Impacts of Forest Plantations on Streamflow

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Characteristics of Plantation Forests

Tree plantations for the production of timber have been established for more than a century (tropical teak and mahogany plantations, for instance, date back to the mid-nineteenth century), but it is mainly in the last few decades that an exponential expansion of this form of land use has occurred. Taking one of the most popular tree types for plantations as an example, eucalypts have been planted on an estimated 17 million ha worldwide, of which more than 90% have been established since 1955 and roughly 50% during the last decade. The total plantation area around the globe is 187 million ha of which over 60% are in Asia, with Europe having the next largest share (17%). *Eucalyptus* and *Pinus* are the dominant genera within the broadleaved and coniferous plantations, respectively. Although forest plantations only occupy about 5% of the world's forest area, they are estimated, as of 2000, to supply 35% of all roundwood, a figure that is expected to rise to 44% by 2020 as natural forests continue to decline and demands keep rising.

Plantations are typically established at a regular spacing (1000–2000 stems ha^{-1}), and individual stands (compartments) have the same age and are composed of a single species or clone. Often plantations are particularly productive because the tree species being grown are exotic to the area and thus free of their native pests and diseases. Generally, a distinction is made between industrial plantations (aimed at producing wood for commercial purposes, including construction timber, panel products, furniture timber, and paper pulpwood) and nonindustrial plantations (aimed at fuelwood production, protection of catchment areas for soil and water conservation, provision of wind- or fog breaks, etc.).

Scope

There appears to be a significant disparity between public and scientific perceptions of the hydrological role of forests in general and of plantations in particular. Arguably, the contrasts in views are especially pronounced in tropical regions where calls for massive reforestation programs to restore reduced dry season flows or to suppress flooding and stream sedimentation are heard more frequently. Often, however, these expected hydrological benefits are not realized and in a number of cases forest plantations have even been observed to aggravate the situation. This article recapitulates the current understanding of how forest plantations affect the hydrological functioning of catchments. Other articles outline the principles of the forest hydrological cycle (*see* **Hydrology**: Hydrological Cycle) and indicate the hydrological effects of various forest management activities and forest conversion to other land uses (*see* **Hydrology**: Impacts of Forest Conversion on Streamflow; Impacts of Forest Management on Streamflow). Strictly speaking, the term 'reforestation' should be used to describe the planting of trees in areas that were once covered by natural forest whereas 'afforestation' applies to plantation establishment in areas that are too dry, or for other reasons, do not support natural forest vegetation. To avoid semantic problems, the term 'forestation' is used mostly in the following to denote either type of planting.

The Forest Plantation Water Budget

The hydrology of tree plantations is most easily discussed with the aid of a simple water budget equation, most simply expressed in equivalent units of water depth (mm per unit of time):

$$P = ET - Q + \Delta S$$

where P is total precipitation (mostly rainfall, sometimes also fog or snow), ET the sum of various evaporation components (often referred to as evapotranspiration), Q the surface runoff or streamflow, and ΔS the change in (subsurface) storage of water in the catchment (soil water and groundwater reserves).

Evapotranspiration ET dominates the water balance of all but the most humid forest plantations. Beyond an annual precipitation of *c.* 2000 mm and under conditions of lowered evaporative demand (e.g., montane or coastal fog belts) the balance between evaporation and streamflow tips toward streamflow. There are two main components to forest ET: transpiration (the water which is taken up from the soil by roots and passes through the trees to be transpired from the stomata of the leaves, E_t) and interception (the water that is caught in the canopy and evaporates directly back into the atmosphere without reaching the ground, E_i). Under closed canopy conditions, usually rather minor additional components of evaporation are evaporation from the soil surface (E_s), which in a forest includes interception by the litter layer, and evaporation from understory vegetation. The presence or absence of a forest cover has a profound influence on the magnitude of *ET*, and by implication, also on streamflow *Q*.

Rainfall Interception

Compared to short, simple vegetation canopies (grassland, agricultural crops), tree plantations increase evaporation losses by intercepting a larger portion of incident rainfall. Generally, annual interception totals associated with the dense canopies typical of evergreen coniferous plantations are higher than those of deciduous broadleaved forests. Interception is also particularly high (expressed as a fraction of total precipitation) where rainfalls are frequent but of low intensity, especially where the evaporation process is aided by the influx of relatively warm air striking a cooler vegetation surface, as is often observed in near-coastal areas. An example of this effect comes from the UK where conifer plantations have been established in upland heath and grasslands in Scotland and Wales. Here the nature of the precipitation, proximity to the ocean, and the change in canopy density may increase interception losses to as much as 35–40% of annual precipitation.

At the other end of the interception spectrum (E_i *c*. 6%) are the *Eucalyptus* plantations of the humid, subtropical eastern escarpment in South Africa. This is an area of high seasonal rainfall (1200–1500 mm), much of which falls in the form of infrequent storms of short duration but high intensity. Interception losses from pine plantations in the same area are somewhat higher (13%), reflecting their denser canopies compared to the more open canopies of the eucalypt stands. In the cooler southwestern part of South Africa, an area of winter rainfall of lower intensity, interception losses from pine plantations are higher again (18%) than in the pine plantations in the subtropical areas. In the case of both pine and eucalypt plantations, though, there is a net increase in interception over the grasslands and scrub vegetation they replace because of the higher leaf area, greater depth of canopy, and aerodynamic roughness associated with timber plantations.

Rainfall interception in tropical tree plantations ranges from relatively low values in eucalypt stands (*c*. 12%) (**Figure 1a**), to *c*. 20% for broadleaved hardwood species such as teak and mahogany (**Figure 1b**), and 20–25% for pines (**Figure 1c**) and other conifers (*Araucaria, Cupressus*), with the higher values usually found in upland situations where rainfall intensities are generally lower. Well-developed dense stands of the particularly fast-growing *Acacia mangium*, on the other hand, may intercept as much as 30–40% of incident rain. Typical interception values for the rainforests replaced by these plantations range from 10–20% in most lowland situations to 20–35% in montane areas.

Transpiration

Transpiration (soil water uptake) is the second large component in the evaporation budget of forest plantations. Usually, plantation water uptake rates are similar to those of natural forest occurring in the area of planting but under certain conditions water use of the (usually exotic) newcomers may be higher, particularly under subhumid conditions where the natural vegetation consists of more open woodland or scrub. Examples include the replacement of dry forest/scrub by fast-growing plantations of *Eucalyptus camaldulensis* and *E. tereticornis* in South India, and by *E. grandis* in southeastern Brazil and South Africa. Likewise, water uptake rates reported for (vigorously growing and densely stocked) stands of *Acacia mangium* in Malaysia and for various species planted in the lowland rainforest zone of Costa Rica are such that they must exceed the water use of the old-growth rain forests they are replacing, possibly by 100–250 mm year^{-1}. Even greater differences in transpiration can be expected where plantations are established in areas with (natural) grassland or degraded cropland. For example, whilst forest water uptake under humid tropical conditions typically exceeds that of pasture by about 200 mm year^{-1}, the difference may increase to as much as 500–700 mm year^{-1} under more seasonal conditions. Such differences reflect the contrasting rooting depths of trees and grassland as well as the tendency for natural grasslands to go dormant during extended dry periods while the (exotic) trees continue to take up water.

Total Evapotranspiration (ET)

It follows from the above increases in rainfall interception and transpiration that are typically associated with the establishment of tree plantations in areas of (natural) grasslands or (degraded) cropland that overall *ET* totals can be much increased after forestation. As shown in **Figure 2**, total *ET* values for actively growing plantations may approach 1500 mm year^{-1} and, occasionally, as much as 1700–1900 mm year^{-1}. Such very high values must be considered the exception rather than the rule, however, and probably reflect the advection of

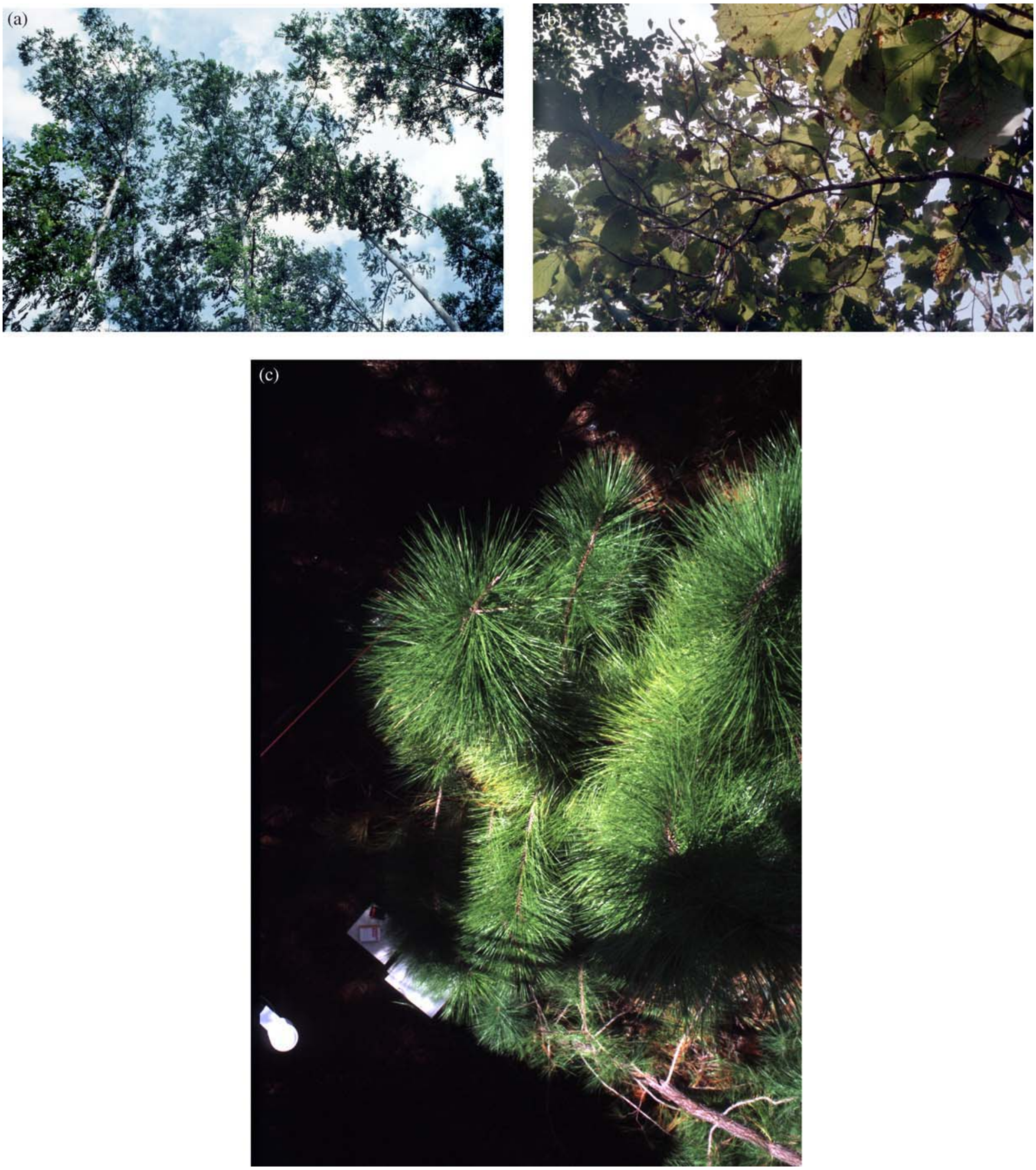

Figure 1 The contrasting canopies of (a) *Eucalyptus* spp., (b) teak (*Tectona grandis*), and (c) pines (*Pinus caribaea*) lead to differences in amounts of rainfall interception and in the drop size spectra (and thus eroding power) of water dripping from the canopy. Photographs by LA Bruijnzeel.

warm, dry air flowing in from adjacent grassland areas which tends to greatly enhance evaporation rates. Nevertheless, the fear is justified that the much increased water use of tree plantations compared to the grasslands and crops they replace will lead to substantial reductions in catchment water yields, particularly during the dry season, if entire catchments are planted.

Effects of Tree Plantations on Streamflow

Effects of Associated Land Management

In discussing the hydrological effects of establishing timber plantations, it is important to be clear about the site-specific conditions and management practices associated with the land-use change and their contribution to the effect of a change in land use.

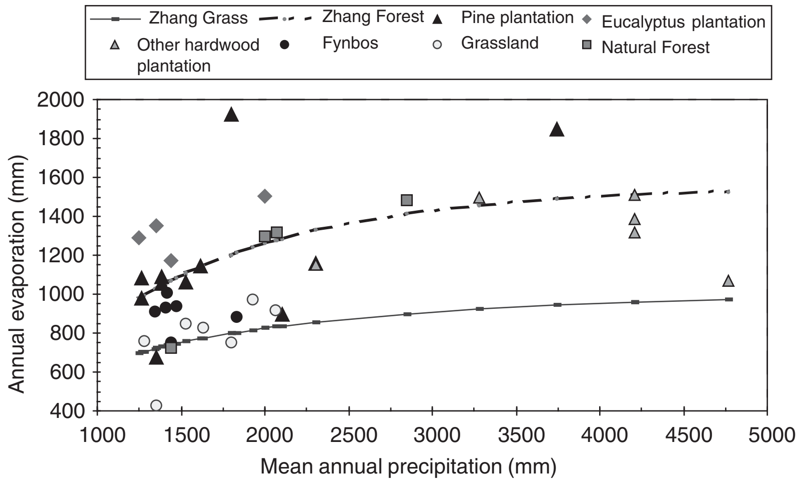

Figure 2 Total evaporation (*ET*) from forest plantations and other vegetation types as a function of precipitation. Data mostly from humid tropical (Bruijnzeel 1997) and South African plantations (courtesy of D Le Maitre, CSIR, South Africa, unpublished compilation). The curves define average forest and grassland water use in southeastern Australia (adapted from Zhang L, Dawes WR, and Walker GR (2001) Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research* 37: 701–708), and have been extrapolated for rainfall >2000 mm.

Such background information may be very important in assessing the overall hydrological effect of the plantations. The following examples illustrate the need to specify more than simply the change in vegetation cover itself.

Firstly, a forest or plantation would be expected, normally, to have a continuous groundcover of leaf or needle litter and some shade-tolerant shrubs. In parts of southern China and adjacent countries, however, all litter and understory plants may be collected for fuel, a practice that has a profound influence on the occurrence of surface runoff and erosion in the plantation (**Figure 3**). Elsewhere (as on the Indian subcontinent) forests and plantations are used to graze cattle, a practice that requires regular burning to stimulate the growth of fresh grass shoots. The combined effect of burning and trampling by livestock may promote massive surface erosion, sometimes to the extent of initiating gullies.

Contrary to popular belief, it is not the interception of rainfall by the main tree canopy that protects the soil underneath against the erosive impact of the rains. Rather it is the combined protection afforded by the understory vegetation and a well-developed litter layer that prevents the soil from being eroded. In fact, the erosive power of rain dripping from the canopies of tall trees is often greater than that in the open, because of the associated increases in drop sizes. The largest increases in drop diameters are observed for drip from large-leaved trees such as teak or *Gmelina*, whereas those falling from eucalypts or pines are more modest in size (**Figure 4**). Such findings underscore the importance of maintaining a good groundcover in plantations if runoff and erosion problems are to be avoided (cf. **Figure 3**).

A final example of the importance of management comes from the wet and peaty hill country of Scotland and the English borderlands, where surface drains are usually excavated prior to the planting of coniferous trees (mostly Sitka spruce, *Picea sitchensis*), to improve the success of tree crop establishment. However, the influence of the drainage ditches on streamflow has proved more important than the vegetation change from heath and moorland to tree plantation itself.

Forestation and Water Yield

The increased evaporation from timber plantations replacing shorter vegetation types (**Figure 2**), not unexpectedly, translates into decreases in annual streamflow totals after plantation establishment. Although there are no stringent (paired) catchment experiments in the humid tropics proper, there is overwhelming evidence to this effect from the subhumid tropics (notably India), the subtropics (mostly South Africa), and the temperate zone (including southeast Australia and New Zealand). Considerable differences have been observed between species but these are not necessarily the same in different areas. For example, in southeast Australia and New Zealand greater reductions in flow were observed after planting pines (*Pinus radiata*) on grassland than in the case of planting eucalypts (**Figure 5**). Conversely, in South Africa, other variables being equal, the effect of planting *Eucalyptus*

Figure 3 The practice of repeated removal of needle litter from coniferous forests in parts of mainland southeast Asia often leads to dramatic increases in surface runoff and erosion. Photographs by courtesy of C Cossalter.

grandis was more pronounced than that of *P. radiata* or *P. patula* (see **Figure 8** below). Such contrasts mainly reflect differences in growth performance between regions and to a lesser extent differences in rainfall interception dynamics.

Published experimental results often represent the maximum possible impacts on streamflow. In the real world, variations in site characteristics and plantation management may exert a moderating influence on the hydrological impacts of forestation. Moderating factors include the fraction of the catchment planted, planting position within the catchment (upstream or downstream parts, close to or away from the streams, blocks vs. strips, etc.), and variations in stand age and productivity between species. These factors are elaborated upon briefly below.

Catchments are rarely completely planted with trees because some land is usually reserved for other uses or it may be inaccessible or otherwise

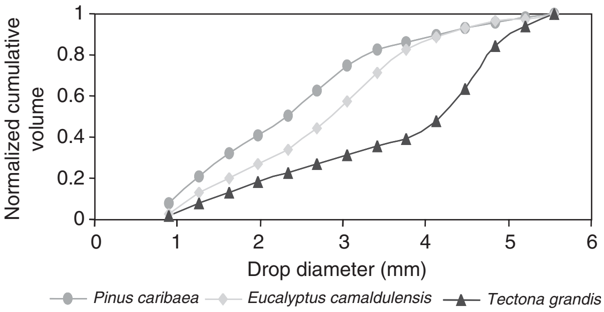

Figure 4 Characteristic drop size spectra for rain dripping from pine trees (*Pinus caribaea*), teak (*Tectona grandis*), and eucalypts (*Eucalyptus camaldulensis*) as measured in South India. Reproduced with permission from Hall RJ and Calder IR (1993) Drop size modification by forest canopies: measurements using a disdrometer. *Journal of Geophysical Research* 98: 18 465–18 470.

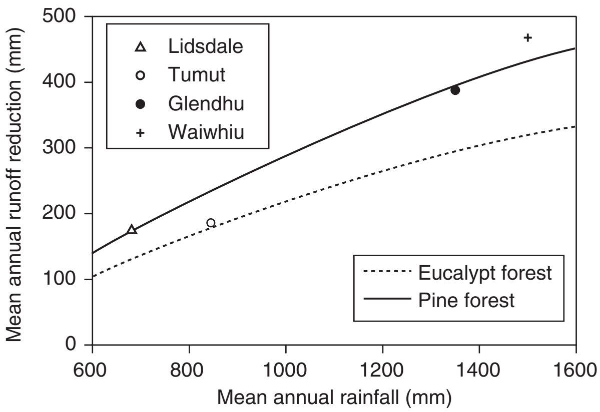

Figure 5 Potential reduction in mean annual streamflow estimated to result from forestation of grasslands with eucalypts and pines in southeast Australia. Shown (as symbols) are field data from four pine forestation experiments in Australia and New Zealand. Reproduced with permission from Vertessy RA, Zhang L, and Dawes WR (2003) Plantations, river flows and river salinity. *Australian Forestry* 66: 55–61.

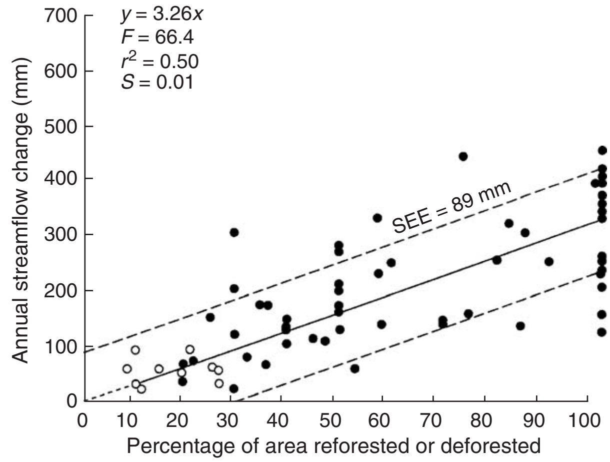

Figure 6 Changes in annual water yield vs. percentage forest cover change (solid circles denote experimental data of Bosch and Hewlett (1982); open circles those of Trimble *et al.* (1987). SEE, standard error of estimate. Reproduced with permission from Trimble SW, Weirich FH, and Hoag BL (1987) Reforestation and the reduction of water yield on the southern Piedmont since circa 1940. *Water Resources Research* 23: 425–437.

unsuitable. The classical forest hydrology literature suggests that the magnitude of the change in catchment water yield is linearly proportional to the percentage of catchment planted or cleared, with increases in flow after forest removal and reductions after forestation (**Figure 6**). Hence, in the case of plantations, one could assume that if only half of a grassland catchment would be forested then the estimated reduction in mean annual runoff would also be about half of the maximum reduction predicted by **Figure 5** for a given annual rainfall total (assuming that plantation position in the catchment does not influence the result).

Few experimental data are available on the influence of plantation position on catchment water balance changes. Under humid conditions in the eastern USA, the reverse operation (i.e., forest clear-cutting) did not show a significant difference in streamflow response after cutting the upper half of the catchment or the lower half. Also, elimination of the vegetation around streams in one experiment in the summer-rainfall zone of South Africa did not lead to greater increases in streamflow than when removing an equal area of forest away from the stream. However, several other experiments in South Africa showed that an area of plantation near streams had roughly double the effect of the same area of mid-slope planting.

Such contrasting results may be explained in terms of average soil water surplus or deficit, depth to the groundwater table and slope morphology. All these factors influence hillslope hydrological behavior. Where rainfall is plentiful, slopes steep and convex, and the groundwater table rather deep (say, more than 3 m), no major spatial effect is expected. This is because rainwater infiltrating into the soil percolates more or less vertically to the water table, then moves laterally as groundwater to the nearest stream without being taken up again by the roots of the trees. Conversely, where soil water is scarcer, slopes gentle and concave, and depth to the water table shallow, a more pronounced effect is possible because trees located closer to the stream will have more ready access to the groundwater table. As such, they are likely to consume more water than trees further away from the stream that have less direct access to groundwater to supplement diminished soil water reserves.

Furthermore, there is the intuitive notion that the further away one gets from a stream, the smaller the probability that water infiltrating into the soil will actually contribute to streamflow. These ideas have been tested in modeling experiments in the context of southeast Australia, the results of which lend support to the notion that plantation position could indeed affect catchment water yield under conditions of low rainfall (700 mm), gentle slopes, and high water-tables (**Figure** 7). Indeed, the predicted effect on streamflow of tree planting differed strongly depending whether forestation started at the top of the hillsides and progressively moved downslope or vice versa. The curves of **Figure** 7 also suggest that under the prevailing conditions planting of the lower 30% of the catchment would have a much greater impact than planting the uppermost 30%. Similarly, a related modeling study indicated that planting trees in strips about 40 m wide parallel to the contour with bands of pasture in between leads to greater tree water use and better growth than when the same number of trees are planted in a single block at mid-slope position.

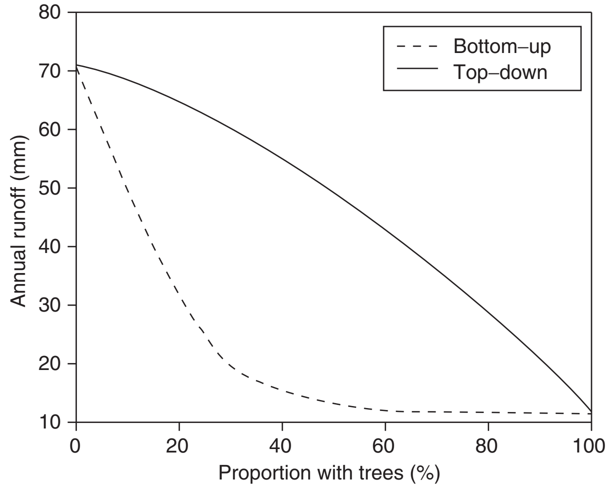

Figure 7 Results from a numerical modeling experiment showing two sets of predictions of annual streamflow after planting trees on a catchment under pasture in central New South Wales, Australia (mean annual rainfall 700 mm). The upper curve (solid line) shows changes in annual flow with forestation starting at the top of the catchment and progressing downslope. The lower curve (dashed line) shows the comparative response when forestation starts at the bottom of the catchment and progresses upslope. Reproduced with permission from Vertessy RA, Zhang L, and Dawes WR (2003) Plantations, river flows and river salinity. *Australian Forestry* 66: 55–61.

More work is needed to ascertain optimal plantation positions to minimize the hydrologic impacts of forestation under contrasting climatic and topographic conditions. Process-based, spatially distributed hydrological models can be used to assess how different planting strategies would impact on catchment flow regimes. Whilst such models are difficult to set up and apply, the effort is surely worthwhile given the level of investment that goes into planning any significant forestation initiative.

Much can be learned on the effects of species, plantation age, and vigor from a particularly comprehensive series of long-term paired catchment studies of the hydrological effects of afforesting natural grasslands and scrublands in subtropical South Africa. Ten paired catchment experiments have studied the effects of afforestation with *Pinus radiata*, *P. patula*, and *Eucalyptus grandis* within catchments. The research sites are all in the high rainfall zone of South Africa (mean annual precipitation 1100–1600 mm). Experimental control was provided by catchments kept under native vegetation. Although generally steep, the catchments have deep, well-drained soils and show very low stormflow response to rainfall. The catchments are all in good hydrological condition (i.e., no significant surface erosion); thus, the experimental comparison is between the two vegetation covers, reflecting, ultimately, the differences in total evaporation.

The resulting streamflow reductions over time after planting follow a sigmoidal pattern comparable to a growth curve (**Figure** 8). There are clear differences between the effects of eucalypts and pines, but there is also a large amount of variation from year to year within a single experiment and between different experiments, even in comparable catchments in one locality. The highest flow reductions occur once the tree crop is mature, and range, for a 10% level of planting, from 17.3 mm or 10% year^{-1} in a drier catchment to 67.1 mm or 6.6% year^{-1} in wetter catchments (**Figure** 8). As such, relative streamflow reductions (%), for a set age, are greater in drier catchments but absolute reductions (mm) are greater in wetter catchments. In other words, the reductions are positively related to water availability. The lower of these reductions in streamflow are similar to results obtained after planting *E. globulus* in high elevation grassland areas in the subhumid South of India (*c.* 20 mm per 10% forest year^{-1}) whereas the highest reductions in South Africa rather resemble the changes observed after planting *P. caribaea* on seasonal grasslands in Fiji (50–60 mm per 10% year^{-1}). Similar effects on streamflow have been recorded under the more temperate conditions of New Zealand (see also **Figure** 5), where conversion of pastures and tussock grassland to *P. radiata* plantations, over a range of climates, led to streamflow reductions of 20–45 mm year^{-1} per 10% of catchment planted, the amount again being dependent on water availability.

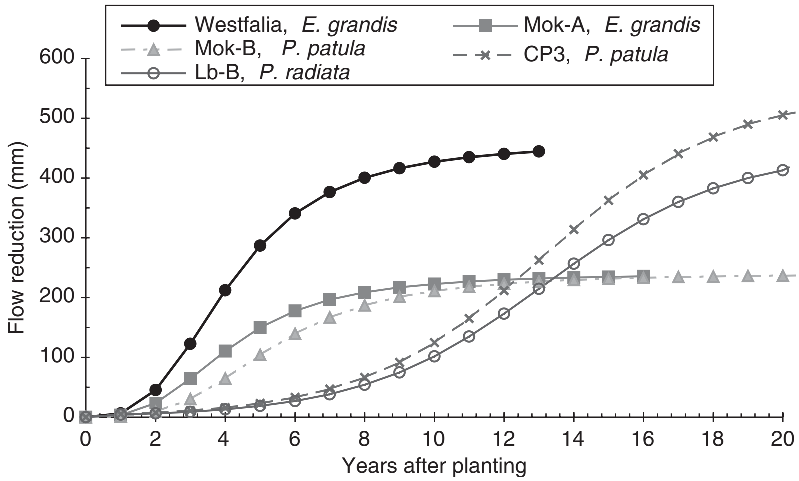

Figure 8 Reductions in streamflow as measured in five catchment afforestation experiments in South Africa. The curves are scaled for 100% planting of the catchment and smoothed to the mean annual runoff (MAR) prior to planting. Based on Scott DF and Smith RE (1997) Preliminary empirical models to predict reductions in total and low flows resulting from afforestation. *Water SA* 23: 135–140.

The timing of the first significant reductions in flow after planting varies quite widely depending on the rate at which catchments are dominated by the plantation crop. The pine plantations in the high altitude grasslands at Cathedral Peak in South Africa (CP in **Figure 8**) usually took several years to have a clear impact on streamflow. However, the same species of pine had an earlier effect on streamflow (within 3 years) under the drier conditions prevailing in the Mokobulaan B catchment in Mpumalanga Province (Mok-B in **Figure 8**). Other conditions remaining the same, eucalypts have a slightly earlier impact on streamflows than pines in South Africa, normally within 2–3 years.

A key factor influencing the degree of streamflow reduction after forestation is the vigor of the trees. Usually, there is a close link between the growth rate of a plantation and its overall water uptake. A new finding from the South African afforestation experiments is that the flow reductions are diminishing again during the postmaturation phase of the plantations, both in the case of pines (after about 30 years) and in at least one of the two eucalypt experiments (after 15 years). This undoubtedly mirrors the gradually decreased vigor of older trees as has also been observed in old-growth native eucalypt forest in southeast Australia and tropical rainforest in Amazonia. In industrial plantation forestry, short- and medium-length tree rotations will tend to keep the trees in their peak water use phase, but longer rotation crops, such as those aimed at producing good quality saw timber, are more likely to have a smaller effect on water yield later on in the rotation.

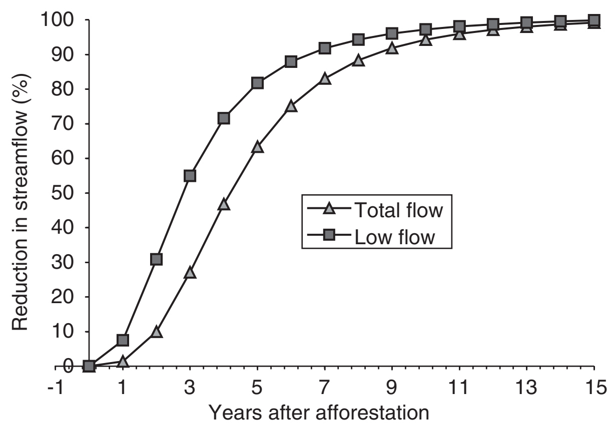

Figure 9 Pooled results from two eucalyptus afforestation experiments in South Africa, showing the pattern of flow reductions as a function of plantation age, and illustrating the greater and earlier effects on the low flow component (both catchments fully afforested). Reproduced with permission from Scott DF and Smith RE (1997) Preliminary empirical models to predict reductions in total and low flows resulting from afforestation. *Water SA* 23: 135–140.

Forestation and Low Flows

Declines in streamflow following the establishment of plantations are recorded in all components of the annual hydrograph (i.e., stormflows and baseflows). In South Africa, effects on total and low flows follow the same pattern, but low flows are decreased more than are total flows at the same age (**Figure 9**). Similar effects have been found in the temperate zone as well as in Fiji, India (even more so after coppicing and resprouting), and Malawi. The effect of forestation on low flows in subhumid areas has two supposed sources. First, exotic plantations, in contrast to the native grasses or scrub vegetation they replace, do not go dormant in the dry season. The second cause, though less easily quantified, is that of steadily reducing soil water reserves as the trees mature. Low flows are a reflection of the amounts of soil water and groundwater stored in the catchment and as these are steadily depleted by tree water uptake so low flow will diminish correspondingly. It is clear from the South African experiments that total water use by the tree crop can exceed annual rainfall in many years and that, once dry season flow has ceased altogether, the occurrence of rainstorms may not easily cause the streams to flow again.

Strongly reduced baseflows after forestation of (nondegraded) grassland or scrubland can thus be expected to be a generally occurring phenomenon. The magnitude of this effect is probably related to the capacity of the soils to store water and to the extent that this water can be accessed by the roots of the tree crop. Thus, where the new trees are able to occupy a much greater volume of soil through their deeper roots, reductions in baseflows following forestation can be expected to be proportionately larger than in situations where rooting volume is restricted.

Finally, it is important to bear in mind that the above examples concern situations where the soil is not degraded and rainfall infiltration generally proceeds unimpaired. Under such conditions, streamflow amounts will simply reflect the change in vegetation water use and low flows will be thus (much) reduced (see **Figures 2** and **6**). However, in areas with degraded, compacted soils where much of the rain may run off along the surface as overland flow (and therefore does not contribute to soil water reserves), the planting of trees can be expected to ultimately have a positive effect on infiltration. Theoretically, the extra water entering the soil through improved infiltration after forestation may moderate or, in extreme cases, even reverse the adverse effect of the larger water use of the trees on streamflow. In all cases, the net effect of tree planting on the baseflow from degraded areas will reflect a trade-off between these two effects. Where infiltration is already sufficient to accommodate most of the rainfall, any further improvements by forestation will not tip the balance. Rather, water yield will be reduced even further (**Figures 6** and **9**). However, where soils are deep but overland flow during rainfall is rampant and much is to be gained from improved infiltration (**Figure 10a**), it cannot be excluded that a net positive effect on low flows may occur. The

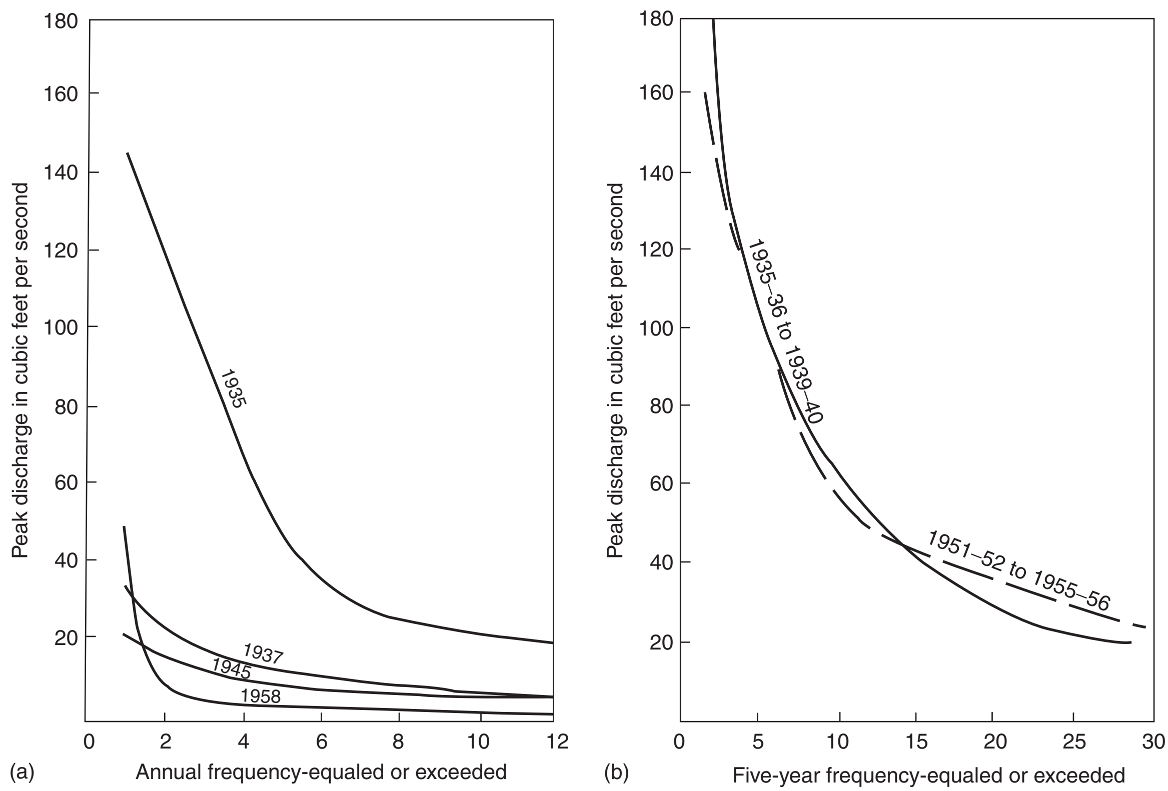

Figure 10 Frequency distributions for peak discharges during (a) summer and (b) winter in the While Hollow catchment, Tennessee, USA before (1935) and after (1937–1958) reforestation. Modified from Tennessee Valley Authority (1961) *Forest Cover Improvement Influences upon Hydrologic Characteristics of White Hollow Watershed, 1935–1958*. Report no. 0-5163A. Knoxville, TN: Tennessee Valley Authority.

experimental evidence for this contention is only indirect, however, and based on a comparison of observed reductions in stormflow response (having a positive effect on soil water reserves) (**Figure 10a**) vs. increases in vegetation water use (having a negative effect on soil water reserves) (**Figure 2**).

Forestation and Stormflows

Forest hydrological research has shown that the influence of vegetation cover or type on catchment runoff response to rainfall ('stormflows') is inversely related to the size of the rainfall event that generates the flows. This can be explained as follows: in small to medium storm events the combined water storage capacity of vegetation layers, litter, surface depressions, and the soil mantle will be considerable relative to the amount of rain delivered by the storm. As a result, the associated catchment response will be much reduced in the case of a good forest cover. The soil mantle is potentially the largest water store, but its capacity to accommodate additional rain varies as a function of soil wetness. Where previous uptake by the vegetation has depleted soil water reserves (as is often the case during summer), storage capacities, and thus stormflow reduction, will be relatively high (**Figure 10a**). However, once the soil has become thoroughly wetted by previous rains (typically during winter or the main rainy season), very little opportunity to store additional water will remain, regardless of vegetation type (**Figure 10b**). In addition, as rainfall events increase in size, so does the relatively fixed maximum storage capacity of the soil become less important in determining the size of the stormflows. In other words, the presence or absence of a well-developed forest cover has a significant effect in the case of small events but this typically makes very little difference (less than 10%) in the case of truly large events (floods) generated by extreme and prolonged rainfall (**Figure 10b**). Under such conditions, runoff response is governed almost entirely by the capacity of the soil to accommodate and transfer the rain.

However, where degradation of a catchment's soils has produced strong reductions in canopy and groundcover (including litter), and above all in infiltration capacity and soil depth through continued erosion (and thus overall soil water storage opportunity), reforestation could clearly lead to an improvement of most or all these factors over time. These ideas are conceptualized in **Figure 11**.

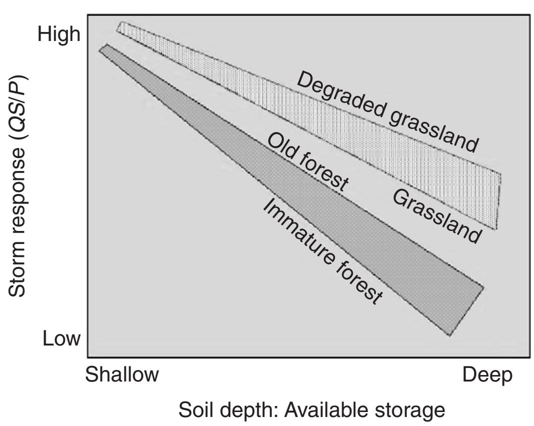

Figure 11 Postulated generalized relationship between catchment storage capacity and stormflow response to rainfall, as affected by vegetation cover. Reproduced with permission from Scott DF, Bruijnzeel LA, and Mackensen J (2004) The hydrological and soil impacts of forestation in the tropics. In: Bonell M and Bruijnzeel LA (eds) *Forests–Water–People in the Humid Tropics*. Cambridge, UK: Cambridge University Press.

Concluding Remarks

Catchment experiments all over the world have demonstrated convincingly that total amounts of streamflow emanating from catchments where forest plantations have replaced (natural) grassland or scrubland, or (degraded) cropland, are invariably much reduced. In addition, the reductions in baseflows during the dry season are relatively greater than during the wetter season. Small to medium-sized stormflows are also reduced significantly by forestation but the effect on occurrence and size of flood peaks associated with truly large rainfall events is very limited.

These observations differ strongly from the popular view held by many foresters, policy-makers, and the public at large that forestation will lead to (more or less rapidly) increased streamflows and the elimination of flooding. Although the establishment of forest plantations on degraded land will improve the soil's capacity to absorb rainfall, this is likely to take at least several decades. However, because water use by the trees is much increased within a few years compared to that of the former vegetation, the balance of probability is that low flows will also be reduced in this case. Establishing the precise hydrological effects of reforesting areas in various stages of soil degradation constitutes a prime research need.

See also: **Hydrology**: Hydrological Cycle; Impacts of Forest Conversion on Streamflow; Impacts of Forest Management on Streamflow; Impacts of Forest Management on Water Quality. **Plantation Silviculture**: Forest Plantations; Short Rotation Forestry for Biomass Production. **Soil Biology and Tree Growth**: Soil and its Relationship to Forest Productivity and Health. **Soil Development and Properties**: Forests and Soil Development; Water Storage and Movement. **Tree Physiology**: A Whole Tree Perspective; Forests, Tree Physiology and Climate; Root System Physiology.

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Impacts of Forest Management on Water Quality

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Introduction

In forested catchments the hydrologic cycle, involving precipitation, interception, evapotranspiration, overland flow, subsurface flow, groundwater flow, and stream flow (**Figure 1**) is closely linked to water quality in that water movement through the forest ecosystem also transports sediment, and dissolved nutrients, as well as fertilizers, and pesticides if they are present. Understanding relationships between forested ecosystems and quality of surface and subsurface water associated with these systems is a key component of sustainable forest management because changes in water quality may result from forest management practices. These changes can reflect either positive or negative outcomes of forest practices. For example, logging road construction and harvesting of timber with improper consideration for erosion control can cause increased sedimentation of stream water and a degradation of water quality. In contrast, conversion from agricultural crop production to forestland can improve water quality by decreasing erosion rates and creating long-term storage pools (e.g., forest floor, woody biomass) for carbon and nutrient retention. This article provides a synthesis of our current thinking regarding (1) the concept of water quality, (2) the role of forested watersheds in providing water of relatively high quality, and (3) commonly evaluated water quality parameters and potential effects