particularly in the tropics. Similarly, the data base for tropical forest water use is small. However, with the continued improvement of process-based hydrological models, equipment, data storing, and computational facilities, significant progress can be expected to be only a matter of time.

See also: **Hydrology**: Impacts of Forest Conversion on Streamflow; Impacts of Forest Management on Streamflow; Impacts of Forest Plantations on Streamflow; Snow and Avalanche Control. **Soil Development and Properties**: Water Storage and Movement. **Tree Physiology**: A Whole Tree Perspective; Forests, Tree Physiology and Climate; Root System Physiology. **Tropical Forests**: Tropical Montane Forests.

Further Reading

Brammer DD and McDonnell JJ (1996) An evolving perceptual model of hillslope flow at the Maimai catchment. In: Anderson MG and Brooks SM (eds) *Advances in Hillslope Processes*, vol. 1, pp. 35–60. Chichester, UK: John Wiley.

Bruijnzeel LA (2001a) Forest hydrology. In: Evans JC (ed.) *The Forests Handbook*, vol. 1, pp. 301–343. Oxford, UK: Blackwell Science.

Bruijnzeel LA (2001b) Hydrology of tropical montane cloud forests: a reassessment. *Land Use and Water Resources Research* 1: 1.1–1.18. http://www.venus.co.uk/luwrr.

Calder IR (1979) Do trees use more water than grass? *Water Services* 83: 11–14.

Calder IR (1990) *Evaporation in the Uplands*. Chichester, UK: John Wiley.

Calder IR (1998) Water use by forests, limits and controls. *Tree Physiology* 18: 625–631.

Chang MT (2003) *Forest Hydrology: An Introduction to Water and Forests*. New York: CRC Press.

Dawson TE (1996) Determining water use by trees and forests from isotopic, energy balance and transpiration analyses: the roles of tree sizes and hydraulic lift. *Tree Physiology* 16: 263–272.

Dawson TE (1998) Fog in the California redwood forest: ecosystem inputs and use by plants. *Oecologia* 117: 476–485.

Gash JHC, Nobre CA, Roberts JM, and Victoria RL (1996) *Amazonian Deforestation and Climate*. Chichester, UK: John Wiley.

Roberts JM (1983) Forest transpiration: a conservative hydrological process? *Journal of Hydrology* 66: 133–141.

Roberts JM (1999) Plants and water in forests and woodlands. In: Baird A and Wilby R (eds) *Eco-Hydrology: Plants and Water in Terrestrial and Aquatic Ecosystems*, pp. 181–236. London: Routledge.

Schellekens J, Bruijnzeel LA, Scatena FN, Bink NJ, and Holwerda F (2000) Evaporation from a tropical rainforest, Luquillo Experimental Forest, eastern Puerto Rico. *Water Resources Research* 36: 2183–2196.

Shuttleworth WJ and Calder IR (1979) Has the Priestley–Taylor equation any relevance to forest evaporation? *Journal of Applied Meteorology* 18: 639–646.

Wullschleger SD, Meinzer FC, and Vertessy RA (1998) A review of whole-plant water studies in trees. *Tree Physiology* 18: 499–512.

Impacts of Forest Conversion on Streamflow

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Introduction

Trees and forests are valued for timber and forest products, for amenity, for biodiversity, and for the cultural and the spiritual well being we derive from their proximity. Forests and reforestation programs are also widely promoted with regard to their perceived hydrological benefits, although often these expected benefits are not realized. This article reviews the scientific knowledge and the public perceptions of important forest–hydrology links, focusing on the vexed questions of whether, when, and to what extent forests increase or decrease streamflow, reduce floods, and increase dry season flows. The effect of forest on rainfall, the impacts of various forestry activities (thinning, selection logging, clear-felling) on streamflow, and the soil and water impacts of reforesting degraded or agricultural areas are discussed elsewhere (*see* **Hydrology**: Hydrological Cycle; Impacts of Forest Management on Streamflow; Impacts of Forest Plantations on Streamflow). Similarly, effects of forest management and conversion to other land use on water quality, and ways to minimize any adverse impacts accompanying such conversions, are dealt with in other articles (*see* **Hydrology**: Impacts of Forest Management on Water Quality; Soil Erosion Control).

Forests and Water: Received Wisdom

Traditionally forests have been promoted as being 'good news' for the water environment. The conventional received wisdom, embodied often in government forest policy and promoted by international and national forestry interests and organizations is that, apart from reducing erosion and maintaining water quality, a good forest cover: (1) increases runoff, (2) reduces or even prevents 'flood,' and (3) boosts dry season flows. Yet when these statements are held against the light of scientific inquiry, the evidence is not always as favorable and sometimes even indicates the opposite.

Put simply, the most widely held view among the general public and, perhaps to a lesser extent, policy-makers and resource managers, is that forests act as 'sponges' absorbing excess rainfall and releasing the water slowly and evenly during lean periods. Because of this, forests are believed to be capable of preventing flooding, and increasing streamflow during the dry season. By analogy, their disappearance invariably brings about havoc (floods, droughts). Likewise, the effect of tree planting on degraded land is expected to result in (rapidly) improved streamflow regimes, i.e., elimination of peak flows and increased low flows. Such views are encountered especially in the tropical and subtropical parts of the world where the adverse hydrological effects of the land degradation that often (but not necessarily) follows forest clearance are felt the most. In the following, the claims with respect to the adverse effects of forest conversion ('deforestation') on streamflow are examined in some detail. The effects of the reverse, i.e., reforestation, are discussed elsewhere (*see* **Hydrology**: Impacts of Forest Plantations on Streamflow).

Forest Conversion and Streamflow: The Scientific Consensus

Forests and Annual Water Yield

It is now recognized worldwide that evaporation from forested areas, with very few exceptions, will be greater than that from alternative land uses, such as pasture or annual cropping (**Figure 1**). Provided the soil is not disturbed too much upon forest conversion, the smaller water use of crops or grassland generally shows up as increases in groundwater recharge, in the volumes of water flowing annually from cleared catchments, and in increased seasonal (dry season) flows. Generally, the larger the proportion of forest removed, the larger these increases in water yield (**Figure 2**).

Whilst the increases in streamflow usually return to preclearing levels within 3–35 years where regrowth of the original vegetation occurs (depending mostly on the vigor with which regeneration takes place), the conversion of native forest to other types of vegetation cover may produce permanent changes in flow. For example, permanent increases in annual

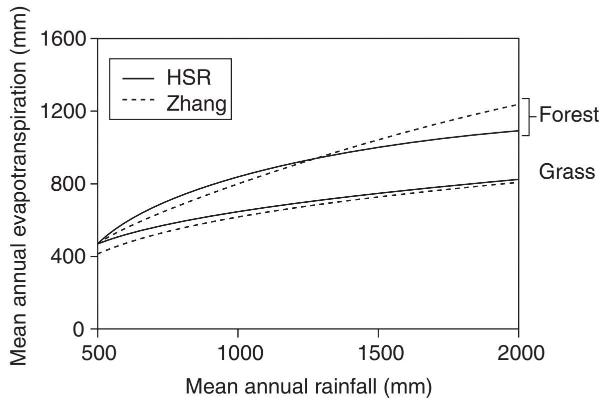


Figure 1 Relationship between land cover, mean annual rainfall and mean annual evapotranspiration, as predicted by the Holmes and Sinclair (1986) relationship (HSR) and the Zhang *et al.* (1999) model. Reproduced with permission from Vertessy RA, Zhang L, and Dawes WR (2003) Plantations, river flows and river salinity. *Australian Forestry* 66: 55–61.

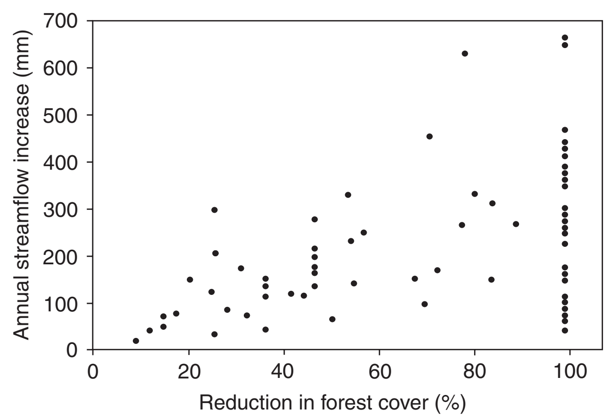


Figure 2 Relationship between reduction in forest cover and increase in catchment water yield. Reproduced with permission from Bosch JM and Hewlett JD (1982) A review of catchment experiments to determine the effects of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55: 3–23.

water yield are normally associated with the conversion of deciduous or evergreen native forest to agricultural cropping or pasture (cf. **Figure 1**). Depending on the nature of the conversion, degree of surface disturbance (affecting surface runoff), and rainfall, reported increases in flows range from 60–125 mm year^{-1} under humid warm temperate conditions to 140–410 mm year^{-1} in the equatorial tropics. These values are somewhat smaller than the maxima shown in **Figure 2** because the latter mostly refer to increases in flows shortly after forest clearance and before a new vegetation cover is established.

There are two principal reasons for the difference in evaporation between forests and shorter crops (cf. **Figure 1**). In wet climates with frequent rainfall, where the surfaces of vegetation tend to remain wet for long periods, rainfall interception by the canopies of forests is much higher than that by shorter crops. The intercepted water is evaporated back into the atmosphere and therefore does not reach the ground where it could have contributed to soil water reserves. Rates of evaporation from a wet forest canopy are so enhanced because the aerodynamically very rough surfaces of forests assist the turbulent transport of water vapor into the atmosphere much more than the smoother surfaces of grassland or low crops. This is analogous to the clothes-line effect: wet clothes pegged out on a line will dry much quicker than those laid out flat on the ground. Not only does the increased turbulent exchange between forests and the atmosphere increase the rate at which evaporated water molecules are moved up into the air; it also promotes the rate at which heat can be supplied by the passing air to the cooler vegetation surface underneath to support the evaporation process. This source of energy, known as advected heat, is of such significance that annual evaporation rates from forests in some wet climates can exceed those that could be sustained by direct radiation from the sun by a factor of 2. Large-scale advection typically occurs in near-coastal or mountainous regions (where the ocean or adjacent lowlands are the main source of relatively warm air, respectively). At a more local scale warmer air may be drawn in from areas that are not wetted and cooled by rain.

In drier climates or during prolonged rainless periods, forests are able to access and take up more soil water than short vegetation or agricultural crops because forests generally have much deeper root systems. This also contributes to higher evaporation rates overall. However, under conditions of ample soil water availability, the internal physiological resistance to evaporation is often slightly greater for trees than for short crops. As a result, the soil water uptake (transpiration) rates of forest may be *c*. 10% less than those of grassland and other short crops (as long as they are well watered) and this may to some extent compensate for the interception and increased rooting depth effects described above.

Although annual water yields from forested catchment areas can thus be expected to be (much) less than those for cleared areas (**Figures 1** and **2**), there are a few exceptions. The first of these concerns so-called montane cloud forests. These wet and mossy, fog-ridden forests are mainly found in the cloud belts of (mostly tropical) mountains and islands although fog-affected forests also occur along the western margins of the American continent. At favorably exposed locations cloud forests may receive hundreds of millimeters of extra water in the form of wind-blown fog and drizzle that impact on and drip from the canopy. In extreme cases annual amounts of fog drip may exceed incident rainfall totals, thereby more than compensating the losses associated with interception evaporation referred to earlier. Because soil water uptake rates are also low under these humid cloudy conditions, areas with cloud forests are generally considered excellent suppliers of water, especially during periods of low rainfall when fog incidence is often greatest. Concerns have been expressed that the indiscriminate clearing of cloud forests to make way for pasture or vegetable cropping will lead to reductions in streamflow because of the associated loss of the former forest's fog stripping capacity (**Figure 3**). Although evidence from the humid tropics for such declines in flows is circumstantial at best, it has been observed in the Pacific Northwest of the USA after the partial cutting of Douglas-fir forest subject to high fog incidence.

The second exception to the rule of increased streamflows after forest conversion relates to cases where old-growth forests with relatively low water use and vigor are replaced by young, actively growing secondary forest or exotic tree plantations. Examples include rapidly regenerating mountain ash (*Eucalyptus regnans*) forest after a wildfire in southeastern Australia, young secondary growth in Amazonia after the abandonment of agricultural fields or pasture, and (most probably) plantations of *Acacia mangium* replacing rainforest in Malaysia. Likewise, converting deciduous forest to coniferous forest will result in more-or-less seriously decreased streamflow totals, mostly because of the much higher interception evaporation associated with the evergreen conifers.

Figure 3 Converting tropical montane cloud forest to pasture may reduce catchment water yields through the loss of the forest's fog stripping capacity. Photograph courtesy of KFA Frumau.

Although the results of small catchment experiments provide a clear and consistent picture of increased water yield after replacing tall vegetation by a shorter one (and vice versa; cf. **Figures 1** and **2**), such effects are often more difficult to discern in (very) large river basins ($>1000\,km^2$). Apart from continuous changes in the mosaic of different landcover types, each with their own influence on local runoff, there are the added complications of strong spatial and interannual variability in rainfall, and withdrawals of water for municipal, agricultural, and industrial purposes in densely populated areas. Nevertheless, a few studies have demonstrated a significant landcover change effect on the flows from (very) large basins. An increase in annual streamflow of about 110 mm has been reported for the Citarum River basin ($4133\,km^2$) on the island of Java, Indonesia, between the 1920s and the 1980s despite unaltered rainfall totals. The increase was attributed to the replacement of irrigated rice fields (not forest) by settlements and industrial estates. Likewise, the conversion of *c.* $33\,000\,km^2$ (19% of basin area) of so-called cerrado forest (scrub with scattered trees) to pasture in the subhumid Tocantins basin ($175\,360\,km^2$) of central Brazil was followed by an increase in streamflow of about $90\,mm\,year^{-1}$ (+24%).

At an intermediate scale ($1100\,km^2$), increases in averaged annual flow totals occurred over a period of four decades in the Mahaweli catchment in Sri Lanka, despite a weak negative trend in rainfall over the same period. Although both trends were not statistically significant at the 95% significance level due to strong interannual variability in the data, the corresponding increase in annual runoff ratios (streamflow: rainfall) was highly significant (**Figure 4**). The increased hydrological response was ascribed to the gradual but widespread conversion of tea plantations (not forest) to annual cropping and home gardens on steep slopes without appropriate soil conservation measures (see also the section on forest and dry season flows below).

To summarize, despite the few exceptions outlined above, there is overwhelming evidence that streamflow totals from forested catchments are reduced compared with those under shorter vegetation. The effect of enhanced water yield after forest conversion has been demonstrated over a range of scales, including some very large river basins.

Forests and Floods

As long as the soil's water intake capacity is not degraded too much by surface compaction, the lower water use of grassland and crops compared to forest (**Figure 1**) will manifest itself in the form of wetter soil conditions and thus increased streamflow (**Figure 2**). This overall increase in catchment wetness leads, in turn, to an expansion of storm runoff-producing areas. These are mostly wet, low-lying areas around watercourses and stream heads, but may also include footslopes and hillslope depressions. The consequence of this is that cleared catchments will respond more rapidly and more vigorously to rainfall; both stormflow volumes and peak discharges will be elevated (**Figure 5**).

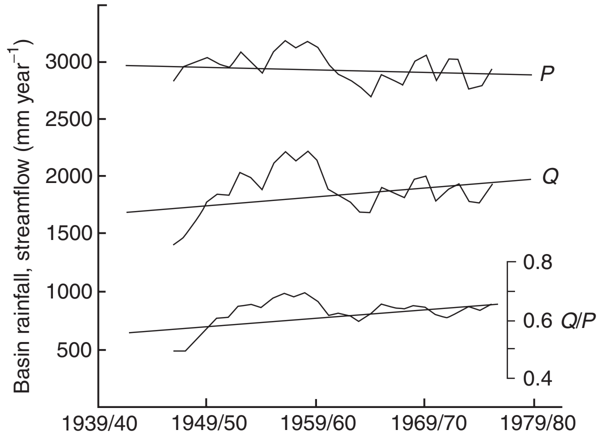


Figure 4 Five-year moving averages of annual rainfall *P*, streamflow *Q*, and runoff ratios *Q/P* for the upper Mahaweli Basin above Peradeniya, Sri Lanka. Reproduced with permission from Madduma Bandara CM (1997) Land-use changes and tropical stream hydrology: some observations from the upper Mahaweli Basin of Sri Lanka. In: Stoddard DR (ed.) *Process and Form in Geomorphology*, pp. 175–186. London: Routledge.

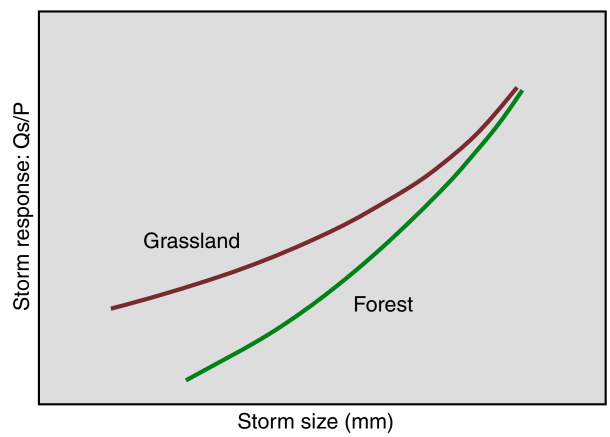


Figure 5 Conceptual relationship between the size of stormflow generating rainfall events (P) and the resultant stormflows and how these are affected by vegetation type. Reproduced with permission from Scott DF, Bruijnzeel LA, and Mackensen J (2004) The hydrological and soil impacts of forestation in the tropics. In: Bonell M and Bruijnzeel LA (eds) *Forests – Water – People in the Humid Tropics*. Cambridge, UK: Cambridge University Press.

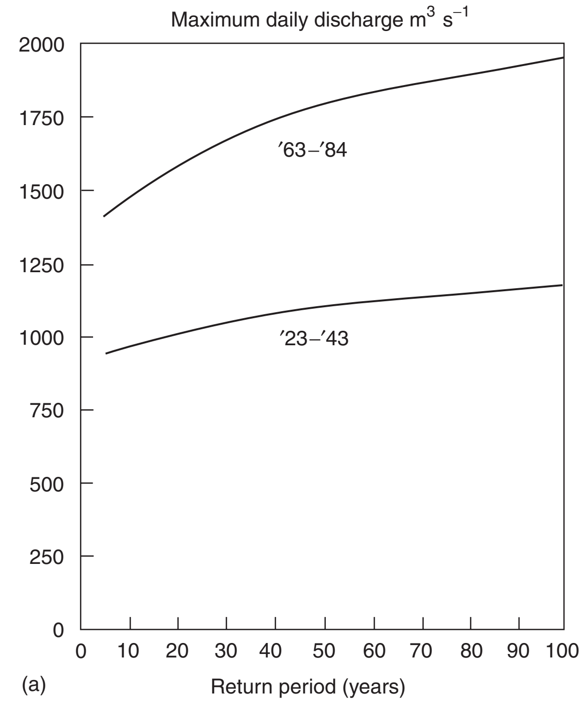
Under conditions of minimum surface disturbance (e.g., when skyline logging techniques are used), relative increases in catchment stormflow response to rainfall are largest for small rainfall events (up to 300%), declining to less than 10% for large events. As such, the influence of vegetation cover or type is inversely related to the size of the rainfall event generating the stormflow (**Figure 5**). This can be explained as follows: for small storm events the combined storage capacity of vegetation canopies, ground-convering litter, surface microtopography and the soil mantle can be substantial relative to the size of the storm depth. Of these 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, storage capacities will be relatively high but once the soil has become thoroughly wetted by frequent rains (typically at the height of the wet season), opportunities to absorb large additional amounts of rain will be very limited. Furthermore, as precipitation events increase in size, so does the relatively fixed maximum storage capacity of the soil become less influential (**Figure 5**). In other words, under conditions of extreme rainfall and soil wetness, the presence or absence of a good forest cover is no longer decisive. Catchment runoff response to rainfall is then governed primarily by the soil's physical capacity to store and transmit water.

Naturally, the effect of forest conversion on stormflow generation will be much more pronounced if soil disturbance is severe and the catchment's rainfall absorbing capacity becomes structurally impaired. Soils may be compacted by machinery during clearing operations and subsequently by grazing cattle, by exposure to intense rainfall (when no longer protected by vegetation or litter), and by the gradual loss of organic matter and the disappearance of burrowing soil animals during extended periods of agricultural cropping. As a result, total stormflow amounts from intensively grazed tropical grassland catchments are typically 25–45% higher than those associated with the forests they replaced. In the case of seriously degraded cropland (also in the tropics), however, the relative increase may easily be 300–400%. Often, catchment response to rainfall after forest conversion (but also in relation to forestry activities) is influenced most by the construction of roads and drainages, settlements and, in urbanized areas, industrial estates. On such densely compacted surfaces typically more than 70% of the rain is immediately turned into surface runoff. In addition, road construction is often accompanied by increased landsliding and erosion. The associated increases in stream sedimentation may, in extreme cases, cause the river bed to be raised to the extent that flood hazards are increased even further.

At larger scales, the overall effect of landcover change on catchment runoff response to rainfall will depend on the relative proportion of the various landcover types (including roads and settlements) and their hydrological behavior. Recent work in the Pacific Northwest of the USA trying to 'disentangle' the effects of logging and the presence of a road network on peak flow enhancement in the 150 km^2 Deschutes River basin suggests the separate effects of the two to be a rise of about 10% each. In contrast to the forest removal effect (cf. **Figure 5**), the road effect was shown to increase with the size of the flood peak (see also **Figure 6a**). Conversely, in northern Thailand relative runoff contributions from rural roads and trails to overall stormflow production in a largely deforested landscape were greatest for small storms but gradually 'drowned' by contributions from agricultural fields during larger storms.

It is generally found that the adverse local effects of forest removal on all but the largest stormflow response tend to be 'diluted' or even become undetectable at larger scales. This is because peak flows from one part of the basin will usually not coincide with those from other parts due to differences in the timing of the rainfall or in the hydrological response of different landcover types. Arguably the most publicized example of highland–lowland interactions in relation to downstream flooding is the Ganga–Brahmaputra–Meghna river system in northern India and Bangladesh. Disastrous floods in the area are almost always attributed to 'deforestation in the Himalayas' rather than to excess monsoon rainfall occurring at a time when most of the river basin has already been wetted up by previous rains. However, a detailed analysis of the hydrological and climatic records for the area over the past 40 years shows that neither the frequency nor the magnitude of flooding has increased over the last few decades. Indeed, flooding must be considered an unavoidable process given the geoclimatic setting of the Ganga–Brahmaputra river basin. Consequently there is no reason to believe that floods in the Indian lowlands have intensified as a result of human impact in the highlands although the degree of damage has increased because of greater floodplain occupancy.

Nevertheless, there is reason for concern, particularly with respect to tropical river basins. For example, most of the increase in streamflow observed after converting tea estates (not forest) to rainfed cropping on steep slopes in Sri Lanka (**Figure 4**) occurred during the rainy season whereas dry



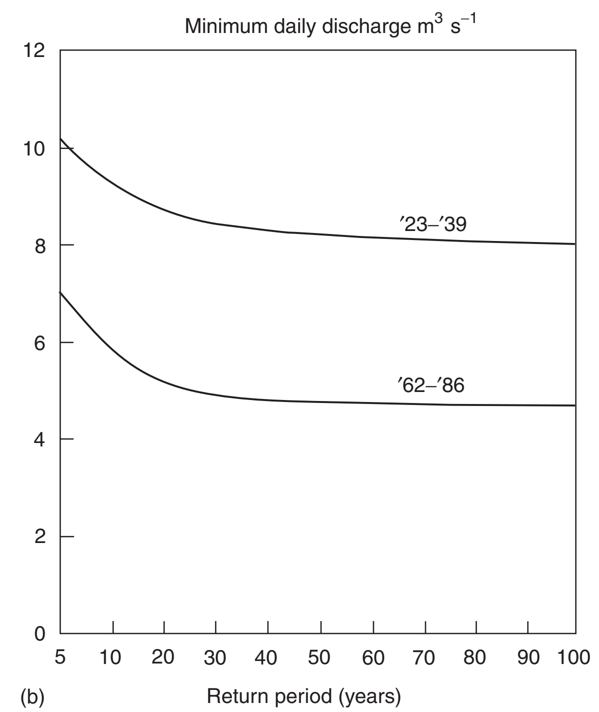


Figure 6 Changes in average maximum and minimum daily flows for the Citarum River basin, West Java, Indonesia between the periods 1923–1939/43 and 1962/63–1984/86. Reproduced with permission from Van der Weert R (1994) *Hydrological Conditions in Indonesia*. Jakarta: Delft Hydraulics.

season flows continued to decline, presumably as a result of steadily worsening surface infiltration conditions (**Figure 7**). Similarly, maximum flows in the densely populated Citarum River basin in

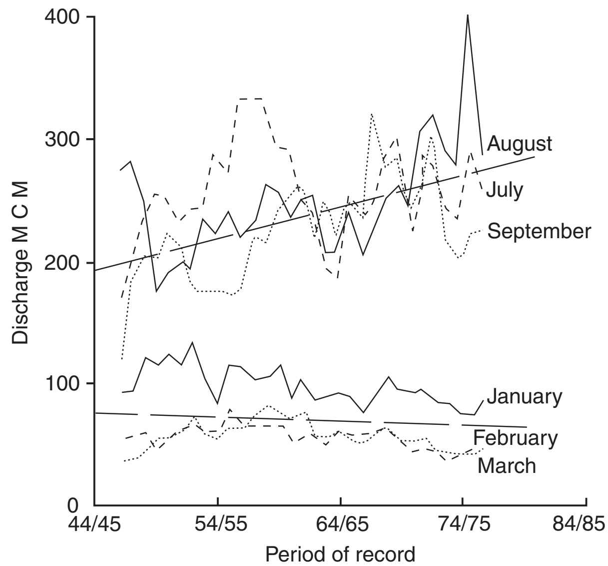


Figure 7 Seasonal trends in streamflow in the upper Mahaweli basin, Sri Lanka. Reproduced with permission from Madduma Bandara CM (1997) Land-use changes and tropical stream hydrology: some observations from the upper Mahaweli Basin of Sri Lanka. In: Stoddard DR (ed.) *Process and Form in Geomorphology*, pp. 175–186. London: Routledge.

Indonesia referred to earlier increased on average by about 50%, with even greater increases for the largest events (**Figure 6a**). This is believed to be caused by the conversion of irrigated cropland to settlements, industrial estates and roads. To make matters worse, dry season flows were also reduced (by about one-third; **Figure 6b**). Although event peak discharges in the much larger Tocantins basin in Brazil referred to earlier were not influenced by the conversion of 19% of its scrubland area to pasture, most of the 24% increase in annual water yield occurred during the wet season. In addition, the seasonal flood peak arrived about 1 month earlier than when the basin was fully forested. Neither urbanization nor altered rainfall patterns could be called on to explain this pattern. The most likely cause is, again, a gradual degradation of soil infiltration capacities, in this case due to the trampling effect of grazing cattle.

To summarize, the role of forest cover in flood mitigation or management is limited to small to medium-sized events. As the severity of the flood increases the impact of land use change appears to be reduced (**Figure 5**). Yet there is increasing evidence that in areas where gradual degradation of catchment infiltration opportunities beyond a critical threshold occurs, peak flows are enhanced considerably, even in (very) large river basins. Finally, there remains a need to better understand the complex relationships between land use change and stream sediment dynamics, including the build-up of riverbeds and changes in channel form, and their effect on flood heights.

Forest and Dry Season Flows

In areas with seasonal rainfall, the distribution of streamflow throughout the year is often of greater importance than annual totals. Reports of greatly diminished flows during the dry season after forest conversion to cropping abound in the literature, particularly in the tropics. At first sight, this seems to contradict the evidence presented earlier that forest removal leads to higher water yields (**Figure 2**), even more so because most of the increases in flow after experimental clearing are generally observed during baseflow conditions. However, the controlled conditions imposed during the catchment experiments of **Figure 2** may differ from those encountered in some real-world situations. As we have seen, rainfall infiltration opportunities are often (much) reduced after forest conversion due to soil degradation, compaction or surface pavement. This is usually a gradual process and it is quite possible that many catchment experiments did not last long enough for sufficient degradation to happen. As illustrated by **Figures 4**, **6** and **7**, once infiltration becomes seriously impaired, increases in surface runoff during the rainy season may become so large that the recharging of groundwater reserves is reduced. When this critical stage is reached, diminished dry season flow is the sad result (**Figures 4** and **7**), despite the fact that the removal of the forest should have induced higher baseflows because of the diminished water use of the new vegetation (cf. **Figure 2**).

If, on the other hand, soil surface characteristics after clearing are maintained sufficiently to allow the continued infiltration of (most of) the rainfall, then the effect of reduced water use after forest removal will show up as increased dry season flow (**Figure 8**). This may be achieved through a well-planned and maintained road system plus the careful extraction of timber in the case of logging operations, or by the application of soil conservation measures (such as terracing, planting contour hedgerows, or grass strips) when clearing for agricultural purposes (**Figure 9**).

To summarize, the effect of forest removal on dry season flows will be positive where the infiltration capacity of the soil is maintained sufficiently to avoid excess surface runoff during rainfall. Where infiltration becomes seriously impaired, however, groundwater recharge may be reduced to the extent that dry season flows are decreased.

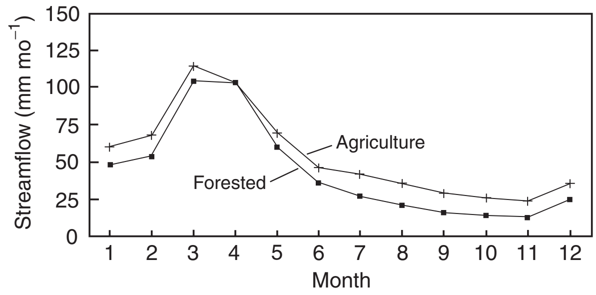


Figure 8 Changes in seasonal distribution of streamflow after replacing montane rainforest by subsistence cropping at Mbeya, Tanzania without significant surface degradation. Based on original data in Edwards (1979); after Bruijnzeel LA (2001) Forest hydrology. In: Evans J (ed.) *The Forests Handbook*, vol. 1, pp. 301–343. Oxford, UK: Blackwell Science.

Reconciling Public and Science Perceptions of Forest – Streamflow Linkages

The most common perceptions of the hydrological impacts of forest conversion ('deforestation') held by many forestry practitioners, policy-makers, and the general public (particularly in the tropics) on the one hand and (most) researchers on the other, are summarized in **Table 1**. Arguably, the contrast between the two is less great than claimed by some. A close inspection of the respective perceptions listed in **Table 1** reveals that in many cases these contrasting views relate to differences in degree or frequency of occurrence rather than representing true differences in kind.

Much of the confusion regarding the increase or decrease of streamflow following forest clearance can be traced to two aspects: (1) the need to distinguish between annual and seasonal water yields, and (2) the fact that most, if not all experimental catchment studies pertain to controlled land use changes, the hydrological impacts of which have been monitored over relatively short periods of time only (typically up to 3 years, occasionally longer). As to the first, in the absence of actual streamflow measurements it is difficult to tell whether the increases in rainy season stormflows and decreases in low flows witnessed by people living in gradually degrading catchments actually add up to increased total annual water yields or not (see **Figure 4**). However, there is little actual difference between the layman stating that 'deforestation' leads to diminished low flows due to the loss of the 'sponge effect' of the forest and the scientist having to agree, provided that surface infiltration characteristics have been degraded sufficiently over time for this to happen. Similarly, the public view that 'floods' invariably increase after

Figure 9 Adverse impacts on streamflow can be avoided largely by applying soil conservation measures following forest clearing. Photograph by LA Bruijnzeel.

forest clearance and that of the scientist acknowledging that stormflows do increase in all but the most extreme cases, and perhaps even then in the case of an extended road network, are not that different anymore either.

Therefore, it is arguably more productive to state that stormflows are increased after forest removal up to a certain threshold (beyond which the effect of landcover is overridden by those of extreme rainfall and limitations in soil water holding capacity), or that low flows will decrease once a certain level of surface degradation has been reached, than to merely dismiss the 'sponge theory' as folklore or an anachronism.

Furthermore, and as hinted at already, in the heated debate on the hydrological role of (especially tropical) forests it is generally overlooked that the circumstances associated with controlled (short-term) catchment experiments may differ from those of some real-world situations in the longer term. No experimental catchment study has lasted long enough, however, to document the long-term effects of increasingly degraded surface conditions on streamflow amounts and regime. As such, both views (diminished or increased dry season flows after clearance) must be considered correct, depending on the situation. Where infiltration is maintained sufficiently, as under controlled experimental conditions or rational land use, the reduced water use associated with forest rsemoval will show up as increased dry season flow (**Figures 8** and **9**). However, where infiltration and groundwater recharge become seriously impaired by surface

Table 1 Common perceptions about the streamflow impacts of 'deforestation'

Commonly held perceptions	*Scientific experience*	*Qualifications*
Forests act like sponges absorbing water during rainy season and releasing it evenly during the dry season. Cutting of forests dries up water supplies, particularly during the dry season, because the 'sponge effect' becomes lost.	Cutting of forests increases total water yield, particularly during low flow periods. Dry season flows reduced if soil water intake capacity seriously impaired (as in severely degraded or urbanized catchments). Clearing of cloud forests may lead to reduced dry season flows and possibly total yield.	Increased total and seasonal water yields under pasture or cropping only manifested as long as surface infiltration capacity is maintained. Fine-textured soils most vulnerable to degradation. Thus, whether the perceived 'sponge effect' remains or disappears depends entirely on postconversion land use practices.
Cutting of forests causes floods as the 'sponge effect' is then lost.	Cutting of forests affects stormflow volumes for small- to medium-sized events and at the local scale ($<10\,km^2$). Little or no impact on size of extreme events (floods) at any scale although adverse effect of extensive roading cannot be excluded. Wet season flows (but not events) from very large basins probably increase due to cumulative effect of reduced infiltration opportunities.	Postforest land use must afford good surface cover. Otherwise stormflows up to medium-sized events much increased (as in severely degraded catchments).

compaction and crusting, as is eventually the case in many real-world situations, diminished dry season flows inevitably follow despite the fact that the reduced evaporation should have produced higher baseflows. In the layman's terms, the 'sponge effect' is lost (**Figures 6** and 7).

A related aspect concerns the fact that long-term fluctuations in rainfall arising from natural climatic variability are not covered adequately by short-term experiments. Such fluctuations have both short- and longer-term impacts on catchment hydrology – notably the (more frequent) occurrence of peak flows during rainier periods or diminished dry season flows during drier periods – which may be attributed erroneously to changes in landcover rather than climatic variability. The massive floods in Central Europe in the summer of 2002 and the extreme drought during the next year are a prime example of the whimsical nature of many climates.

The lack of long-term catchment studies representing actual hydrological conditions experienced by countless people perhaps calls for more modesty on the part of scientists when communicating the results of (controlled) hydrological experiments to practitioners and the public at large. More importantly, it clearly illustrates the need for stepped up efforts to remedy this deficiency.

See also: **Harvesting**: Forest Operations in the Tropics, Reduced Impact Logging; Roading and Transport Operations. **Hydrology**: Hydrological Cycle; Impacts of Forest Management on Streamflow; Impacts of Forest Management on Water Quality; Impacts of Forest Plantations on Streamflow; Soil Erosion Control. **Soil Development and Properties**: Water Storage and Movement. **Tree Physiology**: A Whole Tree Perspective.

Further Reading

Bonell M and Bruijnzeel LA (eds) (2004) *Forests, Water and People in the Humid Tropics*. Cambridge, UK: Cambridge University Press.

Bosch JM and Hewlett JD (1982) A review of catchment experiments to determine the effects of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55: 3–23.

Bruijnzeel LA (2001) Forest hydrology. In: Evans J (ed.) *The Forests Handbook*, vol. 1, pp. 301–343. Oxford, UK: Blackwell Science.

Bruijnzeel LA (2004) Hydrological functions of tropical forests: not seeing the soil for the strees? *Agriculture, Ecosystems and Environment* (in press).

Bruijnzeel LA and Bremmer CN (1989) *Highland–Lowland Interactions in the Ganges–Brahmaputra River Basin: A Review of Published Literature*. ICIMOD Occasional Paper no. 11. Kathmandu: International Centre for Integrated Mountain Development.

Calder IR (1998) Water use by forests, limits and controls. *Tree Physiology* 18: 625–631.

Calder IR (1999) *The Blue Revolution: land use and integrated water resources management*. Earthscan Publications: London.

Froehlich W, Gil E, Kasza I, and Starkel L (1990) Thresholds in the transformation of slopes and river channels in the Darjeeling Himalayas, India. *Mountain Research and Development* 10: 301–312.

Giambelluca TW (2002) The hydrology of altered tropical forest. *Hydrological Processes* 16: 1665–1669.

Hewlett JD (1982) Forests and floods in the light of recent investigation. In: *Hydrological Processes of Forested Areas*, pp. 543–559. Ottawa: National Research Council of Canada.

Hofer T (1998) Do land use changes in the Himalayas affect downstream flooding? Traditional understanding and new evidences. *Memoir of the Geological Society of India* 19: 119–141.

La Marche JL and Lettenmaier DP (2001) Effects of forest roads on flood flows in the Deschutes River, Washington. *Earth Surface Processes and Landforms* 26: 115–134.

Madduma Bandara CM (1997) Land-use changes and tropical stream hydrology: some observations from the upper Mahaweli Basin of Sri Lanka. In: Stoddard DR (ed.) *Process and Form in Geomorphology*, pp. 175–186. London: Routledge.

Sandström K (1998) Can forests 'provide' water: widespread myth or scientific reality? *Ambio* 27: 132–138.

Vertessy RA (1999) The impacts of forestry on streamflows: a review. In: Croke J and Lane P (eds) *Forest Management for the Protection of Water Quality and Quantity, Proceedings of the 2nd Erosion in Forests Meeting*, Warburton, 4–6 May 1999, pp. 93–109. Canberra: Cooperative Research Centre for Catchment Hydrology.

Vertessy RA, Zhang L, and Dawes WR (2003) Plantations, river flows and river salinity. *Australian Forestry* 66: 55–61.

Impacts of Forest Management on Streamflow

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Introduction

The practical overall influence exerted by forests on hydrological processes is most clearly borne out by a comparison of streamflow amounts emanating from catchment areas with contrasting proportions or