

The role of woodland in flood control: a landscape perspective

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Abstract

Sustainable flood management is increasingly looking to the role of catchment land use in alleviating downstream flooding. Woodland presents a number of opportunities that are dependent on its location within the landscape. One way that woodland can attenuate flooding is through the greater water use by trees. The overall impact on the generation of flood flows, however, depends on the interaction of many factors and is most marked at the headwater level. Another way relies on the 'sponge effect'. Improved infiltration resulting from the targeted planting of sensitive soils or the use of down-slope woodland buffers could attenuate rapid run-off at the local scale. Finally, the greater hydraulic roughness associated with riparian and floodplain woodland can aid the retention and delay the passage of flood waters, potentially assisting downstream flood defence in larger catchments. This paper examines each of these opportunities and considers whether woodland can make a significant contribution to tackling future flooding as part of a whole-catchment approach to sustainable flood management.

Keywords: Woodland, water use, soil infiltration, hydraulic roughness, sustainable flood management

Introduction

A series of major floods across Europe in recent years has raised serious concern that the frequency of extreme floods may be increasing due to climate change. Model predictions of a 35% rise in winter rainfall and a 25% increase in daily rainfall totals for storm events in some parts of the UK by 2080, based on the 'business as usual scenario' (Hulme *et al.* 2002), has placed the management of flood risk high up the political agenda. This has been reinforced by the fact that the consequences of flooding are expected to become more severe and expensive with the rise in the value of the built environment and pressure to build on the floodplain.

At the same time, the increasing cost of providing hard engineered flood defences and the growing emphasis on sustainable development has resulted in greater attention being given to finding more sustainable, 'softer engineering' solutions. This is reflected in the Government's Flood and Coastal Erosion Risk Management Strategy 'Making Space for Water' (Defra, 2005). A key pillar of the strategy is to adopt a whole catchment approach and make greater use of rural land use solutions, including the creation of wetlands, washlands and effective land management techniques.

Forests and woodland have long been associated with an ability to slow down run-off and reduce downstream flooding (McCulloch and Robinson, 1993). In fact, deforestation has often been cited as a major contributing factor in the apparent rise in flood events in the developing world. Re-planting or creating new forests is increasingly viewed as offering a number of opportunities to help reduce flood risk. The potential to assist flood defence however, is highly dependent on the scale of forest cover and its location within the landscape. Other important factors include the type of forest and how it is managed. This paper examines whether woodland expansion in the UK could make a significant contribution to tackling the predicted rise in flood risk, as part of a whole-catchment approach to sustainable flood management.

Woodland and floods

Water use by trees

The most obvious way that woodland can attenuate flooding is through the greater water use by trees. Trees and woodlands can use more water than shorter types of vegetation mainly due to the interception of rainwater by their aerodynamically rougher canopies (Nisbet, 2005). A distinction can be drawn between conifers and broadleaves, with evergreen conifers tending to have a greater water use because high interception losses are maintained throughout the year, particularly during the winter when conditions are usually wettest and windiest.

Studies in the UK have found that between 25 and 45% of annual rainfall is typically lost by interception from conifer stands, compared to 10-25% for broadleaves (Calder *et al.* 2003). If such losses could be transferred to flood flows then forestry could make a major contribution to flood reduction. However, interception varies greatly throughout the year and in particular, declines with the size and intensity of a given rainstorm. Light showers can be completely intercepted, while losses as a proportion of rainfall decline with increasing rainfall intensity, reaching a maximum of 6-7 mm d⁻¹ for conifers (Calder, 1990). This reflects the relatively small water holding capacity of forest canopies, equivalent to only a few mm of rain water. As a result, interception losses are likely to be <10% for individual major storm events. The impact of broadleaves is even smaller, especially for events during the leafless period, which is often when the risk of flooding is greatest. Another factor is tree age, with the greater water use of forests only becoming fully established when the canopy closes, which tends to occur at around 10-15 years age in conifer plantations and even later for broadleaves.

A downside of the increased water use by trees is the potential impact on catchment water yield. Any reduction in flood flows could be outweighed by the effect on water supplies and dry weather flows, especially in catchments where water demand exceeds supply. This is likely to become an increasingly important issue as the combination of drier summers and rising water demand generates ever greater pressure on water resources. Conservation and other constraints would also limit the scope for realising the potentially greater flood benefit associated with an expansion in conifer woodland.

The 'sponge effect'

Another way that woodland can affect flood flows is by their soils holding back and delaying the passage of rain water to streams and rivers. Woodland soils tend to have a more

open structure resulting from greater amounts of organic matter, the action of tree roots and soil fauna, and the lower level of soil disturbance by man. The presence of a network of macropores helps to transmit water quickly to depth, reducing the likelihood of surface saturation and rapid run-off. These conditions enhance the ability of the soil to receive and store rain water and are commonly referred to as a 'sponge effect'.

Time of year and soil type affect the magnitude of the sponge effect. It is usually greatest during summer and autumn periods due to the generally drier condition of woodland soils and therefore larger capacity to store rain water. Consequently, the flood alleviation benefit could be expected to be most marked for flood events generated by seasonal thunderstorms. However, this effect can be constrained in organic soils by the tendency for soil drying to result in greater hydrophobicity, which promotes rapid surface run-off. Once woodland soils are rewetted during the autumn, they will have a reduced capacity to receive and hold storm water and thus to influence winter and spring flooding.

The sponge effect is associated with both conifer and broadleaved woodland, but is strongly influenced by management practices (see below). The benefit from new planting would be greatest where woodland replaces land uses associated with a high risk of soil damage. This is especially the case in the UK, where storm rainfall intensities rarely exceed 'natural' soil infiltration rates (Ward and Robinson, 2000). Recent studies at Pont Bren in Wales have found infiltration rates up to 60 times higher under young native woodland compared to grazed pasture (Bird *et al.* 2003). The rates under compacted pasture are readily exceeded during storm events, leading to rapid run-off and potentially higher flood flows.

Soils that are prone to structural damage such as surface capping and shallow compaction would probably benefit most from a change to woodland. Opportunities exist for targeting woodland planting onto the most sensitive soils or in key locations for intercepting and 'soaking-up' surface run-off generated from the adjacent ground. Examples include using woodland buffers along lower field edges or within the riparian zones of streams and rivers.

Hydraulic roughness

The use of riparian and floodplain woodland to delay the progression of flood flows may offer the greatest potential to assist flood control. This relies on the hydraulic roughness created by woody debris dams within stream channels and by the physical presence of trees, shrubs and deadwood on the floodplain. The net effect of these features is to reduce flood velocities, enhance out of bank flows, and increase water storage on the floodplain, resulting in an overall smaller downstream flood event.

Hydraulic modelling studies in south west England demonstrate that the planting of woodland across the floodplain could have a marked effect on flood flows (Thomas and Nisbet, 2004). The additional roughness created by a complete cover of woodland along a 2.2 km reach of the River Cary in Somerset was predicted to reduce water velocity by 50% or more and raise the flood level by up to 270 mm for a 1 in 100 year flood event. This increased the volume of flood storage by 71% and delayed the downstream progression of the flood peak by 140 minutes. These results were considered to be significant in terms of protecting downstream sites and providing more time for issuing flood warnings.

The main concern surrounds an enhanced risk of upstream flooding above the floodplain woodland due to the backing-up of flood waters. In the case of the River Cary example, the flood level was raised by up to 180 mm over a distance of nearly 400 m upstream. Another issue is an increased risk of downstream flooding due to the wash-out of large woody debris blocking bridges and other critical structures in towns and cities.

The role of woodland design and management

The different ways that woodland can affect flood flows are greatly influenced by design and management factors. Forest design determines species, age and structural diversity, as well as the balance of forest cover and open space. Since the water use effect is greatest for closed canopy conifer stands, the smaller that this component becomes the lesser the potential effect on flood flows. In terms of existing forests, the ongoing shift away from single aged plantations to more mixed species and aged stands with a significant component of broadleaves and open space, will act to 'dilute' the present water use effect on flood flows. This is despite the greater length of edge between young and old stands within a mixed-aged forest, which enhances local turbulence and thus interception loss. Research suggests that the edge effect is limited to a very narrow band (<20 m from the stand edge) and is therefore only significant for individual stands or woodlands that are less than 1 ha in area (Neal *et al.* 1991). In contrast, efforts to transform conifer stands into continuous cover crops could be expected to reverse the dilution effect of mixed aged woodlands by maintaining the presence of a fully intercepting canopy.

Forest design has less of an influence on the sponge effect but is a key factor in determining the ability of floodplain woodland to slow down flood flows. To form an effective barrier, floodplain woodlands need to straddle most of the width of the floodplain, otherwise the effect will be negated by increased flows between or around woodland blocks. Relatively narrow, linear strips parallel to the river flow would have a minimal retaining effect. Location, shape, size, age and species choice all influence the flood attenuation effect.

Woodland management also exerts a marked impact on the ability of woodlands to reduce flood flows. Ground cultivation and drainage has the opposite effect of tending to speed-up the removal of water from a site. This is greatest for deep ploughing and intensive drainage, which can increase the density of surface water channels by 60 times or more. Research at Coalburn in north England showed that such ground treatments can increase peak flows by 20-30% and decrease the time to peak by about one third (Robinson *et al.* 2003). However, cultivation treatments have greatly changed in the last 20 years, with the focus now on scarification and mounding rather than ploughing. The need for drains has also reduced with the shift in planting to better drained soils. For new native woodlands, very wet soils are either left unplanted or mounded and planted with a species appropriate for such conditions.

Felling is the most dramatic intervention with effects on both woodland water use and run-off pathways. Clearfelling usually leaves a bare site with minimal water use apart from the interception loss associated with brash residues. The increase in run-off and therefore greater contribution to flood flows is likely to last for at least 10-15 years until the replanted trees close canopy once again. Timber harvesting and extraction, however, can have an even greater effect on flood generation. Poor practice such as the use of inappropriate machines and excessive loads can cause severe ground damage, leading to rapid run-off from compacted soil and along wheel ruts. Best practice guidance was introduced in the UK in the

late 1980's and 1990's to prevent these problems and help protect forest soils and water. The guidelines apply to both public and private forests and together with a shift to alternative forms of felling and smaller sized clearfells, should help to preserve the forest sponge effect.

Forest roads are another important consideration. The extensive network of roads and supporting extraction and other access tracks that permeate large managed forests, together with associated drains, represent a significant surface area for the collection of rain water and its rapid delivery to streams. Older forests that predate modern guidelines will have the largest effect due to less attention being given to drainage design and preventing road drains flowing directly into natural watercourses. As with clearfelling, this factor can act against the flow reduction benefit resulting from the water use and sponge effects of the wider forest area.

The importance of scale

Scale is a key issue when extrapolating the effects of forests and woodland 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. This is especially relevant when considering flood alleviation, with most serious flooding problems arising well down the catchment of major river systems. At this scale, forest cover often forms a relatively small proportion of the total land area, limiting the potential to contribute to flood defence. The diverse and mixed nature of the land cover is a key factor in the UK.

Scale appears to have less of an influence on the impact of floodplain woodland. The significant effect on flood storage and timing that was predicted by the hydraulic modelling study on the River Cary was achieved by a relatively small area of floodplain woodland, covering less than 2% of the total catchment area of 82 km². It is possible that the same barrier effect could have been produced by an even shorter reach of woodland, provided that it straddled the full width of the floodplain. Opportunities for creating a continuous area of woodland across the floodplain will usually be greatest in the middle and upper reaches of river systems, where housing and other forms of habitation pose less of a constraint. The narrow nature of headwater floodplains and high water velocities would require extended lengths of floodplain/riparian woodland to achieve a significant reduction in peak flows.

Modelling work suggests that it should be possible to exert a significant effect on flood flows within large river systems by establishing a series of floodplain woodlands along a major river channel or across several main tributaries (Thomas and Nisbet, 2004). However, woodland location is an important consideration since planting provides an opportunity to desynchronise the flood flow contribution from individual tributary catchments. This could have both positive and negative effects depending on the overall timing and mix of flows within a large river system. A detailed analysis of the hydrographs of each tributary would be required to identify where the restoration of floodplain woodland would exert the greatest benefit in terms of the main flood peak. Site location also needs to consider potential constraints such as the presence of local buildings and transport links that could be affected by the backing-up of floodwaters upstream of any floodplain woodland.

Evidence base in support of woodland controlling flood flows

The impact of forestry on flood flows has been the subject of much national and international research. Earlier hydrological studies in the UK found little evidence of a

significant forest effect either at the headwater or at the large catchment scale. For example, an analysis of 35 years of flood flow records from moorland and forest research catchments at Plynlimon in mid-Wales found that upland floods in excess of the mean annual flood were scarcely affected by land use. A later study of the impact of extensive forest clearfelling in the same catchments also failed to find a significant change in peak flows (Robinson and Dupeyrat, 2003). The Natural Environmental Research Council's Flood Studies Report of 1975 concluded from regional flood studies in Britain that the area of forest was not a significant factor in statistical relationships used for flood prediction. This was supported by McCulloch and Robinson's (1993) review of the history of forest hydrology, which found that forests may reduce small floods but, generally, not extreme events.

Other studies have observed that forestry can have a significant effect on flood flows at the small catchment scale but not within large basins. This was the conclusion of a major pan-European study by Robinson *et al.* (2003) involving hydrological data from 28 research catchments spanning a wide range of forest types, climate conditions and soil/geology. They found that forest growth could result in a 10-20% reduction in peak flows in headwater catchments, while forest drainage and felling could have the opposite effect. These effects could not be detected in larger catchments, leading them to suggest that forestry has probably a relatively small role to play in managing regional or large-scale flood risk. Similarly, a major review of the impacts of rural land use and management by O'Connell *et al.* (2004) concluded that there was substantial evidence of effects on local flooding at the field and hillslope scale, but little sign of these changes propagating far downstream.

These findings are in line with recent assessments by the Food and Agriculture Organisation (2005) and Calder and Ayward (2006). Both studies found that while forests around the world can play a role in ameliorating localised flooding, there is no evidence that they can prevent, or that their removal is a cause of large-scale major floods. The impact of forests on floods was considered to be limited to catchments <100 km² in area.

The downstream progression of headwater effects within larger catchments was examined by Archer (2003) in a study of the River Irthing catchment in north England. A comparison was made between the effects on peak flows recorded within the small 90% afforested headwater Coalburn catchment (1.5 km²) and the larger 19% afforested River Irthing catchment (335 km²), to which it drained. An analysis of the annual number and duration of peak flows pulses found that the significant increases recorded due to deep ploughing followed by subsequent decreases due to forest growth at Coalburn, were effectively lost at the scale of the larger Irthing catchment. This agrees with the work of Cornish (1993) in Australia, who found that forest hydrological effects were very difficult to discern when less than 20% of a catchment was affected.

The lack of evidence of a significant impact of forestry on flood flows at the larger catchment scale may be partly due to the research focusing on conifer plantations, especially in the UK. It is possible that the contrasting effects of the mix of forest ages, species and open space, together with that of forestry management practices such as drainage and clearfelling, effectively cancel each other out. Semi-natural forests that are unaffected by these activities may offer greater scope for flood reduction, although in the case of broadleaved woodland this would be limited by its much lower water use. Unfortunately, few studies have been able to test this due to the small scale of such woodland in many countries and the reluctance to undertake sizeable felling treatments in view of the woodland's high conservation value.

The same problem also applies to floodplain forests, with few measurements available to properly quantify their impact in terms of flood alleviation. Work is now underway to start to address this gap and help test the positive results derived from hydraulic modelling studies (Nisbet *et al.* 2005). Some research has demonstrated the positive effects of riparian woodland and large woody debris dams in reducing peak flows but only for smaller events at the local scale (Linstead and Gurnell, 1999). Further work is also needed on this topic.

The ability of woodland to reduce flood generation, at least within headwater catchments, also has potential benefits for water quality. Rapid surface run-off is usually associated with a greater risk of soil erosion and consequently increased pressure from the entry of sediment and chemical-bound pollutants such as pesticides and nutrients entering watercourses. Therefore forestry can provide a win-win solution by helping to tackle both local flooding and diffuse pollution issues.

Conclusions

Woodland offers a number of potential opportunities for flood control. Research and experience indicates that those provided by the greater water use by trees and the forest sponge effect are largely restricted to the headwater or small catchment level. Modelling studies suggest that floodplain woodland offers the main way of ameliorating extreme flood events at the large catchment scale, although results remain to be tested in practice. Overall, there appears to be significant scope for using woodland to help reduce flood risk, as well as to provide a wide range of other environmental, social and economic benefits. However, in order to achieve these, woodland needs to be better integrated with agriculture and other land uses as part of a whole-catchment approach to sustainable flood management.

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