Forestry Commission
231 Corstorphine Road
Edinburgh
EH12 7AT
www.forestry.gov.uk

Water Use by Trees

INFORMATION NOTE

BY TOM NISBET OF FOREST RESEARCH

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SUMMARY

Trees and forests can use more water than shorter types of vegetation. This is mainly due to the interception of rainwater by their aerodynamically rougher canopies. The resulting impact on water supplies is becoming an increasingly important issue for water resource managers and planners as demands for water continue to rise. Climate change predictions of warmer, drier summers will put further pressure on supplies. This Information Note assesses the factors that influence the water use of trees and considers how conifers and broadleaves are likely to affect water resources in different parts of the UK.

INTRODUCTION

The amount of water used by trees has been the subject of worldwide research spanning the past 100 years (Bosch and Hewlett, 1982; McCulloch and Robinson, 1993). This work has been driven by the needs of water resource managers and planners to understand how forests affect water supplies, as well as by related concerns over downstream flooding and erosion control. Studies in the UK began in the 1960s and initially focused on the impact of conifer afforestation in the uplands. In the 1980s and 1990s interest widened to include the effects of broadleaved woodland and short rotation coppice on groundwater resources in the lowlands. Today, the need to know how forests and land-use in general affect run-off is even greater as water companies strive to deal with the dual threat of rising water demand and the possibility of reduced supplies due to climate change. The introduction of the European Water Framework Directive in 2000 presents another important challenge, as Member States are required to achieve good surface water and groundwater status by 2015. The purpose of this Information Note is to review our understanding of water use by trees in the light of findings from recent studies.

HOW DO TREES USE WATER?

Trees use or lose water by two separate processes (Figure 1). Firstly, water is taken up by tree roots from the soil and evaporated through the pores or *stomata* on the surface of leaves. This is termed transpiration and is a physiological process responding to soil and atmospheric factors.

The second process is the interception of water by the surfaces of leaves, branches and trunks during rainfall, and its subsequent evaporation. Interception losses are enhanced by the high atmospheric turbulence created by forest canopies due to their height and rough aerodynamic profile. Taken together, these two processes are often referred to as evapotranspiration. Both are strongly affected by the amount of sunlight, the temperature and humidity of the air, and wind speed.

DO TREES USE MORE WATER THAN OTHER TYPES OF VEGETATION?

Trees have the ability to use more water than most other types of vegetation, although the issue of whether and by how much depends on many factors. These are considered below.

FACTORS AFFECTING WATER USE

Forest type/species

The main distinction is between conifers and broadleaves. Evergreen conifers tend to have a greater water use because high interception losses are maintained throughout the year, and particularly during the winter period when conditions are usually wettest and windiest. Studies in the UK have found that between 25 and 45% of

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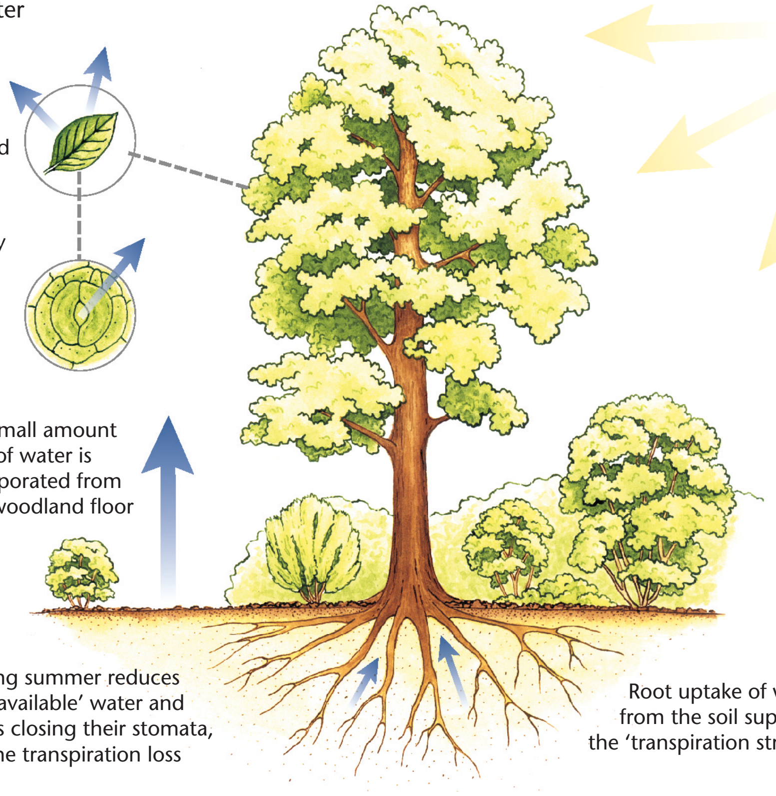
Figure 1 How trees use water



Key terms describing the processes that govern water use by trees:

Evaporation: The process by which water changes from a liquid to a vapour. The rate of evaporation is dependent on the amount of solar radiation, the temperature of the air and water, humidity and wind speed.

Transpiration: The process by which water taken in by tree roots from the soil is evaporated through the pores or *stomata* on the surface of leaves.

Interception: The process by which water held on the surface of leaves, branches and trunk during and after rainfall is directly evaporated back to the atmosphere. Often expressed as a proportion of annual precipitation (interception ratio).

Evapotranspiration: A term describing the total loss of water by evaporation from the land, including that lost by interception, transpiration and directly from the soil surface.

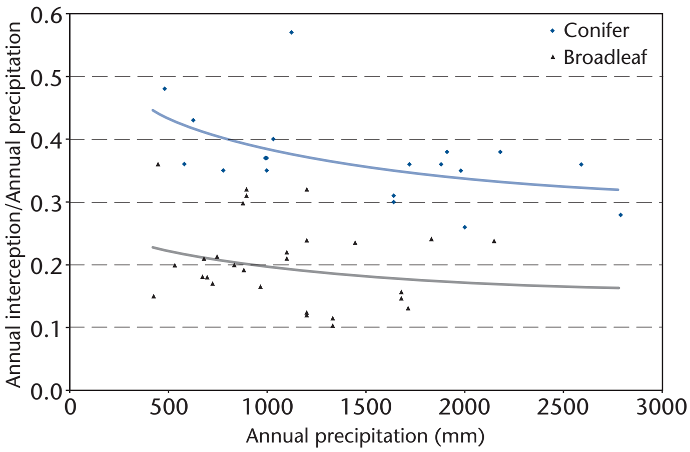
Penman (Potential) Evapotranspiration (PEt): The total loss of water by evaporation from an actively growing, short, green (grass) crop that is never short of soil water (see Alternative land cover).

annual rainfall is typically lost by interception[1] from conifer stands, compared with 10–25% for broadleaves (Calder *et al.*, 2003). These percentages remain remarkably constant over a wide range of total rainfall (Figure 2).

Transpiration rates, on the other hand, vary little between the two forest types, with annual losses mainly falling within a relatively narrow range of 300–350 mm (Roberts, 1983). Recent work in southern England, however, has found higher annual transpiration losses for broadleaves of 360–390 mm (Harding *et al.*, 1992). Therefore if both interception and transpiration are considered together, and assuming an annual rainfall of 1000 mm, conifers could be expected to use some 550–800 mm of water compared with 400–640 mm for broadleaves.

Figure 2

Comparison of interception ratios for conifers and broadleaves.



[1]Rainfall and evaporation are usually expressed as an equivalent depth of water in mm across the land surface. The addition or loss of 1 mm of water to/from an area of 1 m^2 of ground is equivalent to a total volume of 1 litre. Similarly, 1 mm of rainfall or evaporation to/from 1 ha is equivalent to 10 m^3 or 10 000 litres of water.

The variation in water use between individual species at a stand level is relatively small, although there are some exceptions. Interception and transpiration losses appear to be consistent among conifers—including some deciduous species such as larch. The tendency of larch to maintain high interception losses during winter at some sites, despite the absence of needles, can be explained by its very fine branch structure (Reynolds *et al*., 1989). There is evidence for more variation among broadleaves related to differences in canopy density, with the lighter canopies of species such as ash and birch having a lower interception loss than the heavier canopies of oak or beech. For example, research in the south of England has found that ash only intercepted 11% of annual rainfall compared with 15% for beech (Harding *et al*., 1992). The largest difference, however, concerns willow and poplar, which can sustain high transpiration rates of over 500 mm yr^{-1} in wet soil conditions (Hall *et al*., 1996).

Climate/location

The amount of water used by trees is strongly influenced by climate. Annual interception losses are affected more than transpiration and, in terms of absolute volume, reach a maximum in the wet and windy conditions typical of the upland areas of western and northern Britain. For example, studies in Wales have shown that as much as 690 mm of rainwater can be lost over a year by interception from a pole-stage stand of Sitka spruce (Calder, 1990). Daily losses are highly variable depending on the amount of rainfall. Light showers can be completely intercepted, while losses as a proportion of rainfall decline with increasing rainfall intensity, reaching an absolute maximum of 6–7 mm d^{-1} (Calder *et al*., 2002).

In contrast, transpiration losses tend to vary little around the country despite the large climatic range. This is mainly due to the ability of many tree species to control transpiration by closing the stomata on their leaves in response to dry atmospheric or soil conditions. Thus trees growing in the colder northwest of Britain tend to have similar annual transpiration totals to those growing in the warmer southeast.

Soil/geology

Soil and geology can affect water use by influencing the amount of water that is available in the soil to maintain transpiration. However, most tree species are relatively insensitive to soil drying until soil moisture levels become very depleted (Roberts, 1983). This is thought to be due to the greater sensitivity of their stomata to atmospheric humidity than to soil drying, as well as the ability of trees to root deeper and access water at depth. Trees on sandy or shallow soils are most likely to experience severe water stress, which can result in a sharp decline in transpiration through stomatal closure, loss of foliage, dieback of twigs and, in extreme cases, death. In contrast, some rock types such as chalk can maintain root water uptake by capillary action within the rock, even during periods of severe drought.

Forest management

Forest management can have a marked impact on the water use of a stand of trees. Felling is the most dramatic intervention, although the removal of the trees does not eliminate the use of water. Much depends on whether an understorey is present, the degree to which it remains undamaged by the felling operations, and the way in which the remaining cut branches and tree tops (brash) are managed. While the understorey makes a relatively small contribution to the water use of most stands, this situation rapidly changes following the removal of the shade and shelter provided by the woodland canopy. The more developed the understorey and the less it is damaged by felling, then the smaller the change in water use.

The largest reduction in water use will occur for clearfelled conifer stands with little or no understorey or ground vegetation. However, even if felling leaves a temporarily unvegetated site, and thus no transpiration loss, there will remain some rainfall interception by the brash residues, as well as a small amount of evaporation from areas of bare soil. Research has shown that a thick pile of brash can intercept as much as 15% of annual rainfall, which is similar to that lost from a broadleaved woodland canopy (Johnson, 1995). This loss will decline over several years with the breakdown of the brash, although the effect on water use will be counteracted by a rise in transpiration rates as the site re-vegetates.

Normal thinning operations generally have little effect on the water use of a forest stand. Studies at Plynlimon in Wales have shown that the removal of one row of trees in three can lead to a minor reduction in interception loss from 38% to 36% (Calder, 1990). This is likely to be the result of the increased ventilation in the canopy compensating for the reduction in canopy density, as well as the relatively rapid closure of the open space by the expansion of the surrounding canopy.

Soil cultivation prior to planting can have a significant effect on water use. The magnitude of the effect is highly dependent on the extent to which the existing vegetation is disturbed or removed by the operation. Ploughing causes the greatest reduction in water use by leaving a temporary bare soil surface over as much as 40% of the affected area. For example, the removal of the original moorland vegetation by deep ploughing in the Coalburn catchment in northern England in the early 1970s was thought to have been responsible for temporarily reducing evaporation losses and thus increasing water yield by about 70 mm yr^{-1} (Robinson *et al*., 1998). Contemporary cultivation practice with a focus on reduced soil disturbance can be expected to have a smaller effect on site evaporation. The water use will quickly recover following re-growth of the previous vegetation and the growth of the planted crop, although it will not be until the stage of canopy closure, typically at 10–20 years, that the trees will dominate the water use of the site. The use of herbicides to control competing vegetation is another activity that will produce a temporary decrease in site water use.

Design

The design of a forest exerts a marked influence on its overall water use through determining the mix of species and crop ages, and the amount of open space. A mixed-aged forest will usually have a lower water use than a single-aged one (with the exception of the first 10–15 year period of growth in the case of the latter) on account of the smaller proportion of the forest with a fully developed, 'intercepting' canopy. This is despite the greater length of edge between young and old stands within a mixed-aged forest, which enhances local turbulence and thus evaporation rates. Research suggests that the edge effect is limited to a very narrow band (<20 m from the stand edge) and therefore is only significant for individual stands or woodlands that are less than 1 ha in area (Neal *et al*., 1991). This size of woodland is very small in conventional upland forestry but the edge effect could become an issue with the move towards continuous cover forestry (CCF). Depending on the form of CCF, the creation of a permanent or aerodynamically rougher forest canopy could lead to an increase in water use at the forest level. Another factor to consider is the decline in tree water use with age, and the expectation that the proportion of older stands will increase under CCF. Studies overseas have shown that the replacement of an old growth stand with a young one can result in a marked increase in water use (Jayasuriya *et al*., 1993).

Scale

The amount of water used by an individual tree tends to be more variable than that of a uniform forest stand. In general, isolated single trees in the landscape have a much higher water use on account of their larger canopy and greater exposure. Maximum daily transpiration rates tend to range from 500–2000 l for individual trees of varying species. This compares with a maximum loss of around 18 l d^{-1} for individual trees in a stand of unthinned Sitka spruce at a density of 3300 stems ha^{-1}, based on a transpiration rate of 6 mm d^{-1}. Scale also becomes an important issue when extrapolating the water use of a forest to the level of a larger catchment. Obviously, as the proportion of the area occupied by a forest declines, its 'signature' will be progressively diluted by that of the non-forest land cover.

Alternative land cover

The issue of whether forests use more water than non-forest vegetation depends greatly on the nature of the latter. Of alternative land covers, the distinction is most marked for arable crops. Although the transpiration rates of actively growing arable crops exceed those of most trees, overall losses are limited by their short crop cycle with significant periods of fallow, young growth and ripening. Published figures for annual transpiration based on one crop cycle tend to fall within the range of 200–300 mm for barley, wheat, oats and potatoes, although modelled data, which includes some interception losses and soil evaporation during and following harvesting, give values for total annual water use generally in the range of 370–430 mm (Hall *et al*., 1996). As with forests, however, much depends on the management of the arable crop, with the use of autumn sowing greatly reducing the length of fallow and thus the period of low water use. In addition, the frequent use of irrigation in drier parts of the country can significantly raise the water use of crops by as much as 100 mm yr^{-1}.

It is more typical to compare the water use of forest with that of permanent grassland, rough pasture or moorland, since this is the type of land cover that is usually subject to woodland planting. The water use of grassland also forms the basis of an 'industry standard', namely the calculation of the Penman potential evapotranspiration rate or PEt (Penman, 1948). This represents an estimate of the amount of water evaporated by a short grass crop that remains well supplied with soil moisture, and tends to range from 400 mm yr^{-1} in the north to >600 mm yr^{-1} in the south. Essentially, the evaporative loss is dominated by transpiration since the aerodynamic roughness and thus the potential for rainfall interception is minimal for a short sward.

Once again, management is a major factor controlling the water use of grass. A heavy grazing regime or restricted rooting depth (leading to a lack of soil water) can greatly reduce transpiration, resulting in an annual value that is much less than PEt. In contrast, a well-managed grassland with good nutrition and water supply could be expected to maintain PEt in full. The water use of rough upland pasture or moorland can be enhanced in long swards by some interception losses, although these are restricted by climatic conditions that shorten the growing season and flatten the grass during winter periods.

Other types of shorter vegetation with a distinctive water use include bracken and heather. The relatively tall and complete canopy formed by bracken has been found to have a seasonally high interception loss, amounting to as much as 50% of rainfall (Williams *et al.*, 1987). Annual interception (20%) can be similar to, or even higher than, that for broadleaved woodland, while transpiration losses are thought to equate to those of grass (unless heavily shaded). Heather also has a relatively high interception loss on account of its very fine branch structure. Typical annual interception losses for heather range from 16–19% (Calder, 1990). However, the effect of this interception loss is partly counterbalanced by its low transpiration rate, which generally ranges between 200 and 420 mm yr^{-1}.

The annual evaporation loss for different land covers is compared in Table 1.

Table 1

Typical range of annual evaporation losses (mm) for different land covers receiving 1000 mm annual rainfall

Land cover	Transpiration	Interception	Total evaporation
Conifers	300–350	250–450	550–800
Broadleaves	300–390	100–250	400–640
Grass	400–600	–	400–600
Heather	200–420	160–190	360–610
Bracken	400–600	200	600–800
Arable*	370–430	–	370–430

*assuming no irrigation.

EFFECTS OF FORESTRY ON WATER RESOURCES

It follows from the above discussion that it is difficult to generalise about the effects of forestry on water resources. Nevertheless, some important distinctions can be drawn between the likely impact of conifers and broadleaves in the uplands and lowlands. These are considered below.

Conifers – uplands

Most research in the UK has focused on the water use of upland conifer plantations in response to concern over the impact of the major programme of afforestation in the 1960s and 70s. This led to the establishment of three major catchment studies in Wales (Plynlimon), England (Coalburn) and Scotland (Balquhidder) which were designed to quantify the hydrological effects of forestry under contrasting climatic conditions. The results from these and supporting studies of physical and physiological processes have greatly improved our understanding of forest hydrology and led to the development of a range of models to predict the effects of conifer forestry on water yield across upland Britain. In particular, the work of Calder and Newson (1979) led to the rule of thumb that for every 10% of an upland catchment that was covered by mature (closed canopy) conifer forest, there would be a potential 1.5–2.0% reduction in water yield.

Continued monitoring within these catchments, however, has highlighted the contrasting effects of different forestry management operations and led to the conclusion that the impact of a well designed, mixed-aged forest is likely to be less than a 1% reduction in yield per 10% forest cover over the whole forest rotation. For example, the long-term record for the Coalburn catchment shows that the water yield remained slightly higher (by 5–10%) than the baseline moorland period for some 20 years after almost complete afforestation. In fact, the water yield had only declined by 1–5% by the time the forest was aged 25 years, which is over half of the normal harvesting cycle (Robinson *et al.*, 1998). This is thought to be due to a combination of the temporary removal of the original moorland vegetation by the initial deep ploughing treatment, and the slow progression of the planted trees to canopy closure as a result of a wider than normal plant spacing and limiting climatic conditions. The results from another forest catchment study at Llanbrynmair in mid-Wales also demonstrated an initial rise in water yield following extensive cultivation. However, this was followed by a steeper decline due to faster forest growth at this site, with water yield reducing by 4% by the time the trees were 10 years old (Hudson *et al.*, 1997a).

The water balance records for a number of forested catchments at Plynlimon show that the effects of an older forest crop can decline through time. This is thought to be partly due to forest felling and restructuring, and partly to a decrease in water use with forest ageing (Hudson *et al.*, 1997b). For example, during the 1970s when the growth rate of the forest in the upper Severn was at its greatest, the catchment water yield was some 10–15% less than for the moorland cover in the adjacent upper Wye. By the mid-1990s however, the difference had declined to a point where the total water yield from the upper Severn actually exceeded that for the Wye, although only by a margin of 1–2%.

It has proved difficult to identify a response to the felling of between 20 and 30% of the forested catchments at Plynlimon and Balquhidder. There is some evidence of a rise (5–10%) in water yield following felling of 30% of the Hore sub-catchment at Plynlimon but it is difficult to distinguish this from the longer-term decline in forest water use that has been noted in the main Severn catchment (Roberts and Crane, 1997). Research has generally found that the clearance of forest from less than 20% of a catchment results in little detectable change in water yield (Cornish, 1993).

Conifers – lowlands

Unfortunately, the results from upland catchment studies are not directly transferable to the drier lowlands due to the closer match between rainfall and evaporation totals and the much lower water yields. Under these conditions the interception losses of woodland can have a disproportionately larger effect, amounting to a 70% or even a 100% reduction in water yield in some years. For example, recent research at Clipstone Forest in the English Midlands suggests that the water use of Corsican pine comprises around 330 mm transpiration and 280 mm interception, leaving on average only 30 mm from the 640 mm long-term annual average rainfall as drainage (Calder *et al*., 2003). This contrasts with an annual evapo-transpiration of 510 mm and 130 mm drainage for a grass ley, giving an overall reduction of 75% in the available water yield to recharge the underlying sandstone aquifer. While there would be some dilution of this effect within a larger mixed-age forest, it is likely that the overall impact would remain large. Of particular significance is the fact that a further reduction of only 10% in annual rainfall would result in an absence of drainage under pine at this site, which is within the range of climate change predictions for the region by 2080 (Hulme *et al*., 2002).

Broadleaves – lowlands

Until relatively recently, little research has assessed the impact of broadleaved woodland on water resources in the UK. The first major study was undertaken in the late 1980s involving a beech and ash woodland in Hampshire and an ash woodland in Northamptonshire, both in southern England. Modelling work based on site measurements found that, surprisingly, the average volume of water draining beneath beech and ash exceeded that for managed grassland by 17% and 14–25%, respectively (Harding *et al*., 1992). A follow-up study of the Hampshire site in the late 1990s found a similar result, with drainage estimated to be 13% greater under beech compared with grassland during the 18 month period of measurement (Roberts *et al*., 2001). The reason for the lower groundwater recharge under grass is partly due to its longer growing season, especially during the early spring period prior to leaf emergence in woodland. Grass evaporation greatly exceeded that of woodland at this time. Another important factor at the Hampshire site is the influence of the underlying chalk geology, which maintained a sufficient upward movement of water to enable the grass to sustain high transpiration rates during the summer. The absence of this factor at the Northamptonshire site, which overlies clay, was probably responsible for the smaller reduction in drainage by grass compared with ash (14%) than at the Hampshire site (25%). At both sites, the water lost due to the higher grass transpiration was generally more than sufficient to compensate for the woodland's annual interception loss. The main exception concerns clay sites in very dry years (such as in 1976), when soil water stress is predicted to reduce grass transpiration to such an extent that drainage is double that under woodland. Recent modelling work also suggests that grass drainage could exceed that of woodland on chalk in very wet years due to the much higher woodland interception loss (Roberts *et al*., 2001).

Subsequent research at Clipstone Forest has revealed a different outcome when comparing the water use of oak and grass on sandstone, which forms the next most important aquifer for groundwater supply after chalk. In this case, recharge was greater under grass (16–48%) due to its transpiration being significantly reduced by soil water stress on the drought-prone sandy soils (Calder *et al*., 2003). In contrast, the deeper rooting of oak was able to access sufficient soil water to maintain 'normal' transpiration rates. Consequently, broadleaved woodland on sandstone can generally be expected to have lower recharge rates compared with grass, although the limited scale of woodland cover on this geology means that the overall reduction is likely to be relatively small on a wider landscape level. For example, the proposed three-fold increase in broadleaved woodland cover (from 9 to 27%) that is planned for the Greenwood Community Forest in Nottinghamshire is predicted to reduce recharge by only 3–6% (Calder *et al*., 2002).

Other studies have investigated the effect of short rotation poplar and willow coppice on water yield in southern England. This work found that when stands are well supplied with water, recharge volumes can be reduced on average by at least 50% compared with grass in the final year before cutting (Hall *et al*., 1996). However, the reduction will be less when averaged over a three or four-year cutting cycle, since the evaporation from one-year-old shoots was estimated to be only 55% of that from three-year-old shoots. In very dry years the potential reduction in recharge volume can be completely negated by the sensitivity of poplar and willow to soil water stress.

Broadleaves – uplands

There has been no research on the effect of broadleaved woodland on water yield in the uplands, but in view of the results from southern England, it is unlikely that volumes will be very different from those under moorland grass. In fact, higher water yields could be expected from catchments dominated by low stature, scrub types of woodland, especially involving lighter-foliaged species such as birch and where woodland replaces heather rather than grass. The main exception would be in high rainfall areas, where the enhanced interception loss of broadleaved woodland is likely to lead to a small reduction in water yield.

EFFECTS OF CLIMATE CHANGE

Climate change predictions for 2080 suggest wetter winters across the UK and drier summers in the south. Annual and seasonal temperature, and therefore evaporation, are expected to increase in all parts. These changes could exert a strong influence on forest water use and water yields (Nisbet, 2002).

In terms of interception, a wetter and warmer climate is likely to enhance evaporation losses from forest canopies. This would accentuate the difference in water use between forest and non-forest land covers, although any impact of forests on water supplies may be offset by the increase in winter rainfall. In addition, interception losses for broadleaves could be increased by warmer temperatures extending the length of the leafed period and rising CO_2 levels increasing total leaf area.

The effect on transpiration losses is more difficult to predict. At one level, the ability of trees to limit their transpiration rates when the atmospheric demand is high (i.e. when the air is warm and dry) could make them better able to conserve water during warmer summers than most other vegetation types. However, shorter, shallower-rooted vegetation is more likely to suffer water stress and brown-off, limiting their overall water use. Another factor to consider is the expected rise in levels of CO_2. Studies have shown that this may increase the water use efficiency of certain tree species by ≥15% by promoting the closure of leaf stomata, resulting in a significant reduction in transpiration loss (Curtis and Wang, 1998).

LOOKING TO THE FUTURE

Research is continuing to measure and model the impact of forestry on water yield at key sites across the UK. Long-term studies such as at Plynlimon, Coalburn and Balquhidder will help to improve our understanding of the effects of different forestry practices and changes to forest design, as well as the response to climate change. These data are essential for the further development and testing of water use models in order to extrapolate the results to the wider countryside and improve confidence in the predictions. Forest Research is developing an improved catchment hydrology model to support operational decision-making in forestry. This has performed well in initial tests and can be applied at a variety of spatial and temporal scales (Pellenq *et al*., in press). The role of land-use, and in particular forestry, in the management of water resources is likely to become more important in the future as the combination of rising water demand and the likelihood of drier summers generates ever greater pressure on water resources. This is an issue that will be addressed by the European Water Framework Directive as it seeks to establish a new integrated catchment management planning system for the protection, improvement and sustainable use of the water environment.

Further information and advice on water use by trees is available from Forest Research.

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Enquiries relating to this publication should be addressed to:

Tom Nisbet
Forest Research
Alice Holt Lodge
Farnham
Surrey GU10 4LH

T: 01420 526203
F: 01420 520180
E: tom.nisbet@forestry.gsi.gov.uk

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