THE ROLE OF FORESTS IN THE HYDROLOGICAL CYCLE

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Summary

A major land use change is the addition and removal of forests from the landscape. As there are usually substantial differences in evaporation between forests and other vegetation, changes in forest cover can have important impacts on the amount and timing of streamflow. The major differences between forests and shorter vegetation are in the lower solar reflection coefficient (albedo) and higher aerodynamic roughness. Both of these characteristics of forests are related to their tall canopies which are distributed across a large vertical distance. The higher roughness of forests is particularly important in increasing rainfall interception losses compared to short vegetation. In addition, there are likely to be differences in surface conductance. These differences are associated with the ability of normally deeper- rooted forests to acquire water from lower soil horizons in times of limited rainfall and to close stomata in response to air humidity deficit.

Where forest water use by forests is greater than short vegetation, removal of forest cover will increase streamflow. An exception will be cloud forests whose removal may reduce streamflow. The impact of changes in forest cover on the timing of streamflow is less easy to predict. The presence of forests, with deep roots, might exploit deep stores of water in the dry season and thereby reduce baseflows. However, the presence of forests might encourage deep recharge of soil water in wet seasons and this deep recharge will sustain dry season flows.

The removal of forest is not necessarily in itself a cause of flooding. Associated with logging will be substantial soil compaction and an increase in impermeable land surfaces. It is these changes in catchment soil surface properties that are responsible for an increase in flood frequency.
Soil erosion by water occurs naturally even in undisturbed forests but is considerably enhanced in logged forests. The removal of the protection of the canopy cover increases detachment of soil particles by raindrops. In addition, areas compacted by logging activities and roads enhance surface runoff and transport of soil particles. The construction and use of forest roads is a particularly important contributor to sediment in forest streams.

The release of dissolved substances from undisturbed forests is related to the nutrient status of the forest and site. Nutrient release is lowest from forests on nutrient-poor sites. The annual release of nutrients increases linearly with the annual streamflow. Logging activities lead to a sharp increase in the concentration of dissolved substances in the streams that might persist for two or three years. The peak in dissolved substances declines in association with establishment of alternative vegetation or forest regrowth.

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1. Introduction

Future demands and pressures on the water and wood resources of the Earth will be increased for a number of reasons. Demands will increase because of population growth in less developed countries and because of an increase in per capita use in developed areas. The increase in timber needs are often met by afforestation schemes on land not recently covered by trees and also by clearing of natural forests which in many areas also provide a steady supply of water of high quality. Global climate changes may mean that precipitation will become less reliable. There are thought to be strong links between deforestation and climate change. Where there is a critical competition for land and water resources and a pressing need for environmental sustainability, it is necessary to evaluate critically and objectively the functioning of forests within the hydrological cycle. There is a strong interest in the influences of forests on hydrology with the impacts falling into two broad categories: firstly, the effects forests and their manipulation have on the amounts and dynamics of streamflow and groundwater and secondly the role of forests and forest management in influencing water quality.

Before considering the role of forests in the various aspects of water quantity and quality it is pertinent to describe the hydrological cycle in vegetation. It will be possible to focus on elements of the cycle where important differences between forests and other vegetation types exist. Focusing on the processes in the hydrological cycle enables us to identify where the physical and physiological characteristics of forests play important, direct roles in influencing hydrology, and the changes in hydrology when forest cover is increased or decreased. Managers, planners and developers have recognized that the drainage basin is the most convenient unit for resource management. However, a fuller understanding of the hydrological functioning of a catchment often comes from detailed studies at smaller plot or point scales.

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2. The Hydrological Cycle in Forests

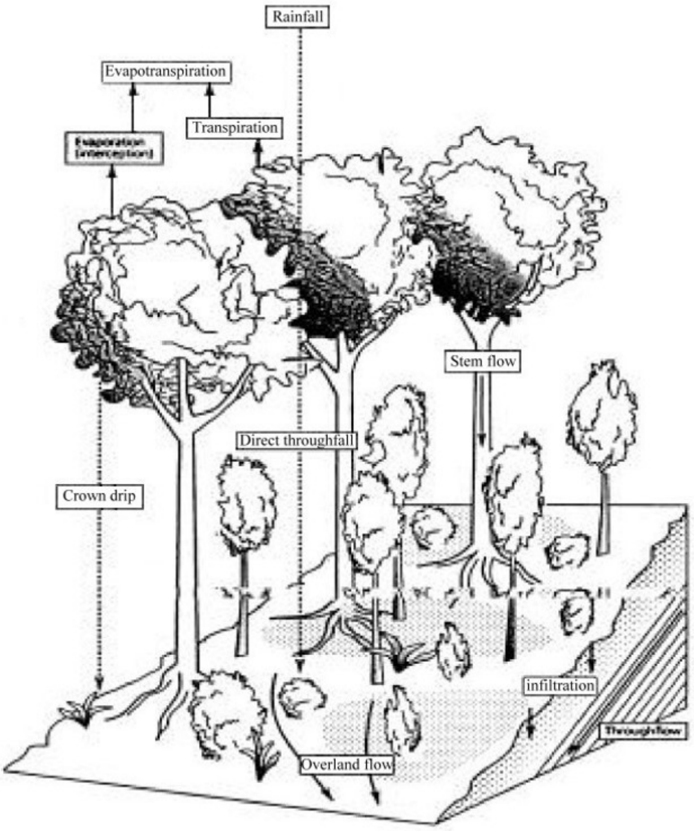

Figure 1: The hydrological cycle in a tropical forest.

The hydrological cycle of a forested ecosystem is presented in Figure 1. Depending on the geographical location, precipitation (P) arrives at the forest either as rainfall, fog or snow, but commonly as some combination of all three. In tropical and most temperate regions, rainfall is the most prevalent form of precipitation. Deposition of cloud/fog water might have a crucial role in some mountainous areas. Because of the interception and evaporation of some rainfall by the vegetation canopy, only a fraction of the total or gross precipitation - the net rainfall - reaches the soil surface and enters the soil. From there it can be extracted by the trees or other forest plants or it may contribute to soil water recharge, and subsequently to stream or groundwater flow.

Three pathways can be distinguished by which incident precipitation arrives at the forest floor: (i) a small fraction of the water reaches the forest floor without touching the leaves or stems – this is known as direct throughfall, (ii) another, also small, fraction of the water flows down the tree trunks as stemflow (SF), some of which will evaporate back to the atmosphere, (iii) the rest of the water hits the canopy and continues to fall as crown drip or is also evaporated during and shortly after the rainstorm. The evaporation of the water from rain held on the foliage, twigs, branches and trunks is the difference between the gross and net rainfall and is referred to as the rainfall interception loss (E_i). Generally, it is not possible to distinguish between crown drip and direct throughfall, so the two are usually combined and simply referred to as throughfall (TF). From the above we can construct an equation describing the water balance for a wet canopy:

$$P = TF + SF + E_i \qquad (1)$$

Water that reaches the soil surface can be redistributed in a number of ways and only a fraction of this water eventually contributes to streamflow. A small fraction will be evaporated back into the atmosphere as litter and soil evaporation (E_s). In any forest that has a dense leaf cover, E_s will be small, but it can be significant in sparse forests and in deciduous forests in the leafless periods. Evaporation losses from the litter layer may be regarded as an additional part of the forest interception loss. A large proportion of the rainfall directed to the soil is taken up by the vegetation and lost as transpiration (E_t). The sum of E_i, E_s and E_t is called evapotranspiration (ET).

It is the differences between forests and other vegetation in either the interception losses or the transpiration or both of these, that determines the changes in streamflow associated with afforestation and the various degrees of forest removal ranging from thinning to complete deforestation.

If the infiltration capacity of the soil is less than the net rainfall beneath the forest, excess water runs off as infiltration excess overland flow. Within undisturbed forests, this occurs infrequently due to the high conductivity of the topsoil. More typically, rainwater infiltrates into the soil, and, depending on vertical and lateral hydraulic conductivities, local soil moisture patterns and slope steepness, may take one of a number of routes to the stream channel.

The permeability of soil usually decreases with depth, and that means most water percolates until it meets an obstruction such as impermeable clay and will then be deflected laterally. Usually, this lateral flow in the soil profile is referred to as

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throughflow. During storms, water can flow laterally as saturated or unsaturated stormflow. When the soil profile – or the upper part of it – becomes saturated, rainfall that reaches these saturated areas will run off as saturation overland flow. The remaining soil moisture drains into the stream network by slow moving throughflow, accounting for a considerable part of the baseflow of the stream. Since rainfall inputs are discrete and sometimes, especially in seasonal temperate and tropical areas, widely separated in time, streamflow shows sharp increases in discharge associated with rainfall events and longer periods of slowly decreasing flow of water stored in the catchment. The rapid response of streamflow to rainfall suggests that part of the rainfall will follow a rapid route to the stream channel, thereby producing quickflow. The water traveling more slowly is termed baseflow.

The routing of flow through these various pathways has important implications to the flood and low flow responses of streams. Therefore there is particular interest in the impact that forests and forest management have on the amount and distribution of soil water and its path and residence time in the catchment.

3. Forests and Hydrological Processes

3.1. Forests and Rainfall

An enduring claim about forests is that they are responsible for creating rain. Later (Section 3.2), the tendency for forests to promote deposition of rainfall from clouds and fog is discussed but the evidence that, at the local scale, tree cover promotes rainfall in other ways is not supported by any substantial evidence. Studies using mesoscale climate models have shown that some of the intercepted water retained by forest canopies and re-evaporated will return as increased rainfall but this does not mean a net increase in rainfall.

There are a number of problems with studying the effects of vegetation changes, e.g., deforestation, on regional climate and rainfall. Many of these changes remain to occur and no direct experiment can be established which can be large enough to replicate the scenario of land use change or indeed change in climate. A solution lies in the use of climate models operating at the global or mesoscale. A general circulation model (GCM) or mesoscale model is a numerical description of the physical processes from the land surface up to the atmosphere in individual grid cells of typically 0.5° x 0.5°. An important process in the development of GCMs and mesoscale models is the implementation in the model of the appropriate surface properties for different vegetation types at the land surface. These properties are those that are fundamental to the exchange of water vapor, heat and momentum at the land surface (see below) and include, albedo (the solar reflection coefficient), surface conductance (the physiological controls of transpiration), aerodynamic roughness, leaf area index, rooting depth and rainfall interception properties. The response of the vegetation to soil water availability is parameterized through the surface conductance. Soil properties are also very important and these include hydraulic conductivity and the capacity for soil water storage. These properties have a major influence on the diversion of soil water to either of a number of pathways. These pathways are either at the surface, subsurface or towards deeper groundwater, and the relative contribution of the different pathways will

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be crucial to the hydrological responses of forests. Changes in the relative contribution of the different pathways is strongly influenced by activities associated with forestry operations and will considerably influence the hydrological responses of the catchment considerably.

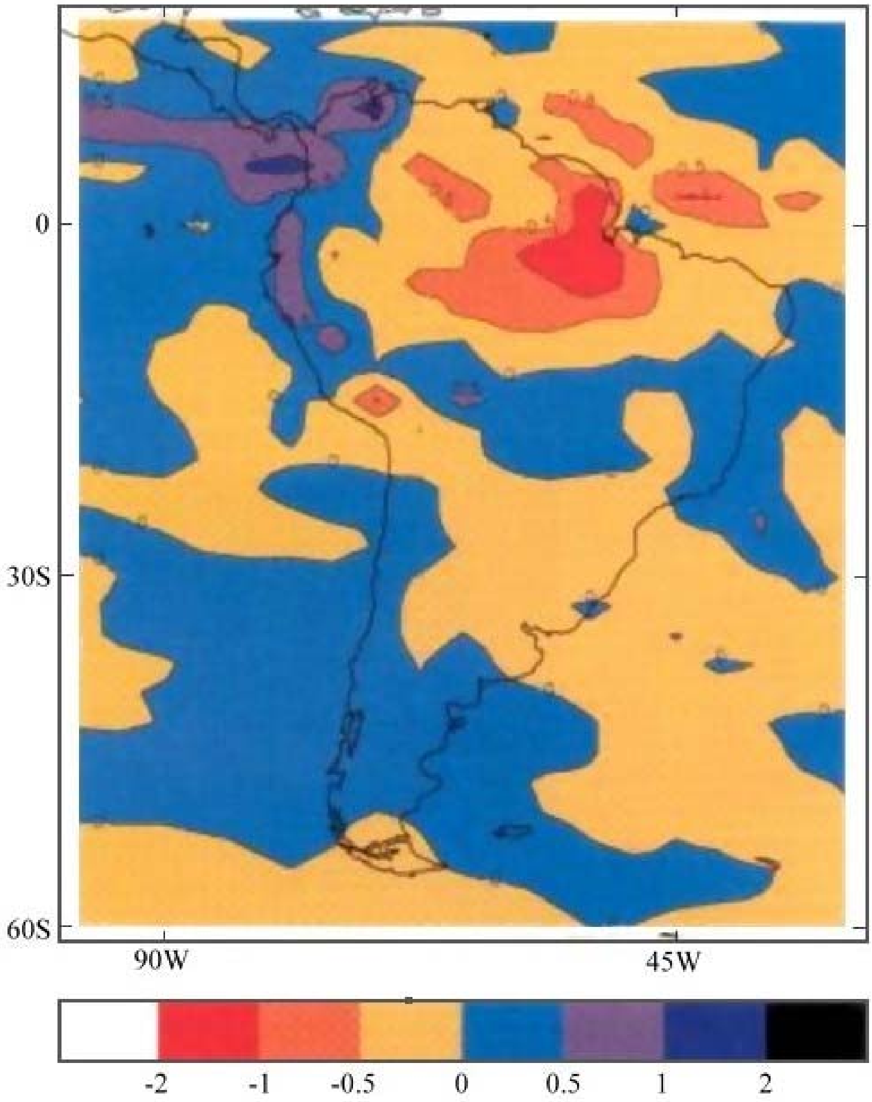

Figure 2: The annual variation in rainfall (in units of mm day^{-1}) predicted by the UK Hadley Centre GCM for complete replacement of the Amazon forest with pasture. The biggest reduction in rainfall occurs at the source of the Amazon River while the rain is increased in Colombia, Ecuador and Peru.

Much of the information required to parameterize GCMs has come from individual studies conducted over previous decades, usually with a more local requirement for that data at the time of the initial work. Nevertheless, new measurement programs have had to be implemented to acquire data, to fill in gaps in surface property data but also to acquire values to calibrate land surface schemes for vegetation types where this information is not available. Such an experiment was ABRACOS - Anglo-Brazilian Amazonian Climate Observation Study in which detailed climate, micrometeorological, plant physiological and soil physical data were collected for three pairs of forest and cleared forest (pasture) sites in the Brazilian Amazon. GCMs parameterized using data from this study have shown that removal of the Amazon forest would affect rainfall patterns with reductions in the drier northeast of the continent, by between on average 0.5 and 1 mm day^{-1}. Over the whole of the Amazon basin the reduction in rainfall would be around 10 percent (Figure 2). Therefore, at the large, regional scale there is support for the view that changes in land cover can have very dramatic effects on climate and rainfall. Strong correlations have been drawn between the land cover changes (and associated changes in surface albedo) and rainfall in the Sahel of West Africa. Further GCM modeling studies for the Sahel have shown that past removal of the native bush vegetation has altered the spatial distribution of rainfall in a way that correlates closely with observed changes in the distribution patterns of vegetation.

3.2. Cloud Water Deposition

There are certain circumstances where vegetation may be able to gain additional water by ‘stripping’ fine airborne water particles (typically ~10 μm radius) from mists or low cloud. The presence of the forest canopy as an obstacle causes these particles to coalesce and be deposited as precipitation. Cloud water deposition (also variously termed fog drip, occult precipitation or negative interception) is likely to be more prevalent in forested areas at high altitudes and/or close to coasts where fog or low cloud is prevalent. High wind speeds will enhance fog deposition in these situations.

The key characteristics of forests that promote cloud water deposition are their deep, well-ventilated canopies with individual leaves, twigs and branches well exposed to movements of air saturated with moisture. The water droplets are condensed out of the air masses moving through the canopies onto leaves and branches of the trees which act as efficient condensation sites for the fine water droplets.

Two main approaches are adopted to quantify the amount of additional precipitation coming from fog or mist. The first entails erection of vertical frames of grids or nets of fine material with associated collecting and recording devices. The second approach is the measurement and subsequent comparison of gross rainfall outside the forest with net rainfall measured in the forest in a range of conditions covering foggy and non-foggy conditions. The amount of additional precipitation afforded by fog deposition by forests is very variable but figures ranging from 20% to as much as 100 % more than gross precipitation have been reported for tropical montane cloud forests.

In a wide number of circumstances, the deposition of fog water can be particularly important to local hydrology. Replacement of high altitude forests that promote the large amounts of fog drip, with agriculture, can have a considerable impact on stream flow. It is not simply the removal of cloud forest that might reduce stream flow. Removal of forest well below the cloud base can alter the extent of the convective boundary layer and raise the cloud base, thereby increasing the altitude at which cloud deposition occurs.

As well as the direct impacts on stream flow of the removal of tropical montane cloud forests, there is an additional concern which is the effect of global warming on both the

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hydrology and biodiversity of tropical montane cloud forests. A general lifting of the cloud base or a reduction in the frequency of mist incidence, due to global or regional warming of the air associated with a rise in sea surface temperature can have fundamental effects on dry season stream flows. A strong relationship was shown between sea surface temperature, the number of rainless days and minimum stream flows in northern Costa Rica. There was also a strong relationship between declining streamflow and endemic amphibian species.

3.3. The Physical and Physiological Background to Forest Evaporation

The biggest advances in the ability to understand and predict evapotranspiration from forests and other vegetation has come from measurements of the components of evaporation; interception losses, transpiration and soil evaporation and subsequent attempts to apply physical and physiological models to the measured values. A further desire has been to produce models capable of predicting evaporation losses, perhaps at new sites, without the need for further detailed measurements. Arguably, the most realistic and successful description of evaporation from vegetation is the Monteith version of the Penman equation.

$$\lambda E = \frac{\Delta(R_\mathrm{n} - G) + \rho c_\mathrm{p} D g_\mathrm{c}}{\Delta + (c_\mathrm{p} / \lambda)(1 + g_\mathrm{a} / g_\mathrm{c})} \tag{2}$$

where,

Δ is the slope of the temperature versus vapor pressure curve
R_n is net radiation
G is soil heat flux
ρ is the density of the air
c_p is the specific heat of the air
D is the air humidity deficit
λ is the psychometric constant
g_a is the aerodynamic conductance
g_c is the canopy surface conductance

The equation incorporates the elements of the environment which are driving variables and two vegetation parameters, the aerodynamic and surface conductances. The aerodynamic conductance is influenced by windspeed and the roughness of the vegetation. The surface conductance is the parameter describing the physiological control of transpiration by the vegetation, and is a compound of the leaf area index (LAI, the foliage area per unit of ground area, $m^2\ m^{-2}$) and the stomatal conductance of the leaves. The surface conductance will change diurnally in relation to weather variables and seasonally, as soil water content influences leaf physiology and the changes in the amount of canopy.

The Penman-Monteith equation is also valuable in an inverted form where evaporation and weather variables are known. Aerodynamic conductance is estimated, and the equation is solved for surface conductance. Inverting the equation in this way allows

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surface conductance to be calculated and the influence on evaporation of physiological factors and soil water to be evaluated. Different methods of measuring evaporation are given below.

When the canopy is wet following rain, the surface conductance is infinitely high (the surface resistance is very low). This means that control of evaporation is dominated by the aerodynamic conductance. The much higher aerodynamic conductance of the taller, rougher forest canopies means that evaporation of intercepted water is more rapid from them compared to short vegetation.

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Biographical Sketch

Dr John Roberts is a tree physiologist specializing in the measurement and modeling of forest evaporation. In 1966 he graduated in botany at the University College of Wales, Aberystwyth and remained there to do a Ph.D. on the controls of growth and production in forest trees with Professor P.F. Wareing. In 1969, John Roberts joined Professor A. J. Rutter at Imperial College, London as a research assistant and worked on the physiological controls of forest evaporation. Field studies were done on Scots pine in Thetford Forest. In 1974 he moved to the Institute of Hydrology (now Centre for Ecology and Hydrology) at Wallingford. As well as continuing studies on the controls of water use by conifer forests in the UK, work was extended to broadleaf woodlands also in the UK. In addition he has participated in projects investigating; the impacts of tropical deforestation on climatology in the Brazilian Amazon, water use by *Eucalyptus* in southern India and the water balance and below-ground competition of agroforestry systems in Kenya. His research has also covered non-forest vegetation including: heather moorland in Yorkshire, rice in Sri Lanka, sugar cane in Mauritius and millet in West Africa.

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