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On the hydrology of industrial timber plantations

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Introduction

Timber plantations have become a rapidly expanding land use over the last half-century, especially in the subtropics and tropics. It has been estimated that there are now some (40–50) $\times 10^6$ ha of forest plantations in the tropics and warmer subtropics, being planted nowadays at a rate of roughly 2×10^6 ha year^{-1} compared with around 1×10^6 ha year^{-1} a decade ago (Evans, 1999). Eucalypt plantations cover more than 17×10^6 ha world-wide (FAO, 2002), more than 90% of which have been established since 1955 and roughly 50% during the last decade (Turnbull, 1999). The area of industrial plantations is often small compared with the area of native forest; however, their contribution to wood production is usually highly significant. Although accounting for only 5% of global forest cover, forest plantations were estimated to supply about 35% of global roundwood in 2000 (FAO, 2002), and this proportion is expected to continue to grow.

The expansion of timber plantations has been associated with concerns regarding their environmental effects, particularly in the case of eucalypts (e.g. Shiva and Bandyopadhyay, 1983). Probably the most prominent of these environmental issues is that of the hydrological effects of timber plantations.

Based on my experience with the thorough set of long-term, paired catchment experiments in South Africa established since 1936 (Wicht, 1967), I set out here my interpretation of the general findings of these experiments. My hope is that these generalizations may stimulate comparison with other parts of the world and prompt the consideration of plantation hydrology as a particular field within the broader discipline of forest hydrology.

My experiences, and the generalizations I make, come from productive timber plantations that grow fast enough to be economically viable and are managed for profit (which implies maintaining plantations in a state of high productivity). Growth rates of the plantations are generally in the range of 15 to 30 m^3 ha^{-1} year^{-1}. Mean annual precipitation (MAP) of the research catchments is above 1000 mm, but is seldom as large as the annual potential evaporation rates (PET); such that the ratio of MAP/PET is generally more than 0·5, and for the best sites is close to and occasionally exceeds unity. Soils have low fertility, but they usually have a depth greater than 1 m and may permit much deeper rooting (deep saprolites or other unconsolidated materials). Such humid conditions on hydrologically deep soils are not unusual for forestry around the globe, and may typify

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conditions for productive plantations in the tropics and subtropics.

The Hydrological Effects of Plantations: Generalized

The establishment of plantations leads to reductions in streamflows relative to the yield under native vegetation (and this is also true where plantations replace native evergreen forest). Under South African conditions the reductions in flow may be significant from as early as the first year after planting eucalypts and from 3 years for pine plantations (these times being closely related to canopy closure and the rate of establishment by the plantation).

Absolute streamflow reductions are greater in higher rainfall zones and in higher rainfall years (when more water is available), but relative reductions (expressed as a percentage of expected flows) are greater in drier zones (all the available water is consumed by the plantations sooner). Thus, plantations may cause streamflow to cease (dry-season flows in particular), and the time it takes for this to happen will be shorter in drier areas or where soil water reserves are smaller.

Dry-season flows (low flows) are reduced earlier and to a greater extent than are total flows (or wet-season flows), and once-perennial streams may cease to flow for part of the year. This stands to reason, as dry-season flows are sustained by subsurface water stores and these reserves are being depleted by the rapidly establishing tree crop.

A plot of streamflow reductions over time (a flow reduction curve) mimics a sigmoidal growth curve for the plantation, but is lagged in time, i.e. peak flow reductions occur later than the peak growth rates of the plantation. The lag in streamflow response is probably the result of trees having access to soil water that is stored in the hydrologically deep soils. Dye (1996a) found that 3-year-old eucalypts extracted water over the whole 8 m depth of a decomposed granite on which they were growing, and that 7-year-old eucalypts were drawing the bulk of their water supply from depths beyond 8 m. Where the soil water reserves have been depleted in this way, the soil's water stores then need to be recharged after harvesting (or once the evapotranspiration of trees is reduced) before streamflow will return to normal. For example, it took 5 years to restore streamflow after the clear-felling of the eucalypt afforested Mokobulaan catchment-A (Scott and Lesch, 1997).

Where a rapidly growing tree crop is exploiting subsurface water reserves that developed previously under a land cover with lower water use, annual total evaporation may exceed annual precipitation. In other words, water use is greater than replenishment rates, sometimes by as much as 100%. Such so-called 'mining' of soil water reserves is possible whether the water is in unsaturated zone or saturated zone reserves. On deep soils in India, water use by eucalypts exceeded annual rainfall by a large margin (Calder *et al.*, 1992), the excess being supplied by soil water reserves that had accumulated during years of above-average rainfall. Similarly, total evaporation from young stands of both *Eucalyptus grandis* and *Acacia mearnsii* in South Africa exceeded precipitation in the second year after planting (Burger *et al.*, 1999). Similarly, Morris *et al.* (1999), studying eucalypt plantations with access to shallow groundwater in Pakistan, found that water use exceeded precipitation. Such results do not necessarily mean that the land use is not sustainable, but do imply that a new and different catchment water balance will be established, and that streamflows will be negatively affected until soil water stores are again fully replenished.

Thus, the soil beneath such plantations acts as a reservoir, supplying water to sustain water use in excess of precipitation for several years, and then absorbing excess rainfall in wet years. From a hydrologist's perspective this means that the hydrological depth and storage capacity of the catchment needs to be taken into account, and that a simple water balance, such as $P = ET + Q$, cannot be established on an annual basis without the addition of full soil water and groundwater accounting. By contrast, in many temperate-zone forests the soil water stores are replenished on an annual basis, e.g. Coweeta (Swank *et al.*, 1988).

The Influence of Plant Vigour

The reasons for the hydrological effects of plantations may seem obvious where the change in land cover is from grassland to trees, especially when the grasslands are seasonally dormant, as is the case in South Africa. Relative to the grassland, timber plantations have deeper, more complex canopies, a deeper and more turbulent boundary layer, larger leaf area index and deeper roots, plus they may be growing actively for longer through the dry season. However, these differences are not the whole answer, as the same effects of afforestation have also been recorded where the change has been from native forest to man-made timber plantations, such as in the Westfalia catchment-D planted to *E. grandis* in South Africa (Bosch and Smith, 1989) and conversion of Nothofagus forest to pine in New Zealand (Fahey and Jackson, 1992).

Part of the explanation is that timber plantations are often particularly productive because the tree species being grown are exotic to the area and thus free of their native pests and diseases.

However, there is also a case for plant vigour as the critical difference; and transpiration is that component of water use that is truly different between the plant covers, accounting for most of the difference between the water use of productive plantation and a slower growing forest. This is not a new idea. Bosch and Hewlett (1982), in explaining the variation in the hydrological effects of forests, hinted at vigour as an important explanatory factor. Dye (1996b) tested this concept and found a strong correlation between the growth rate and transpiration of pine and eucalypt plantations.

Productive plantations can be seen, therefore, as transitional between forest and an agricultural crop, where growth and yield may be modelled as a function of total water use.

This link may be easier to establish in eucalypt plantations where transpiration is greater than interception losses, and more difficult to establish in situations where interception losses are higher, such as in canopy types (e.g. spruce) that typically intercept and retain large amounts of precipitation and climates with more frequent and lower intensity precipitation (e.g. upland plantations in the UK).

The case for vigour is also supported indirectly by more recent catchment study results from South Africa. As both pine and eucalypt plantations mature, so the water yield begins to return toward pre-afforestation levels (Scott *et al.*, 2000). Aging plantations use less water, affording the catchment a period of recharge of subsurface water stores. This 'slowdown' is not unique to plantations, and may be typical for the transpiration component of many forests. It was first reported (Langford, 1976), although over a much longer time scale, for the mountain ash (*Eucalyptus regnans*) forests in Victoria, Australia, in what, at first, appeared to be an exceptional case of streamflows being reduced following wildfire. During the juvenile and immature phases of this native eucalypt forest, which rapidly regrew after wildfire, streamflow was much lower than under the overmature cover of giant trees. However, streamflows were gradually restored to pre-fire levels as the forests matured beyond 40 years of age. Lower transpiration rates in the maturing trees are associated with reductions in leaf area index and a smaller sapwood area (Haydon *et al.*, 1996). In a similar way, it is probable that non-commercial or 'unthrifty' plantations that are slow-growing, old, or partially invaded with native woody species are probably little different from native forest in terms of water use. In other words, growth rate is the critical differentiating factor: highly productive forests (be they plantation or natural) will have the highest water use.

Conclusions

Plantation forestry is an important land use, and one that is expanding rapidly. In its most successful forms it has significant hydrological implications for the larger watersheds in which the planting is located. There appears to be a strong link between the growth rate and water use (and hence hydrological impacts) of plantations, and that this fact may justify considering the hydrology of industrial plantations to be a special case in the field of forest hydrology, somewhere between forestry and agriculture.

Plantation forestry has specific hydrological characteristics that are important. Multiple years are an appropriate time window for considering the water balance of plantations, because effects are lagged and recharge of subsurface water stores may take many years.

Growing trees quickly, something that is implicit in economically successful plantation forestry, is

going to cost water; you cannot have one without the other. In certain places this will cause conflicts. This is particularly likely where there are run-of-river water users downstream of the plantations, such as in Africa and India, and in regions with a distinct dry season, where conflicts over water can be expected to be greatest.

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