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.

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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 types of forest. Forestry activities (thinning, selection logging, clear-felling) and natural disturbances (extreme rainfall, hurricanes, fire) have the potential to more or less seriously alter forest water use and thus change the amount and timing of streamflow. Because climatic differences (notably rainfall) between sites or years, and unmeasured transfers of groundwater from one catchment to another, tend to obscure the effect on streamflow of the vegetation, the 'direct' comparison of streamflows from catchments with contrasting forest covers can be problematic. The same applies to a comparison of the flows from a single catchment before and after a change in cover. The classical approach to these problems has been the so-called 'paired catchment experiment' in which the streamflow from two (preferably adjacent) catchments of comparable geology, topography, exposition, and vegetation are expressed in terms of each other (using regression analysis) during a 'calibration phase.' Once a robust baseline calibration relationship has been established, one of the catchments is subjected to a land cover treatment (for example, strip-cutting or clear-felling) while the other catchment remains undisturbed as the control (**Figure 1**). Following the treatment of one catchment, streamflow from both catchments continues to be monitored. Any effects of the treatment are evaluated by comparing the actually measured streamflow totals from the experimental catchment with the flows that would have occurred if the catchment had remained unchanged. This is usually done by inserting streamflow totals determined for the control catchment into the calibration relationship (**Figure 1**). Although a more rigorous comparison between catchments is obtained in this way than in the case of 'direct' comparisons, the tacit underlying assumption of the paired catchment method is that any differences in groundwater leakage from the two catchments remain constant with time, regardless of the status of the vegetation cover. Also, to avoid unjustified extrapolation of the calibration line to accommodate extremes in streamflow during the treatment phase (e.g., because of drought or extreme rainfall), it is important that the calibration period includes both wet and dry years. This makes the paired catchment method a time-consuming (usually at least 5 years) and expensive affair. In addition, the method is essentially a 'black-box' requiring additional hydrological process research to reveal the relative importance of different causative factors to explain the observed changes in streamflow. All this, plus the limited resolution afforded by the paired catchment approach (usually more than 20% cover change is required for effects on streamflow to be detectable), have led to a general decline in the number of such studies in the last few decades and a gradually greater emphasis on computer simulations (modeling).

This article reviews the hydrological effects of (1) various forms of forest management (thinning, selective logging, removal of undergrowth or riparian vegetation, and clear-cutting) and (2) natural disturbances (mostly fire and storms), and subsequent regrowth. Effects on streamflow of converting forest to other forms of land use, and the establishment of forest plantations on former agricultural

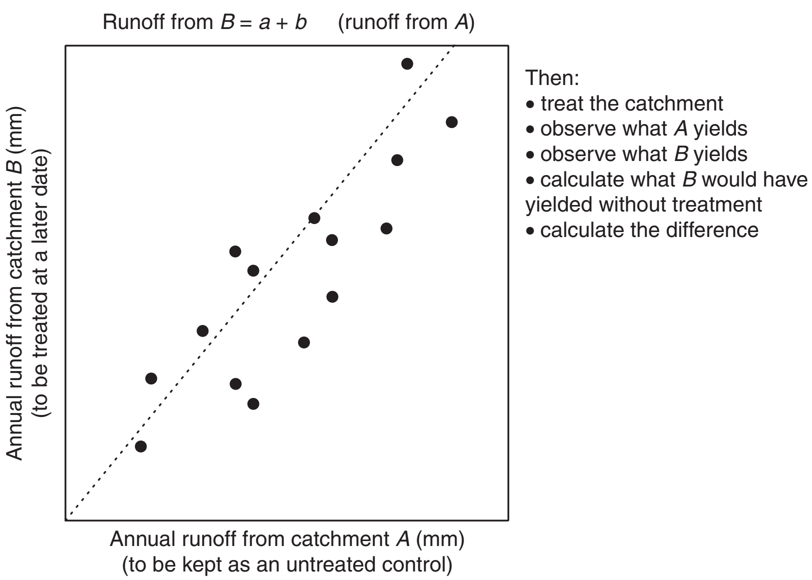

Figure 1 The paired catchment technique to evaluate the effect of landcover change on streamflow. Data shown represent flows as measured during the calibration period; the derived calibration relationship links the flows from the two catchments.

land or natural grassland are discussed in the respective companion chapters (see **Hydrology**: Impacts of Forest Conversion on Streamflow; Impacts of Forest Plantations on Streamflow).

Hydrological Effects of Thinning and Selective Logging

Effects on Net Precipitation

A forest canopy intercepts a large portion of the rain that falls on it. This process is called rainfall interception. Usually, the bulk of the intercepted water drips from the canopy as so-called throughfall, whereas a much smaller portion (usually a few percent) reaches the forest floor along branches and the tree trunks in the form of stemflow. The remainder of the intercepted water is evaporated again during and shortly after the storm and thus never reaches the ground. Therefore this term is often referred to as the interception loss. The sum of throughfall and stemflow is called net precipitation. It has long been recognized that amounts of net precipitation tend to be inversely related to the stocking of a forest. In other words, the denser the canopy, the smaller the amount of rainfall reaching the ground. Although this observation may seem trivial, amounts of intercepted water may be substantial, especially in the case of evergreen, coniferous forests (up to 45% of incoming rainfall). As a result, the amount of water available for infiltration into the soil and contributing to soil water reserves is closely related to amounts of interception. Therefore, it is of interest to examine the effect of management-related and naturally occurring changes in forest cover and structure on amounts of precipitation arriving at the forest floor.

In well-stocked coniferous forest (plantations), amounts of crown drip often show a steady decrease with forest age, reflecting the greater leaf surface area and surface roughness associated with older stands. Naturally, a larger leaf area is capable of intercepting and storing more rainfall whereas increased surface roughness enhances atmospheric turbulence and evaporation rates from the wet canopy, and thus total interception. Amounts of stemflow in these forests, on the other hand, decrease with stand age although the overall effect on net precipitation is small due to the relatively small amounts involved anyway. Together with an increased capacity of the litter layer to intercept and store rainfall in older coniferous stands the overall effect on net precipitation is that of a gradual reduction as these forests mature. For example, in stands of white pine (*Pinus strobus*) in the southeastern USA, net precipitation in 60-year-old stands was about 220 mm year^{-1} less than in 10-year-old forest. No such decline with age was found for (natural) deciduous forest in the same area. Apparently, *c*. 10-year-old deciduous forest has already acquired similar leaf biomass and roughess characteristics as the older forests. In evergreen mountain ash forest (*Eucalyptus regnans*) in Australia, on the other hand, an altogether different pattern has been observed. Here, rainfall interception increases rapidly to a value of about 25% of the rainfall during the first 30 years; then it declines slowly to about 15% at age 235 years, a difference of about 190 mm year^{-1} (**Figure 2**). Such changes reflect changes in the structure of the regenerating forest: in younger stands, the trees are closely spaced and there is little undergrowth. In old-growth forest, the trees are much more widely spaced but the understory is well developed.

Naturally, rainfall interception by deciduous forests during the dormant season is lower than during the growing season. However, the typically observed increase in net rainfall of 5–10% when the trees are leafless is by no means proportional to the reduction in leaf area which can be up to sixfold. Likewise, the decreases in rainfall interception that have been observed after forest thinning are typically three to four times smaller than the degree of canopy opening. For example, a 50% reduction in basal area of a Douglas-fir forest in France resulted in only a 13% drop in interception whereas a 13-fold reduction in basal area in a dense Sitka spruce (*Picea sitchensis*) plantation in Scotland (corresponding to a change in planting interval from 2×2 m to 8×8 m) was accompanied by a less than fourfold reduction in interception. Such findings can be explained by the fact that, although canopy cover is reduced by

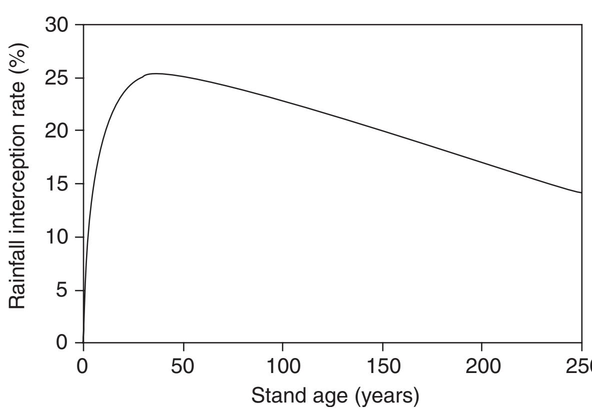

Figure 2 Relationship between mountain ash rainfall interception rate and stand age. Reproduced with permission from Haydon S *et al.* (1996) Variation in sapwood area and throughfall with forest age in mountain ash (*Eucalyptus regnans* F. Muell.). *Journal of Hydrology* 187: 351–366.

thinning or leaf fall, the aerodynamic roughness of the forest is also reduced. As a result, the turbulent exchange between the trees and the surrounding air decreases and rates of evaporation are reduced accordingly. In terms of soil water recharge the effect of forest thinning is even smaller when the felled trees are left to decompose on the site because the slash will intercept part of the gain in throughfall.

To summarize, to achieve significant increases in amounts of net precipitation entering the mineral soil, forest thinning would need to be substantial (up to 70% of basal area). In addition, for maximum effect the slash would need to be removed but this may have adverse implications for soil fertility (erosion and loss of organic matter and nutrients contained in the slash). In areas with snowfall, opening up of the forest will enhance both the rate and timing of snowmelt. Depending on the situation, this may be considered positive (higher water yields) or negative (aggravation of spring flooding).

Effects on Forest Water Use and Catchment Water Yield

Whilst the effect of thinning on interception and net precipitation is thus seen to be rather limited, effects on soil water (and ultimately streamflow) are likely to be smaller still. Opening up of a stand not only enhances the penetration of radiation to the understory vegetation and the forest floor (thereby enhancing evaporation), but also the remaining vegetation will start to compete for the extra moisture supplied by the initially increased throughfall. The magnitude and the duration of such effects will differ between locations, depending on the vigor of overstory and understory vegetation, climatic conditions (including slope exposure), and the configuration of the cutting, as shown by the examples below.

No changes were detected in the streamflow from a deciduous hardwood forest catchment of southeasterly exposure in the southeastern USA (Coweeta) after a selective logging operation had removed 27% of the basal area, whereas only a 4.3% rise in flows was observed after a 53% selective cut. Removing the entire understory (representing 22% of forest basal area) from a catchment of northwesterly exposure in the same area produced an equally modest change. Typically, the moisture gained by removing one component of the forest is rapidly taken up by others. In coastal Douglas-fir forest in western Canada soil water deficits developing during the summer have been shown to be very similar below dense, unthinned stands with little to no undergrowth, and thinned stands with a well-developed understory. After removal of the undergrowth, soil water uptake by the trees increased by 30–50% and the overall effect of the removal on soil water content was insignificant. In an experiment involving two 40-year-old Scots pine plantations of similar tree height but with a more than fivefold difference in stocking in the UK, tree water uptake (transpiration) in the widely spaced plantation was about two-thirds of that of the denser stand. However, relative transpiration rates per tree were more than three times higher in the thinned plot, and intermediate in magnitude between the relative increases in average water-conducting area (so-called sapwood) per tree (2.9 times) and leaf area per tree (4.2 times), compared to the unthinned stand. Therefore, although water use by the thinned forest had not reached prethinning levels yet, the large increases in leaf and sapwood areas of the remaining trees could be seen as representing a tendency towards complete re-equilibration following a set of physiological relationships aimed at maximum site utilization. Finally, in an extreme case from South Africa any positive effects on streamflow of three rounds of thinning (45%, 35%, and 50% after 3, 5, and 8 years) *Eucalyptus grandis* plantations were masked entirely by the continued reduction in flows resulting from the overall vigorous growth (and thus water uptake) of the trees. The message from these examples is a clear one: thinning has to be rather drastic before a marked effect on streamflows can be expected.

Selection logging in tropical rainforest does not produce measurable effects on streamflow for harvesting volumes up to $20\,m^3\,ha^{-1}$ but the much higher logging intensities practised in the rich forests of Southeast Asia have a marked effect. Typical increases in annual water yield under 'average' rainfall conditions (*c.* $2000\,mm\,year^{-1}$) and harvesting intensities (33–40% of the commercial stocking) amount to 100–150 mm but larger increases are possible where harvesting is more intense and disturbance of the soil more widespread. The effect usually disappears within a few years as logging gaps become recolonized (**Figure 3**) although compacted surfaces like tractor tracks, roads, and log landings continue to be sources of enhanced runoff for much longer (decades).

Apart from the degree of cutting, the configuration of the resulting gaps also has an influence. During the first dry season after the creation of differently sized gaps in tropical rainforest in Costa Rica, soil water reserves were depleted most rapidly under undisturbed forest, followed by 6-year-old regrowth, pioneers in an elongated narrow gap, and pioneer vegetation in the center of a large square gap (**Figure 3**). Only 1 year later, however, soil water depletion in the smaller gap already resembled that of the 7-year-old vegetation,

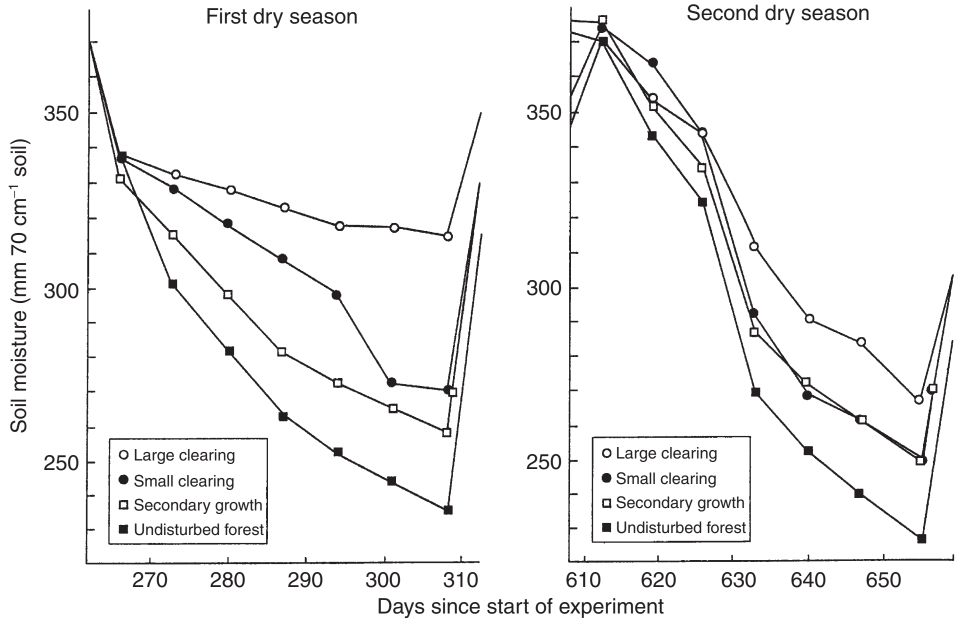

Figure 3 Soil moisture content in the top 70 cm of soil below undisturbed tropical rain forest, 6-year-old secondary growth, and in a narrow (10 × 50 m) and a large (50 × 50 m) clearing in lowland Costa Rica during two consecutive dry seasons. Reproduced with permission from Parker GG (1985) *The Effect of Disturbance on Water and Solute Budgets of Hillslope Tropical Rainforest in Northeastern Costa Rica*. PhD thesis, University of Georgia, Athens, GA.

whereas that for the larger gap had increased considerably as well. The higher water uptake by the vegetation in the smaller gap compared to that in the larger gap reflects the more rapid recolonization of smaller gaps as well as additional uptake by trees from the surrounding forest sending their roots into the gap (**Figure 3**).

The influence of the configuration of the cutting on the magnitude and duration of any increases in streamflow has been investigated in some detail. In the eastern USA the removal of 24% of the basal area from catchment LR 2 at Leading Ridge (Pennsylvania) caused a nearly twofold larger increase in flow than cutting 33% of the forest on catchment HB 4 at Hubbard Brook (New Hampshire) or catchment FEF 2 at Fernow Experimental Forest (West Virginia) (see **Figure 4**). The cutting at Leading Ridge consisted of a single block on the lowest portion of the catchment, whereas the cutting at Hubbard Brook took the form of a series of strips situated halfway up the catchment, and that at Fernow involved harvesting trees from all over the catchment. Therefore, increases in streamflow associated with strip cutting are smaller than for single blocks. This is in agreement with the finding of increased water uptake by surrounding trees upon opening up of the canopy (**Figure 3**) and the limited effect on rainfall interception by thinning described earlier.

No significant differences in streamflow increases were found between the cutting of the upper half of a

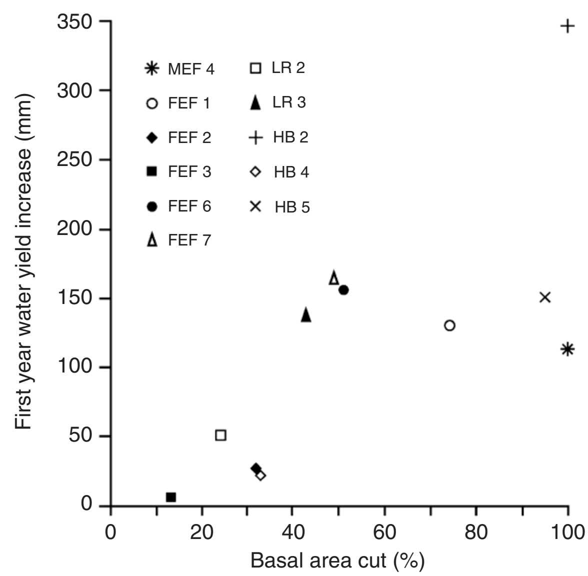

Figure 4 First-year increases in water yield in response to forest cutting in the northeastern USA. Reproduced with permission Hornbeck JW, Adams MB, Corbett ES, Verry ES, and Lynch JA (1993) Long-term impacts of forest treatments on water yield: a summary for northeastern USA *Journal of Hydrology* 150: 323–344. MEF, Marcell Experimental Forest, MN; FEF, Fernow, WV; LR, Leading Ridge, PA; HB, Hubbard Brook, NH.

catchment (such as at catchment 7 at Fernow; FEF 7 in **Figure 4**) or the lower half (catchment FEF 6 in **Figure 4**). Likewise, removal of the vegetation around watercourses in areas with a high rainfall surplus did not produce increases in water yield above those associated with the removal of an equal area of forest elsewhere in the catchment. However, where forest evaporation consumes a much larger proportion of the rainfall and where the terrain is more gently sloping than in the examples shown in **Figure 4**, the effect of cutting trees in the lower third to half of a catchment may well be rather more pronounced than that of cutting the upper third to half. Under such subhumid conditions, water uptake by trees having ready access to groundwater is usually higher than that of trees further up the slopes. High water tables are typically associated with the areas around streams (the riparian zone), footslopes and depressions in the landscape; these, in turn, are mostly found in the lower parts of catchments.

Effects of Forest Clear-Felling and Regrowth on Water Yield and Hydrological Response

Well over 100 (paired) catchment treatment experiments have been conducted (mostly in the temperate zones of the world) to ascertain the nature and extent of streamflow change resulting from forestry operations (mostly clear-felling). Analysis of the literature on catchment treatment experiments indicates that one can confidently generalize about the direction and approximate magnitude of streamflow changes following particular alterations in forest cover. Some of the more robust generalizations are discussed below.

Generalization No. 1: Forested Catchments Yield Less Total Streamflow than Cleared Catchments and the Difference Increases with Mean Annual Rainfall

Almost all catchment treatment experiments have shown that streamflow increases as forest cover decreases, and vice versa (**Figure 5**). The reason for this is that forests evaporate significantly more water than grasslands or crops. Although transpiration rates (soil water uptake by plants) under conditions of ample soil water do not differ much between forests and nonforest vegetation, rates of evaporation from vegetation wetted by rain (rainfall interception) are much higher from tall, aerodynamically rough surfaces like forests. In addition, the deeper roots of trees allow continued water uptake when more shallow-rooted plants have to give up during prolonged rainless periods. Because rainfall interception totals are higher in wetter years, the impact of forest clearance (i.e., after interception falls away) increases with mean annual rainfall (**Figure 6**).

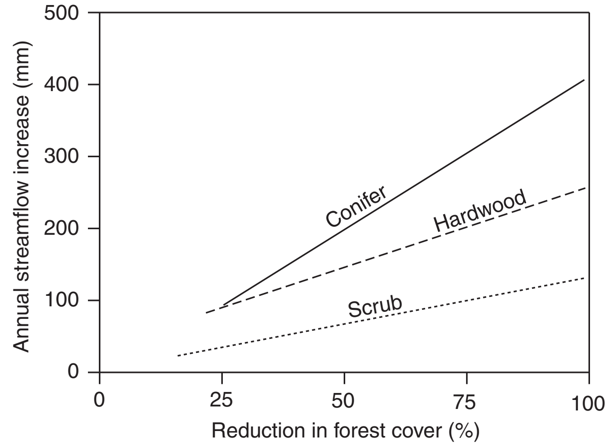

Figure 5 Relationships between reduction in forest cover and increase in annual catchment water yield. The general trend lines show the respective relationships for three types of woody vegetation. Reproduced with permission from Bosch JW and Hewlett JD (1982) A review of catchment experiments to determine the effects of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55: 3–23.

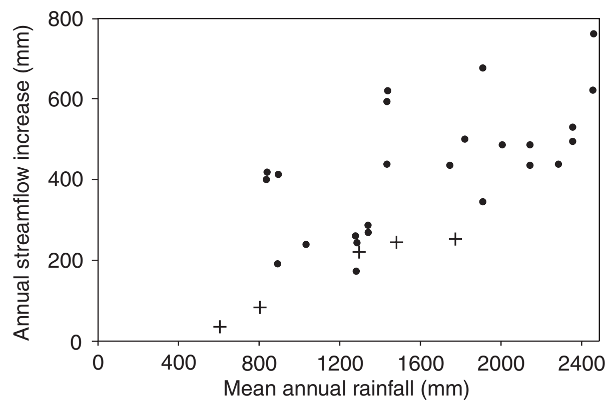

Figure 6 Effect of mean annual rainfall on increases in total water yield caused by total clearance of conifer and scrub vegetation (adapted from Bosch and Hewlett 1982). Crosses denote the expected gains in water yield from converting eucalypt forest to pasture in Victoria, Australia. Reproduced with permission on Holmes JW and Sinclair JA (1986) Water yield from some afforested catchments in Victoria. In: *Hydrology and Water Resources Symposium*, 25–27 November 1986, Brisbane, pp. 214–218. Melbourne, Australia: Institute of Engineers.

Apart from rainfall, the magnitude of the change in annual streamflow is also affected by forest type and slope aspect. Generally, the largest changes are observed in the case of clearing conifers, owing to their dense evergreen habit and high interception, followed by native (but not exotic) eucalypt forests, then deciduous hardwoods (leafless in winter or dry season) and finally woody scrub vegetation (found in low rainfall areas) (**Figure 5**). Mean annual streamflow can be expected to rise by between 10 and 80 mm (but usually between 25 and 50 mm) for each

10% of catchment area cleared of forest, depending on the forest type and rainfall as discussed above (**Figures 5** and **6**). The importance of catchment exposition is illustrated by the difference in first-year streamflow gain after cutting differently exposed deciduous hardwood forest catchments in the southeastern USA. Flows from northerly exposed catchments increased by about 130 mm year^{-1} but increases from southerly exposed catchments (whose forests consumed much more water in response to the greater insolation of their slopes) were as high as 400 mm year^{-1}. Most studies indicate that the relationship between treated area and streamflow change is linear (**Figure 5**), although there is some evidence that in subhumid areas the magnitude of streamflow change is reduced if forest treatments take place away from streamside areas.

Generalization No. 2: Streamflow Increases Following Forest Cover Reduction Are Transient and Temporary when Same-Species Regeneration Occurs

In a forest which is cleared or killed by wildfire but permitted to regenerate with the same species, streamflow increases are both transient and temporary. Streamflow increases normally reach a peak within 2–5 years after clearance, then decline to pretreatment levels over a period of between 3 and 35 years (but usually within 10 years), depending on rainfall, soil factors, and forest regrowth rates. This pattern can be explained by the fact that a new vegetation first has to establish itself before water use is gradually increased again. Also, elevated streamflow levels tend to last much longer (15–35 years) when regeneration has to originate from seeds than when massive resprouting occurs (3–7 years).

Part of the increase in streamflow after cutting reflects an increase in catchment response to rainfall. Usually, such storm runoff is generated in wet spots in the landscape, mostly around streams and depressions. Runoff-producing areas are enlarged after forest removal because of the associated increase in water inputs to and reduced uptake from the soil. Once a new vegetation cover is established which starts to actively withdraw water from the soil the extent of the runoff-producing areas is reduced again. However, roads and other compacted areas continue to deliver storm runoff to the streams on a more permanent basis although their areal extent is usually small.

Generalization No. 3: Forest Age Affects Evapotranspiration Rate and Hence Streamflow

A small but significant set of catchment treatment experiments and hydrological process studies indicate that young forests have higher evapotranspiration rates than mature forests, resulting in notable streamflow differences between young and old-growth stands. One of the most comprehensive studies of forest age on streamflows concerns work undertaken in the mountain ash forests of southeast Australia. The ecology of these forests is distinctive, in that they only regenerate after severe wildfire which kills the trees and produces a heavy seedfall. These forests are thus usually even-aged and monospecific, and tend to live for several hundreds of years unless they are killed earlier by wildfire. Significantly, the eucalypts thin out naturally over time, resulting in major changes in forest structure and hydrologic function as stands age. It has been shown that regrowth mountain ash forests aged 25–30 years yield about half the mean annual streamflow of mature stands aged 200 years (i.e., 580 vs. 1195 mm year^{-1} for 1950 mm mean annual rainfall). It has further been shown that it may take between 50 and 200 years before mean annual streamflow in a regenerating mountain ash catchment returns to levels observed in old-growth stands (**Figure 7**).

The effect of stand age on forest water use, and by implication streamflow, is not confined to mountain ash forests. Similar findings have been reported for mixed-species eucalypt forests in the northeast and southeast regions of New South Wales, Australia, in conifer plantations in South Africa, in deciduous hardwood forests in Japan and central France, as well as in coastal redwood forests in California and secondary forests in the Brazilian Amazon.

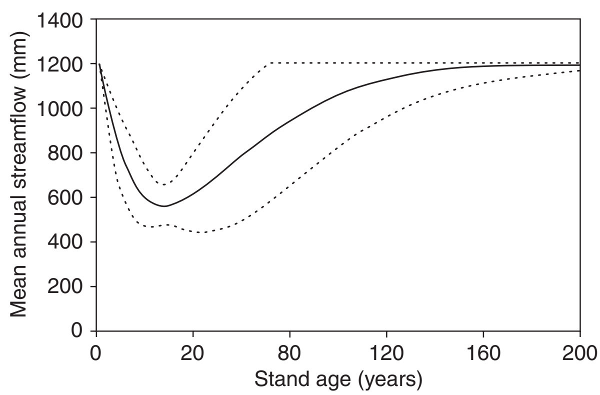

Figure 7 Relationship between forest age and mean annual runoff from mountain ash forest catchments, southeastern Australia. Dotted lines denote the 95% confidence limits on the relationship. Reproduced with permission from Vertessy RA, Watson FGR, and O'Sullivan SK (2001) Factors determining relations between stand age and catchment water yield in mountain ash forests. *Forest Ecology and Management* 143: 13–26.

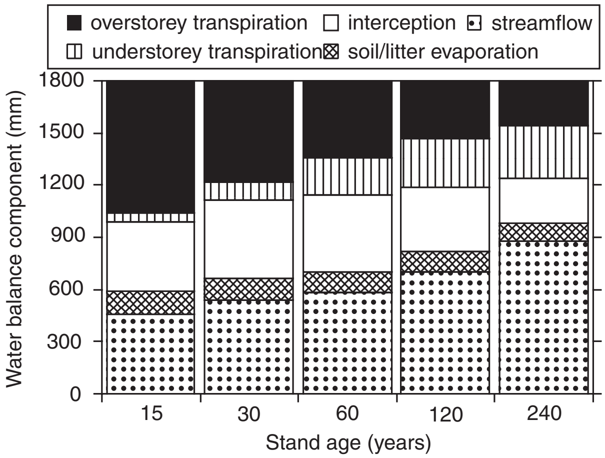

Figure 8 Water balance components for mountain ash forest stands of various ages in southeastern Australia, assuming an annual rainfall of 1800 mm. Reproduced with permission from Vertessy RA, Watson FGR, and O'Sullivan SK (2001) Factors determining relations between stand age and catchment water yield in mountain ash forests. *Forest Ecology and Management* 143: 13–26.

An explanation for the stand age–streamflow relationship in mountain ash forests has been provided by elucidating the leaf area and evapotranspiration dynamics of stands of various ages (**Figure 8**). As the forest matures, total leaf area declines and a greater proportion of the leaf area is allocated to the understory which experiences a gradually more humid and less ventilated microclimate. This results in lower overall water use and hence increased streamflow. Tree physiological measurements indicate that tree sapflow rates decrease with age, owing to increases in the resistance experienced by the flow as stems and branches lengthen and leaf ages increase. Such age-dependent effects on forest water use will tend to be maximized in long-lived, self-thinning, very tall forests.

Generalization No. 4: Forest Cover Affects the Magnitude of Streamflow Peaks for Small and Medium Events

As outlined earlier, the clearance of forests leads to an increase in catchment soil water status which tends to expand wet, runoff-producing areas. Therefore, cleared catchments respond more quickly and more vigorously to rainfall events. Most catchment treatment experiments show that the magnitude of discharge peaks is increased by forest clearance for small and medium-sized rainfall events, particularly when soils are disturbed by logging machinery and the establishment of road networks. However, it is generally accepted that modification of forest cover has little to negligible impact on flood peaks generated by extreme events, say those with recurrence intervals of 100 years and upwards. Under such extreme conditions, catchment runoff response is governed by the capacity of the soil to accommodate additional rainfall. If this capacity has been filled already by previous heavy rainfall, then the presence or absence of a forest cover is no longer decisive. Also, it is important to bear in mind that the local effects of forestry activities on stormflow tend to be diluted at larger scales by more modest flows from other areas receiving less rain or being less disturbed. Generally, the overriding factors in extreme flooding are the duration and intensity of the rain and the spatial extent of the rainfall field.

Nevertheless, there is reason for caution. Recent work in the Pacific Northwest region in the USA has demonstrated that forest clear-felling and the presence of an extensive road network each increased average stormflow volumes by *c.* 10%. Whilst the relative effect of the clear-felling diminished with the size of the stormflow generating event, the effect of the road network increased with event size.

Modeling the Hydrological Impacts of Forest Manipulation

As shown in the preceding sections, different forest manipulations affect the water flows through catchments differently. Traditionally, forest hydrologists have relied on costly and time-consuming paired catchment experiments to evaluate such effects. Whilst this approach enabled the construction of general curves from which changes in annual streamflow totals can be read as a function of annual rainfall (see **Figure 6**), or first-year increases in flow as a function of percentage basal area reduction and catchment aspect for particular areas at best, the results are often so variable as to render their applicability for more detailed water resources planning rather limited (**Figures 5** and **6**). Also, the black-box nature of the paired catchment technique is unable to evaluate the relative importance of the governing factors underlying the observed changes in flow, and this severely limits the possibilities for extrapolation of results to other areas or years.

Process-based hydrological models represent an alternative way of predicting how catchments might respond to different forms of management. Because many practical forest management questions have a spatial dimension to them, and because landscapes are usually made up of a complex mosaic of different land uses, such models should preferably be 'distributed,' that is: capable of taking into account spatial variations in topography, soils, vegetation, and climate. During the last 10–15 years, considerable progress has been made with the modeling of forest hydrological and ecological processes over a range of spatial and temporal scales. Within-catchment applications of such models relevant to forestry include the prediction of wet zones in the landscape (governing machine access) and the delineation of areas especially prone to surface erosion, gullying, or landsliding. Another example concerns the evaluation at the hillslope scale of the water balance and growth performance of different tree planting configurations (e.g., block planting vs. strip planting) under subhumid conditions. Whole-catchment applications include the simulation of changes in tree growth and water yield after clear-felling during forest regeneration or of a conversion of forest to pasture. To address forestry-related questions of catchment water management at larger scales (100–1000 km^2), simpler (but still spatially distributed) models have been developed and used to simulate (for instance) long-term changes in water yield due to forest fire and subsequent regeneration in a spatially distributed manner. Such models, if applied properly, can lead to more rational land and water management decision-making. However, whilst distributed models represent the only class of simulation models capable of capturing the complex feedback mechanisms that occur upon disturbing hydrological systems, they are also data-demanding. In addition, at larger scales there is the problem that good results require equally good data on the spatial distribution of rainfall. However, there is reason for optimism as various remote sensing technologies that are currently still in their infancy can be expected to become widely available within the next decade. This will greatly facilitate data acquisition and upscaling of hydrological results over larger areas.

The last decades have seen the waning of the 'empirical age' of catchment treatment experimentation and ever more rapid developments in our ability to model complex natural systems in a spatially explicit way. Although the arrival of process-based distributed hydrologic models and ongoing improvements in measurement equipment, remote sensing technology and computing power guarantee that there are exciting times ahead for forest hydrologists, continued field experimental efforts will remain important for model calibration and testing.

See also: **Harvesting**: Roading and Transport Operations. **Hydrology**: Hydrological Cycle; Impacts of Forest Conversion on Streamflow; Impacts of Forest Management on Water Quality; Impacts of Forest Plantations on Streamflow; Snow and Avalanche Control; Soil Erosion Control. **Operations**: Forest Operations Management. **Soil Development and Properties**: Water Storage and Movement. **Tree Physiology**: A Whole Tree Perspective.

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