils and between blanket and basin peats, and it is clear that the effects of afforestation on streamflow response over the full range of flows is a much neglected area of research. This is the more serious because it is an area of land-management practice that could be guided by the results of such research.

Robinson & Newson (1986) have also drawn a distinction between 'technical drainage' (cultivation, ditching during ground preparation), which is relatively ineffective in the uplands, and 'biological drainage' (i.e. reduced, net rainfall entering the soil as a result of interception) which reduces saturation levels in the soil much more impressively than does the ditch network. The resulting increase in soil storage capacity for storm rainfall naturally reduces runoff during rainfall events. Robinson & Newson suggested, however, that this 'flood-reducing' capacity is limited to small and moderate floods. The flood-producing storm, which is equalled or exceeded once a year or less, is likely to be too intense for any appreciable effects of interception or soil moisture storage to influence streamflow. It is possibly for this reason that the Flood Studies Report (NERC 1975), a major review work on hazardous floods, found that forest cover on catchments was not a significant variable in explaining the regional variability of flooding.

There are two crucial features of the potential effect of a closed forest canopy on drought flows under British upland conditions. One is that interception loss occurs only when the canopy is wet (i.e. not during dry weather). Walsh & Walker (1985), for example, demonstrated the way in which the interception fraction reaches a winter peak at Stocks Reservoir. Secondly, if the reduced, net rainfall beneath canopies is to influence deep water storage, and hence the replenishment of streamflow during droughts, the deeper soil layers and upper rock layers must behave as an aquifer capable of storing a large proportion of the gross rainfall. This is not often the case in the uplands where true aquifer rocks are rare. Most deeper storage occurs in relatively impermeable drifts and peats. In addition, tall crops such as conifers control their rates of transpiration more effectively during droughts than do shorter crops (Gash & Stewart 1977) because of their tighter coupling to atmospheric conditions and, therefore, the great influence of canopy conductance (McNaughton & Jarvis 1983; Jarvis & McNaughton 1986).

The influence of closed canopies on stream flows during drought is much affected by local influences. Only one general effect is certain: interception will reduce runoff from sporadic rainfalls that characterize British droughts, and reduce soil moisture replenishment, delaying the recovery of reservoir levels. Records of the effects of the rare British drought of 1976 in forested catchments and the complications in their interpretation are presented by Clarke & Newson (1978) and Newson (1980*a*).

5. Forests and sediment yields: site factors dominate

The British upland climate is severe, but erosion rates are low where the semi-natural vegetation cover is intact. Where it is disrupted, the influences of wetting–drying, freezing–thawing and the erosive power of heavy rainfall combine to increase the yield of sediments (both mineral and organic) by up to several orders of magnitude (see the review by Newson (1986)). Cultivation and drainage increased the density of surface channels in typical moorland areas from less than 10 km km^{-2} to more than 200 km km^{-2} (or 31- to 62-fold) (Francis 1987). Francis also calculated that, as a result of creating furrows, ditches and planting ridges at a typical recent scheme (Llanbrynmair), there was a 45- to 79-fold increase in the exposure of peat and mineral material, exposed for the first time in up to 6000 years.

Obviously the detachment and removal to streams of fully exposed mineral and organic particles is at its maximum in the period immediately after ground preparation. Results from Coalburn are again instructive here. Robinson & Blyth (1982) indicated that most of the fine sediments released left the catchment in the first five years after ground preparation. After five years, yields declined, but a new long-term equilibrium yield was still four times that before afforestation. Burt *et al.* (1984), studying feeder streams to Holmstyes reservoir, suggested that the Coalburn model of response may be only one variant in terms of sediment availability over time, and stressed the importance of storms in the winter after ground preparation. The timing of this operation is critical because the recolonization of ditches and furrows by vegetation reduces sediment runoff much more effectively than does the use of buffer strips between furrows or drains, and streams; spring cultivation is therefore preferable.

Despite recommendations advising how effects of land disturbance can be minimized, there have been many problems of excessive silt runoff from land being prepared for afforestation (Stretton 1984; Austin & Brown 1982). Suspended sediments are not the only category of stream-load changed by this activity. As table 2 shows, coarser sediments that are transported as bed-load are also released and are important in their subsequent effects on channel geometry, and in modifying the substrata for stream biota. The major source of increased bed-load, largely in the gravel size range, is the incision of drainage ditches, particularly those aligned directly downslope. Newson (1980*b*) indicated that gradients as shallow as 2° lead to incision of ditches in loose shale gravels in Wales.

At present there is little indication as to the effect of clear felling on sediment yield in the British uplands. Leeks & Roberts (1986) recorded an increase of suspended sediment yield for the Hore catchment during timber harvesting from 24.4 t km^{-2} per year to 57.1 t km^{-2} per year. Volumes of bed-load increased 20-fold in the ditch system of a recently felled stand, only to recover to a 4-fold increase after log-jams and debris dams formed across the channel. In some ways this form of carelessness in harvesting (or even the deliberate dumping of timber waste in channels) is detrimental to streams and eventually promotes further erosion (Murgatroyd & Ternan 1983) but, equally, such obstructions initially slow the movement of gravel downstream. Leeks & Roberts (1986) stressed that rates of bed-load movement must be monitored for long periods to allow for its slow and episodic movement downstream.

The most recently published findings from the sediment monitoring at Balquhidder during

Table 2. Sediment loads at moorland and forest sites

location	fine sediments transported as suspended load (moorland)	forest	coarse sediments transported as bed-load (moorland)	forest
Plynlimon	6.1 t km^{-2} a^{-1}	12.1 t km^{-2} a^{-1}	6.4 t km^{-2} a^{-1}	38.4 t km^{-2} a^{-1}
Balquhidder	38 t km^{-2} a^{-1}	131 t km^{-2} a^{-1}	0.1 t km^{-2} a^{-1}	2.1 t km^{-2} a^{-1}
Coalburn	2.9 t km^{-2} a^{-1}	12.2 t km^{-2} a^{-1}[a]	0.6 t km^{-2} a^{-1}	no change
Llanbrynmair	3.7 t km^{-2} a^{-1}	9.0 t km^{-2} a^{-1}	(not significant 0.5–2 % of suspended load)	
	0.7 t km^{-2} a^{-1}	3.1 t km^{-2} a^{-1}		

[a] After temporary 50-fold increase.

timber harvesting (Ferguson & Scott 1987) indicated a 20 % increase in suspended sediment yield after construction of a loading bay; bed-load also increased after roading, but these effects were highly localized.

6. Conclusions

In an attempt to produce an up-to-date review of the relation between forests and water resources under contrasting climatic régimes we have been unable to avoid bias in the topics, the literature and the geographical coverage provided. This situation is inescapable for the following reasons.

1. Forests modify mechanisms across the full range of environmental processes occurring at the earth's surface, from microclimate to nutrient cycling; their presence or absence as a cover, therefore, influences all aspects of water resources over the full spectrum of timescales. The degree to which an influence becomes an impact will also depend on spatial and temporal variables and on the sophistication of the society developing the water or timber resources.
2. Characteristic forest types vary not only across climatic zones but in relation to the characteristic short vegetation of the region (or unvegetated surfaces) and, spectacularly, in relation to the way they are managed.
3. As a result of the many regional and local variables implicit in 1 and 2 above, it is almost impossible to generalize and predict for any but the simplest processes, mainly those concerned with water use by forests (see Bosch & Hewlett 1982; Schultze & George 1987). For the remainder of the field the reviewer is restricted to local empiricisms, and the very unequal distribution of these, e.g. between developed and developing countries, further hinders progress.

Faced with these scientific problems but a continuing need for answers, it is not surprising that many water managers and foresters are still utilizing 'forest lore', which may still include the views that 'trees drink water because of their long roots' and 'trees attract rainfall'. The former still prevails in regions where windblow results from shallow rooting and the latter is made to sound convincing even where the clouds hanging over the canopy are clearly composed of evaporated moisture leaving it.

This situation is a clear challenge to the science of forest hydrology, which has tended to acquire a regional orientation and has consequently been too often lured into site-specific studies. Unfortunately, the commonest methodological option in hydrology, the catchment experiment, falls solidly into the trap, as Ward's (1971) review describes. Left to their own devices, most hydrologists would now advance their study towards the calibration of general models through controlled field or laboratory experimentation on processes. They are diverted by two powerful forces: the great devotion of water managers and particularly water engineers, to 'relevant' empiricism and the increasing tendency to concentrate declining funds on 'high-profile' field experiments.

How does the hydrologist incorporate the plethora of regional and local effects? Recent technical advances in remote sensing and geographical information systems provide the key. If used as a framework for process investigations, keeping the investigator aware of full-scale (geographical) deflection of the controlling variables, and if used again at the modelling stage to gross up from well-proven component algorithms, they hold great promise for increasingly relevant, firmly based generalizations.

The authors acknowledge the work of their colleagues, past and present, at the Institute of Hydrology. Despite the compilation of this paper across distances of several thousands of miles, Sheila Spence has coped admirably with its production.

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Discussion

A. Henderson-Sellers (*Department of Geography, University of Liverpool, U.K.*). Professor Newson has given a very fluent description of the hazards of 'scaling up' in hydrology. He has, however, only taken us from leaf stomata to basin catchment. I invite him to comment on how one should go about scaling up from the catchment to the size of a general circulation climate model grid element, i.e. about 500 km × 500 km?

M. D. Newson. What I have tried to show is the danger of scaling up from stomata to catchments where the engineering interest in the catchment is in site-specific (or regionally representative) water balances and predicted extremes of flow. In our paper we also point to the even more difficult task of scaling up water quality predictions.

In commenting on the next quantum leap in scale it must be said that catchment experiments seldom yield suitable, parametrized data for the climate models Professor Henderson-Sellers describes. In a sense her models are best calibrated by the parameter quantification provided by small-scale, controlled environmental physics experiments. The outputs of climate models thus calibrated can then be tested (for example predicted mass balances) against the results of comprehensively instrumented catchment experiments. Herein lies another pitfall: catchments whose results would be directly relevant to areas of 250000 km^2 (the size of your grid element) can never be comprehensively instrumented. We therefore await much finer global models or much greater investment in ground truth before the three scales couple up effectively.

J. B. Williams (*Overseas Development Natural Resources Institute, Surrey, U.K.*). It is not clear to me why catchment scale results cannot be extrapolated over larger spatial areas for use in GCM models (as suggested by Professor Newson's response to Professor Henderson-Sellers). Could Professor Newson please explain the constraints and limitations of catchment work in this regard?

M. D. Newson. I merely wished to point out that catchment results are normally in the form of simple (but expensively obtained) mass balances, or extremes, obtained for the purposes of a much more specific, often engineering, application. Catchment results can, therefore, be of value in testing GCM models, whereas environmental physics data can be used much more readily in model calibration. It is partly a problem of research design, but also one of expense. Hudson (1988) perhaps makes this clearer than I can by showing the way in which mass balances calculated for the Plynlimon catchments, two of the world's most densely instrumented hydrological reasearch areas, introduce doubts about instrumental performance, spatial representativeness and experimental design. He defends catchment experiments by saying that, 'while process studies are indispensable as a means of defining and quantifying the different evaporation characteristics of the vegetation types, catchment experiments provide the more realistic regional calibration because they are performed on "true" environmental units' (p. 306). However, Hudson's paper clearly demonstrates the investment involved in obtaining such calibrations: he utilizes eight years of data from over 70 instrument sites to produce data for less than 20 km^2. Professor Henderson-Sellers has spoken of units of 250000 km^2; with the exception of the Danube I cannot find a gauged catchment in Europe of that size.

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M. H. Unsworth (*Department of Environmental Physiology, University of Nottingham, U.K.*). The measurements at Balquhidder indicate that the afforested catchment uses less water than the un-afforested. This appears to disagree with the generally held view. Can Professor Newson speculate on the cause of this discrepancy and indicate whether there should now be doubt over the validity of maps that have been used to show where it would be inadvisable to afforest catchments that are currently used for water supplies?

M. D. Newson. I have no wish to intrude on the progress being made by the Institute of

Hydrology in answering this thorny problem. One of the vicissitudes of contract research is that data become published at a very early stage and in catchment experiments this is dangerous; when I worked at Plynlimon it took ten years to produce the first conclusive results.

There seem to me to be three possible explanations for the early water balance results from Balquhidder.

1. The lower losses measured by water balancing the forested catchment may be the result of the difficulties of making hydrometric measurements in rugged terrain.

2. That terrain itself may explain the contrast with other reported results by preventing full ventilation of the forest (which is in the bottom of the deep glacial trough of Kirkton Glen).

3. The extreme climate may result in much reduced annual duration of transpiration by montane grasses above the tree line in the forested catchment. The control catchment has a greater proportion of heather which, as reported by our paper, can exhibit high loss rates under the conditions of the Scottish Highlands.

As a geographer I have to say that more care should have been exercised in choosing topographically representative sites for a Scottish catchment experiment. Using the Institute of Terrestrial Ecology's Land Classification System (Bunce *et al.* 1981) it is clear that the Balquhidder site is quite unlike Plynlimon, the Pennines, the Southern Uplands and other sites at which the 'Calder–Newson method' of predicting water loss on gathering grounds has been vindicated.

As a practical hydrologist, however, I realise that Balquhidder 'chose itself' because the Forestry Commission presented ideal opportunities to pace the calibration of the catchments in time with a sympathetic planting and felling programme.

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P. G. Jarvis (*Department of Forestry and Natural Resources, University of Edinburgh, U.K.*). I should like to comment on the discussion about *Eucalyptus* plus water use. In Australia native stands of eucalypts generally have a leaf-area index (LAI) of around one, i.e. the LAI is small, and transpiration is small as a result. Plantations in Australia, Brazil and Portugal – and elsewhere – do have a much larger LAI and transpire a lot more. However, there is nothing particular or peculiar about eucalypts. They transpire in relation to their leaf area like other trees. It is because they grow quickly and can get to a larger LAI in 12–18 months, that they seem to use a lot more water than other trees and crops, but they only do so because they have got big quickly.

M. D. Newson. That seems a very useful point to make alongside the observations made in our paper about interspecific variation in the control of water loss exercised by *Eucalyptus* and the experimental results reported for a three-year-old stand. It is quite clearly the rapid growth of these trees and the transpirational loss by some species growing in wet soils that attracts the phenomenal amount of comment from land and water managers.

J. L. Monteith, F.R.S. (*International Centre for Research into Crops for the Semi-Arid Tropics, Hyderabad, India*). The figure of 1 mm per day from a *Eucalyptus* stand is unlikely to be a representative figure because it would be associated with a very slow growth rate. If it was obtained during the long dry season it should not be used to suggest that *Eucalyptus* trees use much less water than other types of vegetation.

M. D. Newson. Professor Monteith is correct to point out the dangers of generalizations of this type. Under the specific conditions of the tracer experiment done on *Eucalyptus tereticornis* in southern India (Calder *et al.* 1986), i.e. three-year-old trees, under dry pre-monsoonal conditions, the daily water use of 1 mm suggests that moisture conditions are limiting both their transpiration and possibly their growth rate. The trees root in 2–3 m depth of soil overlying granitic bedrock in which the water table lies at −20 m (at the time of the experiment). Calder *et al.* (1986) take care to point out that 'more comprehensive studies are required over a wider range of tree ages, soil types and climatic conditions', rather nicely pointing up the words in our title, 'problems of prediction in a regional science'.

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Calder, I. R., Narayanswamy, M. D., Srinivasahr, N. V., Darling, W. A. & Lardner, A. J. 1986 Investigation into the use of deuterium as a tracer for measuring from eucalypts. *J. Hydrol.* **84**, 345–351.

J. Roberts (*Institute of Hydrology, Wallingford, U.K.*). In response to Professor Monteith's query to Professor Newson I should like to point out that the *Eucalyptus* transpiration data given in the paper were taken in the period before the monsoon when there would be quite severe water stress, stomatal closure and limitation of transpiration.

P G. Jarvis (*Department of Forestry and Natural Resources, University of Edinburgh, U.K.*) It sesems likely to me reduced stocking and thinning will reduce interception loss. I wonder if someone could elaborate on the remarks that recent experiments by the Institute of Hydrology show this not to be so.

I. R. Wright (*Institute of Hydrology, Wallingford, U.K.*). The results referred to are from an experiment in the Hafren Forest, Wales, and arose from an opportunity to replace plastic sheet net-rainfall gauges into their original position after line thinning. One row in every three was removed from an 18 m stand of sitka spruce. Data from the sheets were recorded for two or three years until canopy closure was regained.

Forest thinning operations will reduce the proportion of rainfall available for re-evaporation by removing part of the intercepting canopy. However, increased ventilation will enhance the transport of water vapour from the canopy, increasing the rate of evaporation from the reduced water storage. In any thinning operation the change in interception loss will be the result of these two opposing processes.

The results presented by Professor Newson show that increased ventilation is an important process in that the loss from larger storms is increased. However, the reduced canopy storage reduces the loss from small storms. At this site there was no significant change in interception loss on an annual basis. The effects of increased ventilation and reduced canopy storage cancel each other over this time scale.

Many factors contribute to the likely outcome of thinning practices, including species, stand density, aerodynamic exposure and thinning technique. In the case of line thinning, the row orientation to the wind direction will be important. Individual experiments will always be site specific and a general result must be in the form of a model.

M. D. Newson. This material does not appear in the paper as written, only as presented. Because Professor Jarvis initiated this particular discussion perhaps we can prolong it in private?