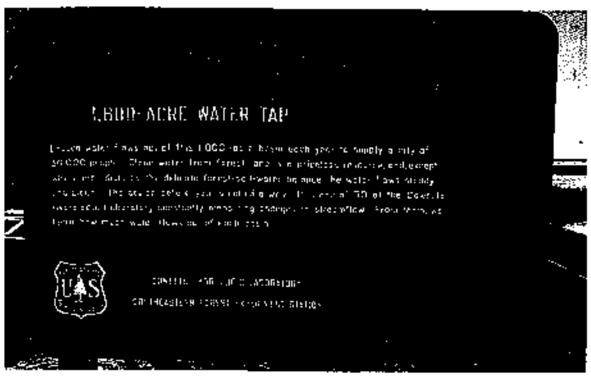
Forests or floods?

Tim Burt and Wayne Swank

This article shows how experiments at the Coweeta Hydrologic Laboratory in North Carolina have deepened our understanding of the ways in which forested catchments respond to land use change. Drainage-basin hydrology is a popular topic, often at AS. Human impact on stream discharge as a result of changes in vegetation cover is an important theme.



***Above:** The Coweeta basin is in the southern Appalachians, not far from Smoky Mountain National Park. There was extensive logging in the region as people settled from the mid-eighteenth century onwards. During the twentieth century, forests were allowed to grow again.*

***Left:** Signs giving information to visitors have long been a feature at Coweeta.*

Some information about Coweeta — inset 1

The Coweeta Hydrologic Laboratory is in the Blue Ridge province of the southern Appalachian mountains in western North Carolina (latitude 35° 3' N, longitude 83° 25' W). The Coweeta basin has a total area of 16.3 km². Altitude ranges from 1,592 m to 675 m at the basin outlet. Since 1934 a total of 32 weirs have been installed on streams within the basin, of which 16 are still used today. Some were abandoned after particular studies were completed.

Figure 1 shows the main catchments that have been used in paired catchment studies; the numbers indicate individual catchments referred to in this article. Eight catchments, ranging in size from 12 ha to 49 ha, have remained relatively undisturbed since 1934 and serve as controls for the paired catchment experiments.

The climate of the region is classified as marine, humid temperate because of high moisture and mild temperatures. Precipitation is distributed fairly evenly throughout the year. Annual totals average 1,800 mm at low altitudes increasing to 2,500 mm at the highest altitudes; snowfall makes up less than 5% of the total. Annual streamflow tends to be about 45% of rainfall in lower basins but as much as 75% in the higher basins, which have less soil-moisture storage capacity, return more rainfall as storm runoff and have a lower evaporative demand. Mean annual temperature is 12.6°C at the base station, with an average monthly low of 3.3°C in January and a high of 21.6°C in July. The predominant trees at Coweeta are a mixture of deciduous oaks, maple, hickory and poplar. Chestnut used to be the dominant species but this died out in the 1930s after the invasion of the chestnut blight fungus.

We are used to doing controlled experiments in the laboratory: we keep most conditions the same but by varying one variable systematically, we can see how the system output changes. The same approach can be used in small field trials (e.g. to see how crop yield varies with fertiliser application) but it is difficult to conduct such experiments at the larger landscape scale. In hydrology, one notable exception has been the use of 'paired catchments'.

Paired catchment experiments

Most people agree that the first paired catchment experiment was conducted at Wagon Wheel Gap in Colorado, starting in 1909; this set the pattern for others to follow. For a paired catchment study, two catchments are selected, as close together and with as similar characteristics as possible. To start with, flow records are collected from both catchments - this is the **control** (or calibration) period. Then one catchment is 'treated' (e.g. trees are chopped down). This is the **treatment** period. Measurements continue and the actual flow in the treated catchment is compared to the flow predicted using data from the control catchment. This is the **treatment** period. Any differences between actual and predicted data are presumed to be due to the effects of the treatment. At Wagon Wheel Gap, the US Forest Service and Weather Bureau wanted to know the effect of different types of vegetation on evaporation loss; this has been a persistent theme of paired catchment research ever since.

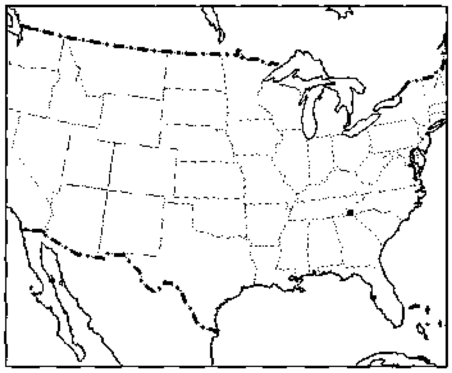
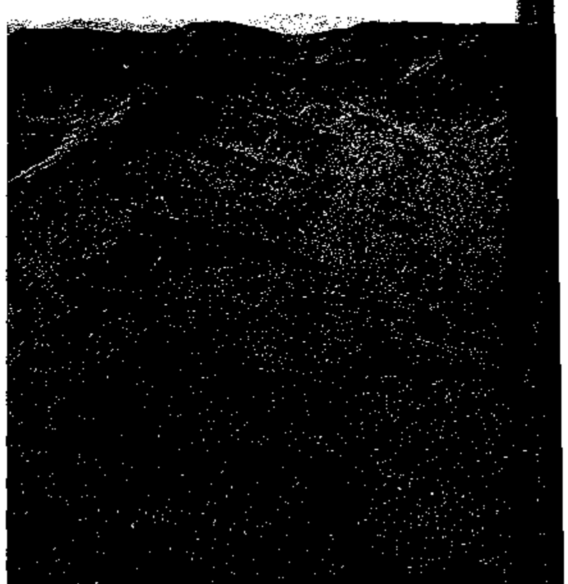
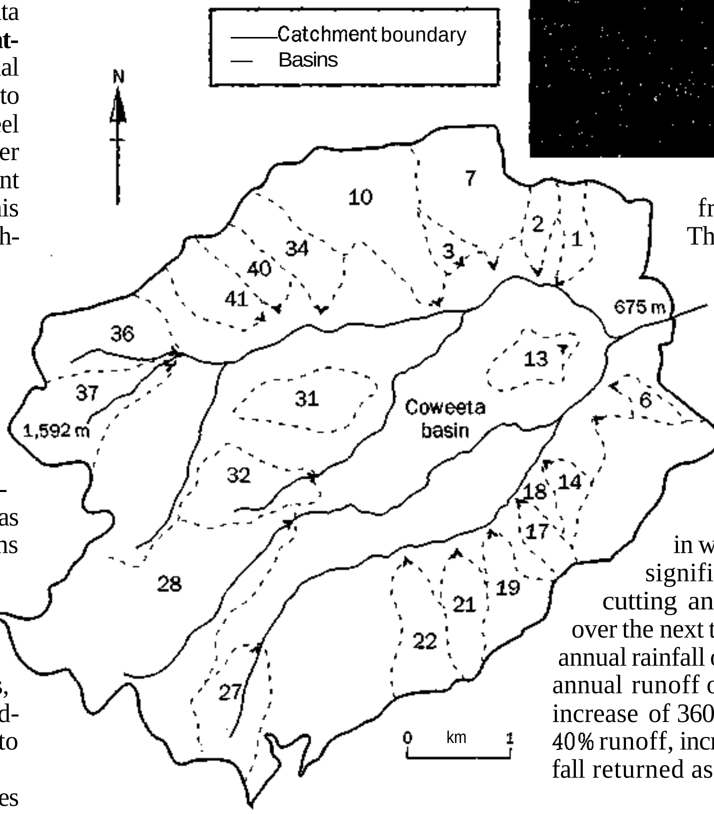


Figure 1 Map showing the location of Coweeta.





Setting up Goweeta

Controversy over the role of forests in regulating streamflow peaked in the USA after the disastrous 1927 flood of the Mississippi, and a vigorous effort to collect information on forest cover and streamflow began. At the same time the USA was in the depths of depression, with millions unemployed and hungry. So, when the Coweeta Experimental Forest was established in the southern Appalachians in 1934, the labour needed to construct the necessary infrastructure (roads, laboratories, gauging stations, etc.) was funded by the federal government, which provided money to put the unemployed to work.

Coweeta was the brainchild of Dr Charles Hursh: he saw many purposes in setting up the study, but two were especially important. The first task was to investigate links between vegetation and runoff in undisturbed forest. The second need was to establish the relationship between agricultural land use, runoff and erosion. There was still a good deal of farming on the steep slopes of the Appalachian mountains at this time and Hursh regarded forests as 'corrective' cover, protecting soils and reducing flood risk. It was within this context that the paired catchment experiments at Coweeta began. A brief site description is provided in Inset 1.

Streamflow changes at Coweeta after disturbance

Streamflow response to clearcutting and regrowth

Long-term effects of clearcutting on water yield are important in both water resource planning and evaluation of nutrient export from forest ecosystems. There have been four experiments at Coweeta, almost 200 years of streamflow data in total. One catchment has been clearcut twice, in 1940 and 1963, with no removal of forest products and with natural regrowth allowed.

Figure 2 shows the way in which streamflow increases significantly immediately after cutting and then recovers steadily over the next two decades. Assuming an annual rainfall of 1,800 mm and a 'natural' annual runoff of 900 mm, the first-year increase of 360 mm represents an extra 40% runoff, increasing the fraction of rainfall returned as streamflow from 50% to

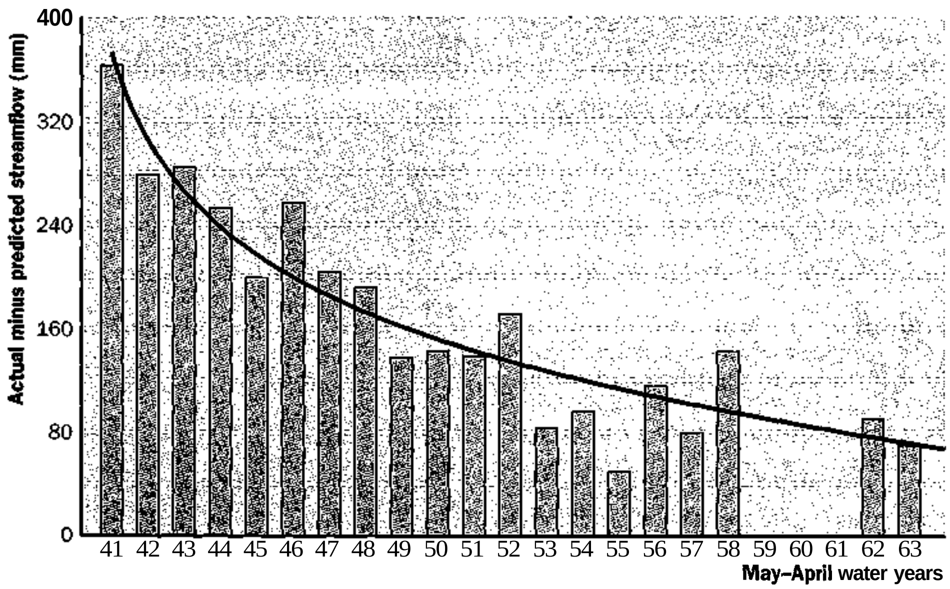
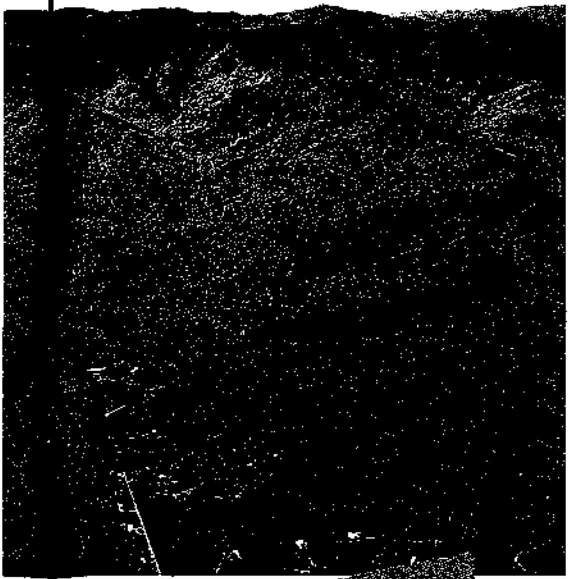
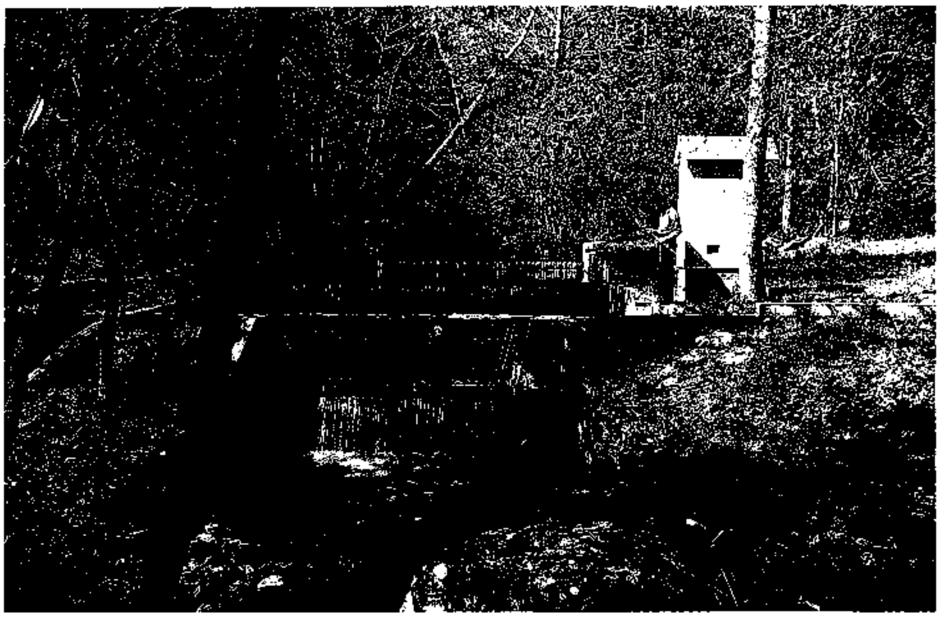


Figure 2 Changes in annual streamflow following clearcutting and natural regrowth.





Above: *View of the Coweeta basin looking west towards the Appalachian ridge.*

Above right: *The main gauging station on the outlet from the Coweeta basin. This trapezoidal shape of weir structure is known as a cipolletti.*

70%. Clearly, if this effect is mirrored across an entire region, then the impact of forest clearance on increased runoff downstream must be significant.

Changes in annual and monthly streamflow

The effects of clearcutting on mean monthly flows are shown in Figure 3. This shows an increase in streamflow in all but one month for a catchment that was clearcut and then cut annually for 7 years. The biggest absolute differences are in November and December, when the soil in the forested catchment is still relatively dry; in the cut area, soils have wetted up more quickly and streamflow has increased accordingly. By the end of the winter, soils are equally wet in both catchments and there is no difference in streamflow. The biggest relative difference in streamflow is in the autumn when the cumulative effect of evaporation though the summer has dried out soils in the undisturbed forest. The cut area has lost less water by evaporation so there is more available to generate streamflow.

Effects of cutting on the storm hydrograph

Two aspects must be considered here: the peak flow rates and the overall increase in quickflow volume. The increase in peak discharge depends on how the forest is cut: if there is minimal disturbance then there is little effect, but the construction of roads in particular is very significant and can cause peak discharges to increase by as much as 30%. The total volume of quickflow increases in similar manner: about 10% in less disturbed clearcutting, rising to 17% where 'commercial' logging was undertaken.

It is the increase in quickflow *volume* that is most significant for downstream flooding. It causes a problem because it means the total size of a flood peak downstream (i.e. the addition of all the floods from individual headwater catchments) will be greater. Thus, deforestation in regions like the Appalachians in the nineteenth and early twentieth centuries did cause an increase in flood risk in surrounding lowland areas. Hursh's notion of forests as 'corrective' cover was proved correct.

It follows that afforestation should reduce flooding downstream, but only if it is done

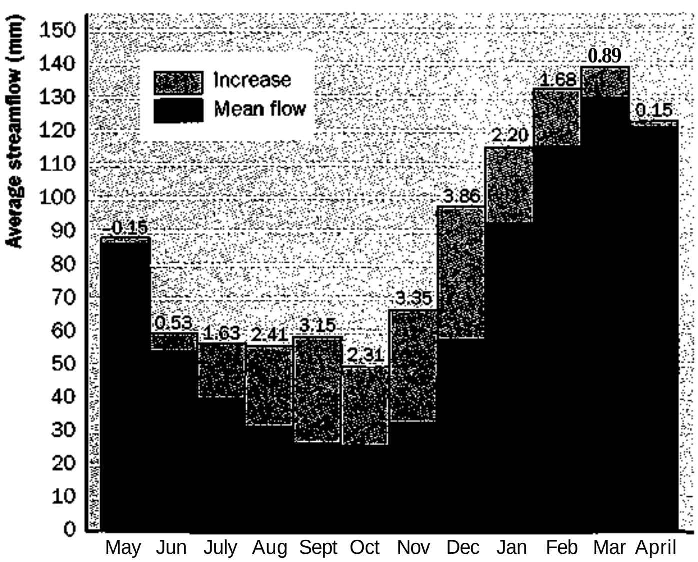


Figure 3 Increase in mean monthly flow after clearcutting.

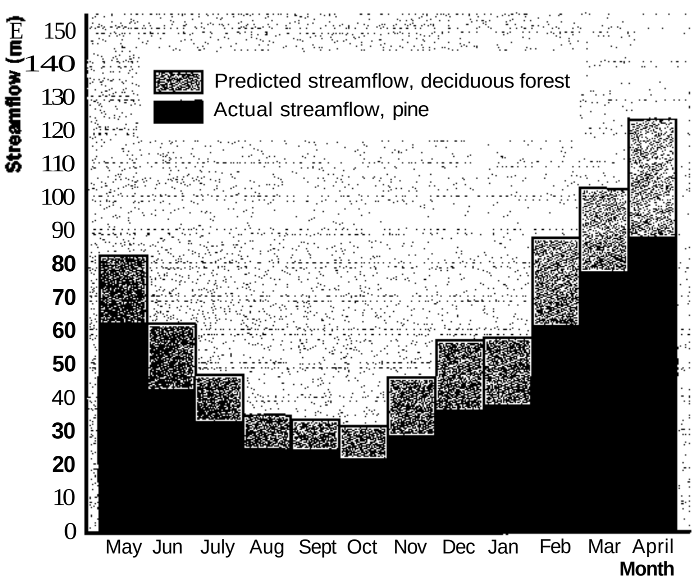


Figure 4 *Decrease in mean monthly flow following conversion from deciduous forest to white pine.*

Above: Subcatchment 17; the evergreen white pines are clearly distinguishable from the surrounding deciduous trees (late autumn view).

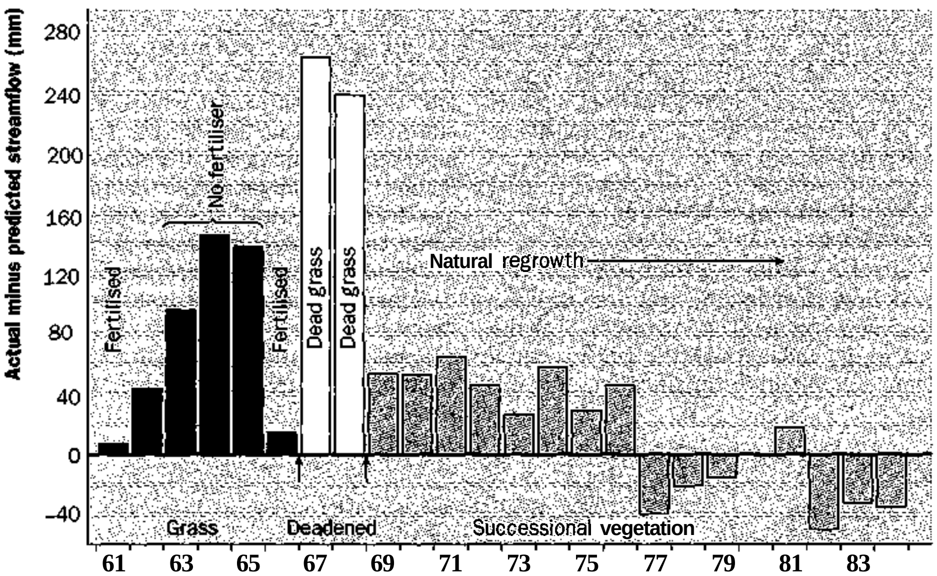


Figure 5 Changes in annual streamflowfollowing conversion of deciduous forest to grass.

Evaporation

Evaporation is defined as the conversion of water into vapour. In a catchment, there are four mam ways in which evaporation is achieved:-

(1) Direct evaporation from open water surfaces such as rivers and lakes.
(2) Evaporation of water from the soil.
(3) Transpiration of water by plants — waterjs drawn up through the plant stem or trunk and is lost as vapour through the leaf pores (**stomata**).
(4) Evaporation of water held on the leaf canopy (the most important fraction), branches, free trunks and forest floor ('interception loss').

Interception is now known to be the major reason for extra water loss from forests. Evaporation of intercepted water is very efficient given the turbulent airflow over tall trees. The American climatologist Thornth... lite invented the word **evapotranspiration** to remind us of the role of transpiration in contributing to evaporation losses. However, the simpler term **evaporation is** preferred.

carefully. If there are too many access roads or if land drainage is needed to make trees grow - as was done in the British uplands postwar - then the forests will not protect from flooding since storm runoff will still be rapid.

Species conversion

Two types of experiment were tried at Coweeta: one was the replacement of deciduous trees with evergreen white pine. Monthly flows for the pine compared to deciduous forest are shown in Figure 4. The differences are small in the summer but increase through the winter. The effect of the evergreen canopy is to intercept rainfall that would otherwise fall through to the forest floor. The interception loss element of total evaporation (see Inset 2) is therefore larger for pine because interception takes place throughout the year. Interception is most significant in the deciduous forest in summer when there are leaves on the trees.

The other experiment involved conversion from forest to grass, followed by natural succession. When the grass was fertilised (1961, 1966), there was very little difference between forest and grass, suggesting that lush grass can intercept and transpire a similar amount to a mature forest. However, as the grass declined in quality, runoff increased, amounting in 1964 and 1965 to an extra 140 mm or about one sixth of the annual total.

In 1967 and 1968 the grass was killed using herbicide and runoff increased dramatically, by about 240 mm (over 25% extra). There would still be interception by the dead grass and evaporation of soil water, but no transpiration, of course. From 1969 the catchment was allowed to regenerate naturally and soon the runoff was less than before clearance, probably due to the dense shrubs and small trees that grow rapidly at the start of the new forest succession.

Glossary

Baseflow Low flow that occurs during rain-free periods when river discharge is sustained by groundwater discharge or by outflow from lakes and reservoirs.

Discharge The rate of flow in a stream channel, measured in units of volume per unit time, usually cubic metres per second (or 'cumecs').

Quickflow As the name suggests, discharge that occurs quickly after rainfall. Sometimes called stormflow or flood runoff.

Runoff This is the discharge divided by the area of the catchment to give an equivalent depth of water. It can be useful to compare the depth of rainfall in a storm with the runoff depth.

Streamflow A generalised term to describe the flow of water in a stream. The words runoff and discharge may also be used in a general way too. However, they have more specific definitions (see above).

Conclusions

A mature deciduous forest cover in a catchment reduces streamflow compared to a clearcut area. This result has been replicated in many places around the world and is certainly not unique to Coweeta. There is both less quickflow and less baseflow from the forested catchment. Thus, as Charles Hursh correctly surmised, forests in headwater areas provide flood protection for locations further downstream. However, if water resources are scarce, it could be argued that more water could be supplied by clearing the forest. The benefits of increased water supply would have to be set against the increased risk of flooding.

Critical thinking

(1) Explain why streamflow increases when a deciduous forest is clearcut. What are the main changes in (a) evaporation, and (b) runoff processes?
(2) Is afforestation of the British uplands different in hydrological terms from natural regrowth of forests in the Appalachians? Would the same changes be observed in both cases?
(3) What happens when a tropical forest is cleared? Would the Coweeta experiments provide a helpful guide?
(4) What happens to rates of soil erosion and nutrient leaching when a deciduous forest is clearcut?

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Key points

- Paired catchment experiments are used to investigate the effect of changing vegetation cover on streamflow.
- The Coweeta Hydrologic Laboratory was established to investigate the impact of forests on floods and water yield.
- Streamflow, both quickflow and baseflow, increases when deciduous forest is cleared. The biggest differences arise when soils have rewetted in the clearcut catchment but not in the forest. The effect gradually disappears as the forest regrows.
- In relation to floods, the main effect of clearcutting is to increase quickflow volumes, but there may be some increase in peak flood discharge depending on the degree of disturbance.
- Replacing deciduous forest with other types of vegetation cover can increase or decrease streamflow depending on the nature of the new species used.

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